# Effect of Temperature and Current Stressing on Low Temperature Solder BGA Drop Performance

Alyssa Yaeger, Ph.D., Michael Meilunas
Universal Instruments Corporation
NY, USA
meilunas@uic.com

Sufyan Tahat
Auburn University
AL, USA

## ABSTRACT

BGA components constructed with low temperature solder (LTS) SnBiSbNi spheres were assembled using a matching alloy paste and then subjected to simultaneous direct current and temperature stressing to generate electromigration of the bismuth atoms. The samples were then drop tested to evaluate solder joint lifetime performance and the results were compared to non-stressed control samples. Solder joint failure analysis was performed by cross-sectional examination using scanning electron microscopy. The experiment described indicates that the current densities, joint temperatures, and stress durations examined could result in a significant reduction in drop reliability - even when minimal bismuth electromigration was observed in cross-section. The extent of the reliability reduction was highly dependent upon the solder joint temperature with joint temperatures of 85°C and 100°C resulting in rapid joint degradation while joint temperatures of 75°C showed little or no reduction in reliability relative to the control samples – even when the 75°C samples were subjected to relatively high current densities.

Key words: electromigration, drop/shock, LTS, bismuth, BGA.

## INTRODUCTION

Low temperature tin-based solders containing high weight percentage bismuth allow for electronic assembly at temperatures below those required for traditional SnPb and SAC alloys. One such alloy consisting of tin, 58% bismuth and small amounts of antimony and nickel was evaluated during the described experiment. According to the supplier, this LTS alloy has a liquidus of 145°C and a solidus of 140°C [1].

One concern with the adoption of bismuth-bearing alloys is the electromigration of the bismuth atoms. Electromigration is a transport phenomenon in which bismuth moves within the solder in the direction of electron flow from the cathode side to the anode side of a solder joint, resulting in a bismuth-heavy accumulation region at the anode. The rate at which bismuth migrates is directly proportional to current density and temperature, i.e., higher current densities and higher temperatures increase the bismuth migration rate.

Given that the electrical resistivity of bismuth is approximately 11 times greater than the electrical resistivity of tin, and that the thermal conductivity of bismuth is $1/8^{th}$ that of tin (Table 1), the formation of a continuous bismuth layer of increasing thickness at the anode may ultimately result in undesirable thermal and/or electrical performance. Also, given that bismuth is a relatively brittle material, it is believed that an accumulation of bismuth may result in a solder joint which is easily susceptible to failure when subjected to the high strains and/or strain rates encountered during accidental drop or other mechanically induced events.

**Table 1.** Material Properties of Bismuth, Tin and Copper [2]

| | Bismuth | Tin | Copper |
|---|---|---|---|
| Thermal Conductivity (W/m·K) | 8 | 67 | 401 |
| Electrical Resistivity (nΩ·m) | 1290 | 115 | 16.8 |

The experiment described in this paper was an investigation into the effects of temperature and current stressing on LTS BGA assemblies using mechanical drop testing in which multiple current densities were evaluated for solder joint temperatures ranging from an estimated 75°C to 100°C. To accomplish this, current was passed through the test samples using constant direct current power supplies while joint temperature was controlled by housing the samples in thermal chambers with heating and cooling capabilities. Samples were removed from temperature / current stress and drop tested as described in the following sections and selected samples were then subjected to solder joint failure analysis.

## EXPERIMENTAL DESIGN

### Test Vehicle

A dummy, daisy-chained BGA and mating circuit board were utilized for the work described. This test vehicle was specifically designed for high-current applications in that the circuit board and component traces were both wider and thicker than typical designs in order to conduct high current loads with minimal heat generation. The test vehicle was also designed specifically for drop testing by solder mask defining both the PCB and component attachment pads in order to reduce the likelihood of pad cratering during the drop test while increasing the likelihood of solder joint failure.

The test board measured 100x100x1mm and contained a six-layer construction. Signal layer 1 was designed for BGA attachment by including 0.8mm wide copper traces along the perimeter of the BGA footprint. These traces were measured to be approximately 69µm thick. The BGA attachment pads were created by using 0.38mm diameter solder mask openings within the traces, resulting in a mask defined pad geometry on the circuit board side of the solder joint. The board was procured with a copper OSP surface finish. Eight tooling holes were included on the test board, each located 46.7mm from the center of the board. The four tooling holes located nearest the corners of the board were used for fixturing the boards to the drop table. See Figure 1 for an image of the test board.

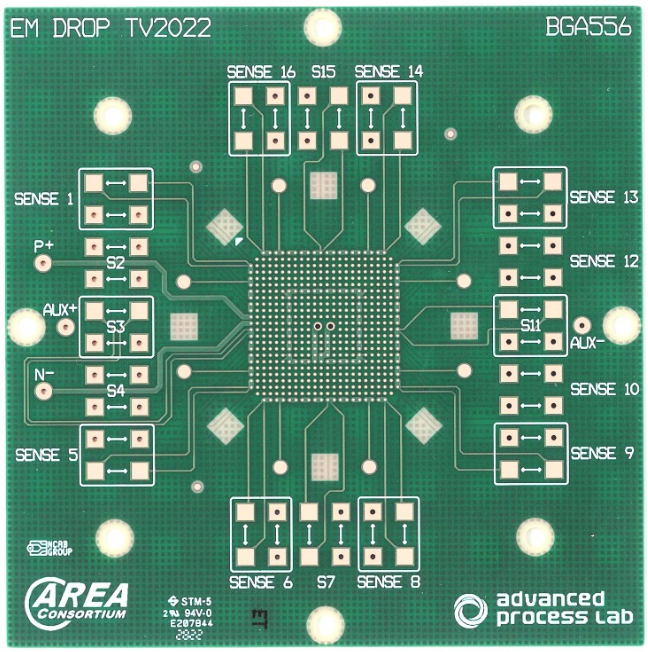


**Figure 1.** Image of Test Board Side A with BGA556 footprint.

The component, designated BGA556, was constructed from two layer, 25x25x2mm FR4 substrates containing an ENIG surface finish. The substrates contained 556 I/O arranged in a 24x24 array at 1.0mm pitch with corner and center bumps depopulated as shown in Figure 2. The BGA556 daisy-chain pattern included 0.8mm wide perimeter traces that were measured to be 65µm thick. These traces, much like those on the test board, were designed with 0.38mm diameter openings to which 0.40mm diameter LTS spheres were attached to form the BGA solder bumps.

The BGAs and boards also contained sense wiring in the form of 0.25mm wide surface traces that could be used for high accuracy voltage and/or four-wire resistance monitoring at individual solder joint positions during temperature / current stressing and drop testing. A total of 16 individual solder joints were configured with the high accuracy sense capabilities including the eight corner-most solder joint positions.

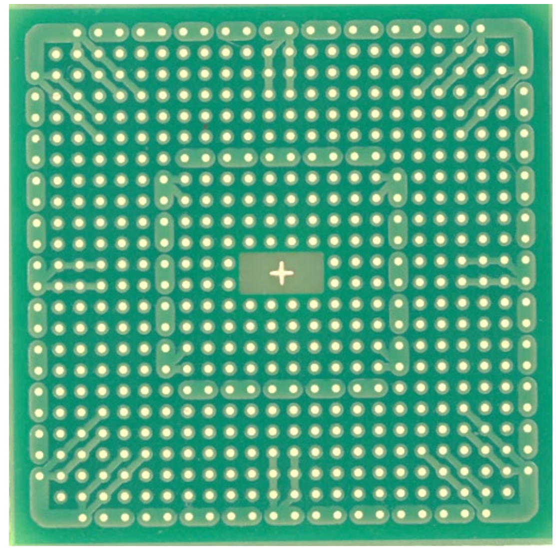

**Figure 2.** Image of BGA556 solder ball side prior to ball attachment.

**Assembly**

The test vehicles were assembled using a solder paste printing process. LTS solder paste was screen printed over the test boards using a 0.10mm thick stencil with 0.38mm diameter apertures and reflow soldering was performed in a forced convection oven with a nitrogen atmosphere containing less than 50ppm $O_2$. The reflow profile was designed to heat the solder joints to approximately 185°C with a total time above 140°C of 73 seconds. The reflow profile was based on supplier recommendations for the LTS paste and the peak temperature was intentionally maintained about 20° to 30°C below typical Sn37Pb processing temperatures to ensure a "low temperature" assembly process. A graphical representation of the reflow profile may be found in Figure 3.

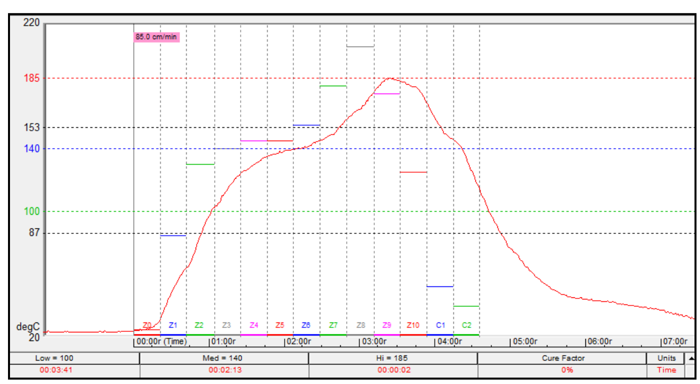


**Figure 3.** Reflow Profile

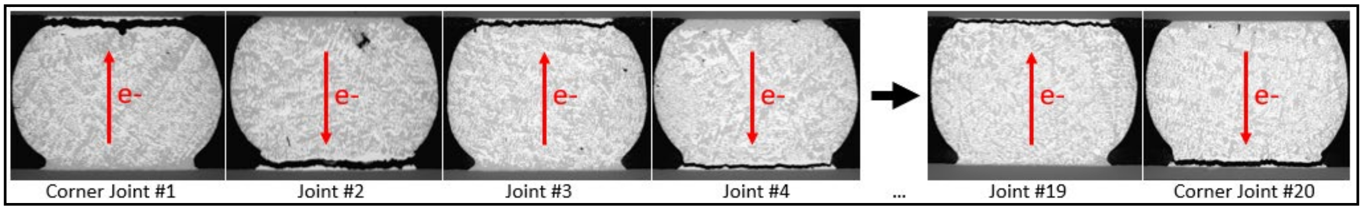


**Figure 4.** Scanning electron micrographs showing SnBiSbNi BGA solder joints stressed at 4.2A and 100°C for 120 hours and drop tested. All joints in the field of view failed at the anode side where bismuth accumulation had occurred [3].

Although the LTS paste was a no-clean formulation, the samples were cleaned shortly after reflow using an aggressive IPA rinse process to remove flux residues. This step was undertaken because the samples were to be exposed to high temperatures for extended times and the authors did not want potential hardening of the flux residues to impact the drop test results.

**Current and Temperature Stressing**

Previous research by the authors indicated that SnBiSbNi BGA556 specimens subjected to 4.2A with 100°C solder joints resulted in relatively quick bismuth migration and significant drop test degradation after just 24 to 120 hours [3]. Analysis of these samples showed that the solder joints always cracked near the anode side of each joint where a relatively thick layer of bismuth had accumulated (see Figure 4 and Figure 5).

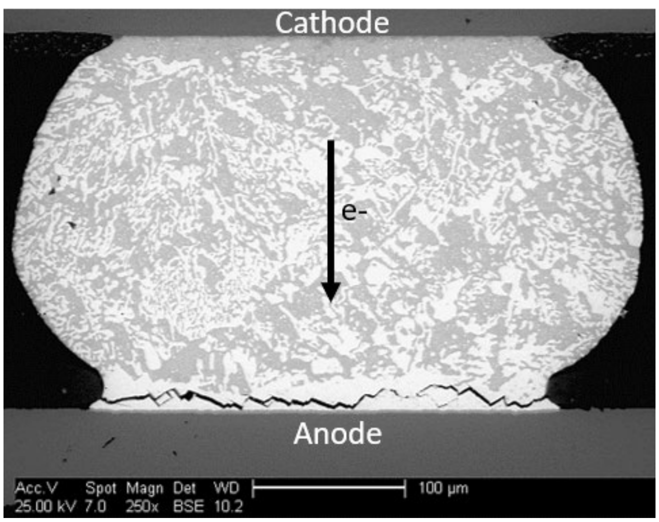


**Figure 5.** Scanning electron micrograph showing SnBiSbNi BGA solder joint stressed at 4.2A and 100°C for 120 hours and drop tested. Bismuth accumulation at the anode side and lack of bismuth near the cathode side are apparent [3].

Based on the previous results, it was decided that 4.2A, which equates to a current density of 3.7kA/cm$^2$, and 100°C solder temperature represented a "highly accelerated" test condition which at the time had no real-world analogue. Thus, for the research described, stress conditions were chosen to include current densities and solder joint temperatures similar to in-service conditions and to include a variety of "accelerated" conditions with higher temperatures and/or current densities than encountered during in-service conditions.

Based on conversations with industry experts, it was determined that a 75°C solder joint was a reasonable peak temperature for an LTS BGA in a commercial product and that current levels per joint typically range from 0.25 to 0.80 amps. Using this information, nine test cells with amperages of 0.25A, 0.50A, or 0.80A with 75°C solder joint temperatures were produced to represent the usage environment stress conditions while six populations using 0.50A or 0.80A with 85°C solder joint temperatures were produced to represent slightly temperature-accelerated stress conditions and three populations were produced using 2.27A at 75°C to represent a potentially current-accelerated stress condition. Eight additional populations were also stressed at 1.20A or 2.27A with 100°C solder joints or 2.84A with 85°C solder joints to represent highly accelerated temperature and current stress conditions.

The final Design of Experiment may be found in Table 2. Current densities provided in the table were calculated based on a 0.38mm pad diameter.

**Table 2.** Design of Experiment

| Joint Temperature (°C) | Current (A) | Current Density (kA/cm$^2$) | Stress Duration 1 (Days) | Stress Duration 2 (Days) | Stress Duration 3 (Days) |
|---|---|---|---|---|---|
| 75 | 0.25 | 0.22 | 30 | 90 | 120 |
| 75 | 0.50 | 0.44 | 30 | 90 | 120 |
| 75 | 0.80 | 0.71 | 30 | 90 | 120 |
| 75 | 2.27 | 2.00 | 10 | 20 | 30 |
| 85 | 0.50 | 0.44 | 30 | 90 | 120 |
| 85 | 0.80 | 0.71 | 30 | 60 | 75 |
| 85 | 2.84 | 2.50 | 15 | 30 | 45 |
| 100 | 1.20 | 1.06 | 15 | 30 | N/A |
| 100 | 2.27 | 2.00 | 5 | 20 | 30 |

Current stressing was applied by passing direct current through the primary daisy-chain pattern which utilized the perimeter 0.8mm wide traces. Current polarity was configured such that electron flow was "counterclockwise" through the sample as shown in Figure 6. The daisy-chain pattern was such that, of the eight corner-most joints, half experienced electron flow from the PCB toward the component while the other half experienced electron flow from the component toward the PCB. This pattern was incorporated to ensure that both potential bismuth accumulation regions (i.e., the top and bottom of the joints) were generated at the most-likely-to-fail solder joint positions in equal numbers. It should be noted that only the 80 outermost solder joints were current stressed during the experiment and that the remaining 476 solder joints did not experience current flow.

DC power supplies with constant current outputs were used to generate the desired current densities. The test samples were actively monitored during temperature / current stressing by using a datalogger to measure the voltage drop across the outer daisy-chain loop and/or the voltage drop across one or more individual corner joints.

It is important to note that temperature calibration and temperature / current stressing was always begun within 24 hours after the BGA556 was assembled to the test board. The reason for this is discussed in the following section.

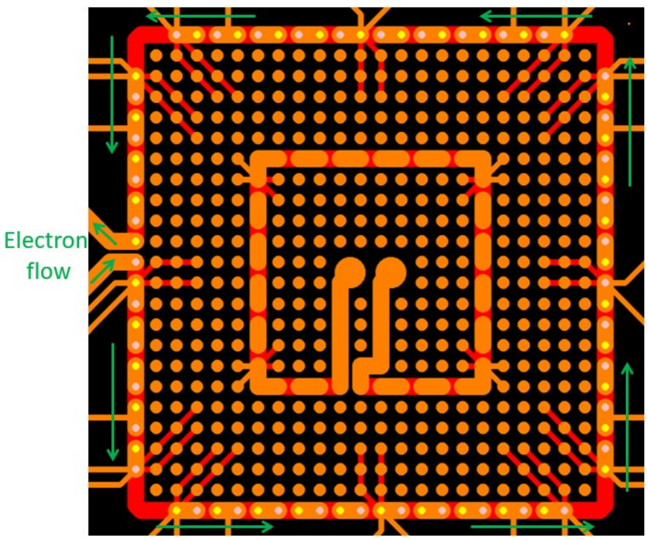


**Figure 6.** BGA/PCB electrical map. Orange indicates PCB copper features, Red indicates BGA features. Yellow indicates electron flow from BGA toward PCB (down), grey indicates electron flow from PCB toward BGA (up). Only perimeter joints were current stressed.

**Temperature Calibration**

Samples were placed in thermal chambers with heating and cooling capabilities. A small current of 0.08A was then applied to the outer daisy-chain loops. Such current was not expected to impact the sample temperature as joule heating was expected to be insignificant. The thermal chambers were then heated to the desired solder joint temperatures and when the temperatures stabilized, the voltage drops across individual solder joints were measured using the datalogger. Ohm's law was then used to calculate solder joint resistances for the given temperatures.

The resistive values calculated for 0.08A at temperature were then used to determine the voltage drop needed to produce the desired solder joint temperature during current stressing by multiplying the calculated joint resistance by the required test amperage. The thermal chamber temperatures were then reduced to 20°C and amperage was increased to the levels needed to drive the desired current densities for each test leg. The thermal chamber temperatures were then carefully increased until the solder joint voltage measurements indicated that the joints had reached their intended temperatures. Given that each thermal chamber had different air-flow characteristics, the necessary air temperatures required to produce the desired solder joint temperatures at the desired current stress levels were not necessarily scalable. Table 3 provides the various chamber temperatures used during the experiment. Note that the 476 non-current stressed solder joints in the BGA array are effectively "aged" at the chamber air temperature during temperature / current stress conditioning.

**Table 3.** Air temperatures required to produce desired solder joint temperatures

| Joint Temperature (°C) | Current (A) | Current Density (kA/cm$^2$) | Chamber Air Temperature (°C) |
|---|---|---|---|
| 75 | 0.25 | 0.22 | 75 |
| 75 | 0.50 | 0.44 | 75 |
| 75 | 0.80 | 0.71 | 75 |
| 75 | 2.27 | 2.00 | 68 |
| 85 | 0.50 | 0.44 | 85 |
| 85 | 0.80 | 0.71 | 85 |
| 85 | 2.84 | 2.50 | 67 |
| 100 | 1.20 | 1.06 | 95 |
| 100 | 2.27 | 2.00 | 73 |

It must be noted that in addition to constant current, the chamber air temperatures were also held constant for the duration of the experiment. Thus, any increase in solder joint resistance due to bismuth migration, crack growth or other factors during the temperature / current stressing could result in an increase in solder joint temperature given that temperature is directly proportional to resistance and no attempt to reduce any increase in temperature was undertaken.

**Drop Testing**

Samples were mounted to the drop table BGA side down using 12mm tall hex standoffs bolted at the four corners of the test board (Figure 7). The drop table was configured to produce a half-sine shock pulse of 200G with 1.3ms duration and a velocity of 1.65m/s (Figure 8). Failure was determined using an event detector with a 150Ω, 1.0µs event threshold. The number of drops to failure was recorded as the first drop with an event which could be confirmed by two subsequent events occurring within the next five drops.

A control population was assembled and stored at ambient conditions before being subjected to drop testing. This population was not current stressed and was used to establish drop test expectations for the LTS alloy. Much of this work had been previously reported by the authors using the same test vehicle, alloy, and assembly parameters and it was shown that these LTS BGA556 assemblies demonstrated dramatic improvement in drop test performance as time after assembly increased from several minutes up through 120 days [4]. A scatterplot of the control population results may be found in Figure 9.

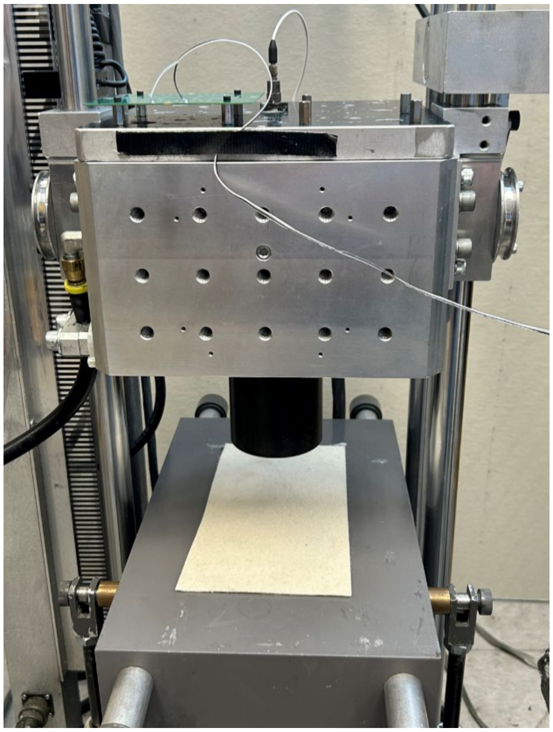

**Figure 7.** Drop Table Setup

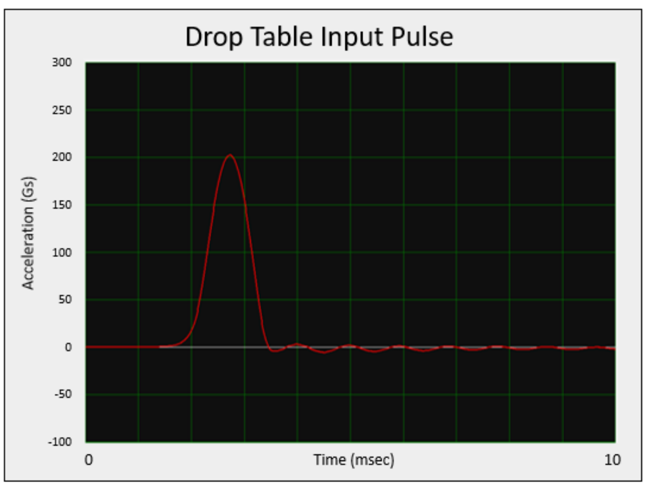


**Figure 8.** Example drop table input pulse.

In addition to the dramatic change in drops to failure with increased time after assembly, analysis revealed that samples dropped within a few hours of assembly typically failed due to cracking at or very near the component side nickel layer while those dropped 24 hours or later almost always failed due to cracking through the solder [4]. With two exceptions, the eight worst performing samples among the control population were tested between 12 minutes and 3 hours after assembly. These eight samples failed between 29 and 69 drops, demonstrating a characteristic lifetime of just 57 drops. In contrast, the eight control samples tested between one and four days survived 112 to 305 drops producing a characteristic lifetime of 201 drops. Among the samples tested after one day, the two potential outliers occurred at 50 drops (day 11) and 68 drops (day 21).

Currently, it is unknown whether this time effect holds true for samples subjected to temperature / current stressing. However, for consistency and in an effort to reduce or eliminate the nickel interface failure mode, all specimens tested for the described experiment were dropped between 24 and 96 hours after temperature / current stressing. Using this testing window combined with Monte-Carlo Weibull simulations of the control data, it was determined that individual stressed samples failing in under 50 drops and stressed populations with characteristic lifetimes under 145 drops would be strong indicators of solder joint degradation due to bismuth migration.

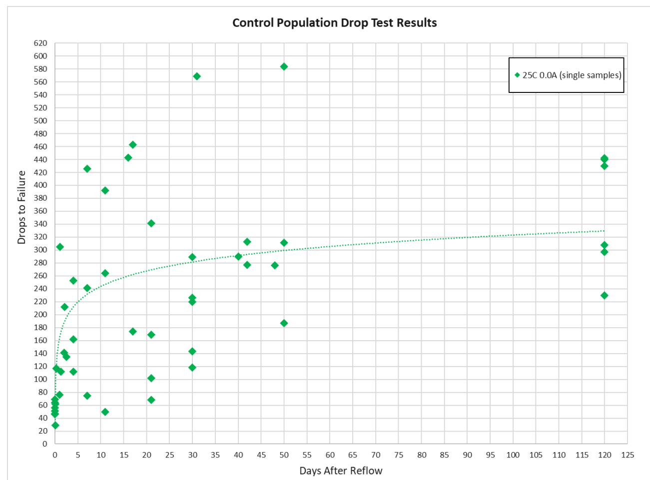


**Figure 9.** Scatterplot showing drop test results for Control Population as a function of time after assembly. Data previously published in [4] with additional data provided for 120 days.

**DROP/SHOCK RESULTS & DISCUSSION**

Ultimately, eight BGA556 samples were tested at each current level and duration noted in the design of experiment and the characteristic lifetime (N63.2) of each population was computed using Weibull analyses. These results are summarized in Table 4, which also notes the conditions failing to meet the 50 and/or 145 drop benchmarks.

It is abundantly clear from Table 4 that the accelerated stress conditions generated using 100°C solder joint temperatures negatively impacted the characteristic lifetimes of the test samples, as neither the 1.20A or 2.27A populations produced characteristic lifetimes in excess of 63 drops, with first failures occurring in 31 or fewer drops. This result was not unexpected given that bismuth is expected to migrate rapidly at 100°C if sufficient current is applied to the joints [5].

It is also clear that the 85°C populations at 0.80A and 2.84A perform poorly relative to the control samples as all six test cells failed to pass the 50 and 145 drop benchmarks. However, the milder test condition of 85°C at 0.50A passed at the 30 and 90-day durations while barely failing at the lengthy 120-day duration.

As for the 75°C populations, eleven of twelve populations exceeded the 50 and 145 drop benchmarks including all three populations stressed at the relatively high current level of 2.27A. Interestingly, the only 75°C population to fail the benchmark test was the 0.50A 30-day population, which was a relatively low current level and short duration.

**Table 4.** Drop test results. Red text indicates performance levels lower than control benchmarks as determined by Monte-Carlo Weibull simulations.

| Joint Temperature (°C) | Amperage (A) | Current Density (kA/cm$^2$) | Stress Duration (Days) | First Failure (drops) | Characteristic Life (drops) |
|---|---|---|---|---|---|
| 75 | 0.25 | 0.22 | 30 | 80 | 201 |
| 75 | 0.25 | 0.22 | 90 | 304 | 454 |
| 75 | 0.25 | 0.22 | 120 | 107 | 278 |
| 75 | 0.50 | 0.44 | 30 | 72 | **119** |
| 75 | 0.50 | 0.44 | 90 | 165 | 238 |
| 75 | 0.50 | 0.44 | 120 | 163 | 306 |
| 75 | 0.8 | 0.71 | 30 | 99 | 169 |
| 75 | 0.8 | 0.71 | 90 | 163 | 339 |
| 75 | 0.8 | 0.71 | 120 | 84 | 268 |
| 75 | 2.27 | 2.00 | 10 | 82 | 194 |
| 75 | 2.27 | 2.00 | 20 | 86 | 180 |
| 75 | 2.27 | 2.00 | 30 | 98 | 180 |
| 85 | 0.50 | 0.44 | 30 | 121 | 227 |
| 85 | 0.50 | 0.44 | 90 | 72 | 149 |
| 85 | 0.50 | 0.44 | 120 | **46** | **138** |
| 85 | 0.80 | 0.71 | 30 | **38** | **67** |
| 85 | 0.80 | 0.71 | 60 | **15** | **37** |
| 85 | 0.80 | 0.71 | 75 | **15** | **36** |
| 85 | 2.84 | 2.50 | 15 | **30** | **98** |
| 85 | 2.84 | 2.50 | 30 | **35** | **49** |
| 85 | 2.84 | 2.50 | 45 | **25** | **34** |
| 100 | 1.20 | 1.06 | 15 | **13** | **45** |
| 100 | 1.20 | 1.06 | 30 | **13** | **24** |
| 100 | 2.27 | 2.00 | 5 | **31** | **63** |
| 100 | 2.27 | 2.00 | 20 | **18** | **45** |
| 100 | 2.27 | 2.00 | 30 | **14** | **29** |

A possible explanation for the observed behaviors including that of the low performing 75°C 0.50A 30-day population becomes apparent when the characteristic lifetime data is plotted versus time and overlayed with the control data. As shown in Figure 10, there are three potential behavioral patterns observed when time is considered. Those patterns are:

1.) Drop performance decreases with time
2.) Drop performance increases with time
3.) Drop performance increases and then decreases with time

When one considers the normal variability observed in drop testing as demonstrated by the control population, the results as presented in Figure 10 make sense:

First, the 100°C populations show the worst performance due to their high temperatures and relatively high currents. Furthermore, these populations show a clear degradation in performance over a short time span. Statistically, Mann-Whitney analysis confirms that the performance of the 100°C 1.20A and 2.27A populations are similar. In both cases the worst performers "bottom out" around 13 drops to failure – indicating that there is likely a limit to the impact of additional bismuth accumulation on the drop test results.

Second, the 85°C populations show declining reliability with time – potentially indicating bismuth migration and accumulation with as little as 0.50A current. Additionally, the 85°C population performances align well with each other, with the 0.50A samples surviving more drops at a given duration than the 0.80A samples, which in turn survive more drops than the 2.84A samples at the same stress duration. Importantly, it is noted that the 0.80A samples only perform slightly better than the 2.84A samples, indicating that 0.80A at 85°C joint temperature is a relatively high acceleration condition.

Third, the "mild" conditions generated with 75°C solder joints and 0.25, 0.50 and 0.80A current levels show reasonably good performance at day 30 which appear to improve through day 90. Furthermore, although the characteristic lifetimes of the 75°C 0.25A and 0.80A populations appear to decrease between day 90 and day 120, statistical analyses found the day 90 and day 120 results to be comparable to each other and to the appropriate control samples. In these cases, it is thought that perhaps the temperature / current stress levels inhibited but did not stop the improvement over time that had also been observed with the control samples. This reasoning potentially explains why the 75°C 0.50A population produces a lower than desired lifetime of 119 drops at day 30 (i.e., the "mildly" stressed samples are improving slower than the comparable control samples).

Fourth, the "mild" temperature condition of 75°C with a more "severe" current level of 2.27A performed relatively well against the control samples while showing little change between days 10 and 30. Given that this test condition produced characteristic lifetimes of 180 to 194 drops while the comparable 100°C populations resulted in lifetimes of 63 drops or lower, it is reasonable to assume that bismuth does not rapidly migrate in the samples at 75°C even when the applied current is relatively high.

## FAILURE ANALYSIS

Probable failure locations were determined after drop testing by systematically probing the various test points included on the circuit board using the event detector with a threshold sensitivity of 50Ω at 1μs duration. Given that drop testing is a dynamic test and that many test samples were subjected to no more than two drops after failure detection, most samples tested "good" when evaluated flat on benchtop due to either incomplete solder joint cracking or contact

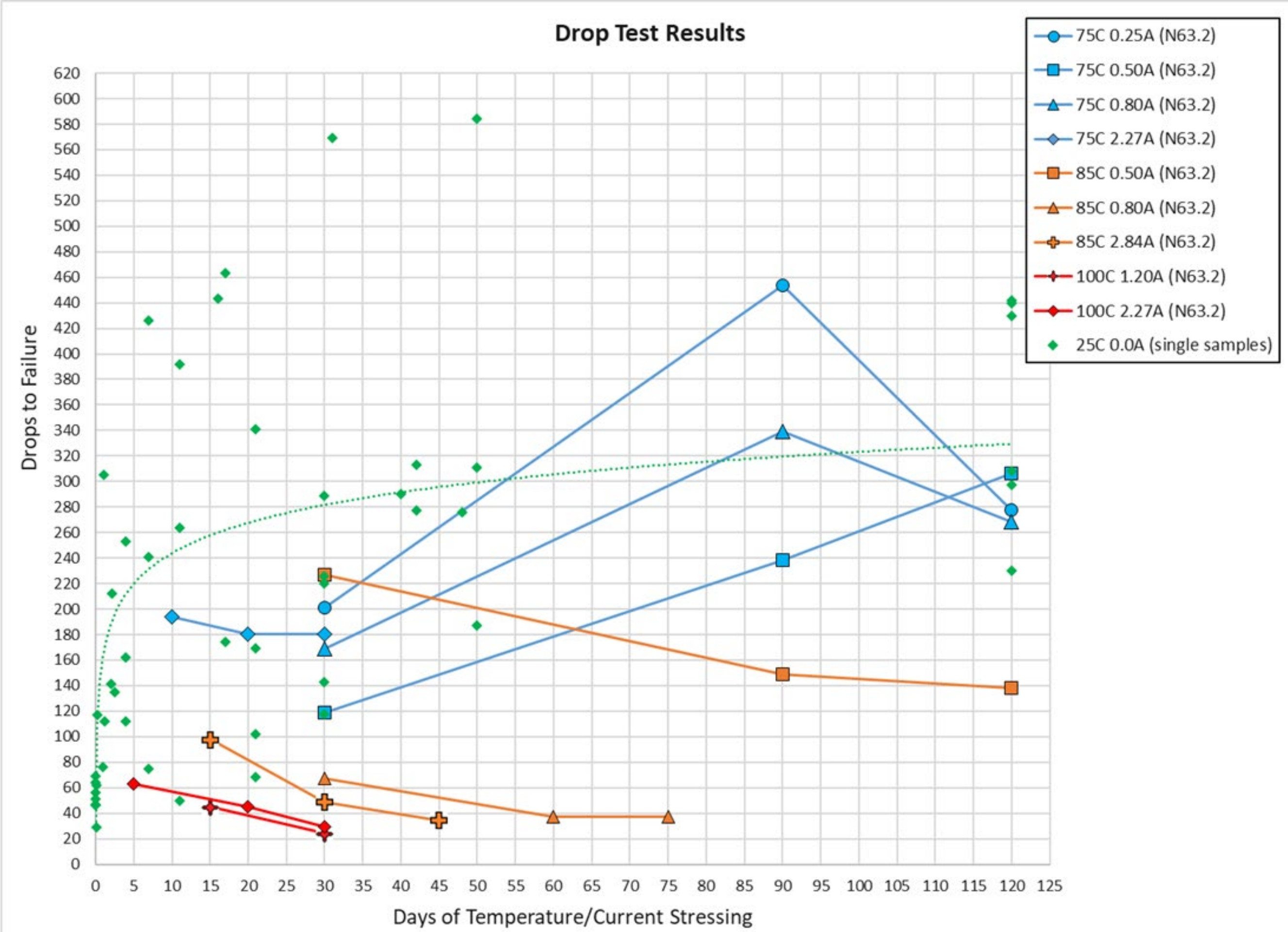


**Figure 10.** Characteristic Lifetimes vs. Stress Duration Overlayed with Control Data. Blue indicates solder joint temperatures of 75°C; Orange indicates solder joint temperatures of 85°C; Red indicates solder joint temperatures of 100°C; Green indicates Control samples (i.e. no current stress conditioning; ambient storage)

resistance between the crack surfaces. Therefore, each sample was lightly tapped from beneath using the eraser end of a pencil to encourage event generation during probe-out.

Ultimately it was determined that approximately 95% of samples failed specifically at corner-most solder joint positions while approximately 5% demonstrated failure simultaneously at perimeter and corner joints. In fact, only two of the 208 samples evaluated after temperature / current stressing appeared to have failed with corner joints intact.

Select samples were cross-sectioned to examine the joint microstructure and crack characteristics at the probable failure locations. The primary objective of the failure analysis was to determine if the failed joints cracked at the anode and/or cathode side and to document the observable bismuth accumulation or lack thereof at the crack location. Previous work with the control samples had established that most non-stressed samples failed due to primary crack growth near the PCB side of the solder joints, with some joints demonstrating partial secondary crack growth near the component side at the time of failure [4]. Thus, it was assumed that the four corner most solder joints within the BGA array with bismuth accumulation expected near the PCB side (i.e., the anode side) should fail in fewer drops than the control samples due to their increased brittleness at the anode.

**75ºC Stressing**

Samples subjected to 75°C and 0.25A failed in a manner comparable to that reported for the control samples. That is, the samples typically failed with a large, complete crack forming near the printed circuit board side of the joint with some joints showing both component and board side cracking. This test condition did not result in any obvious bismuth migration through 120 days (Figure 11, Figure 12).

Bismuth accumulation at the anodes was not observed in the 75°C 0.50A 60-day and 90-day populations. These samples typically failed at the PCB side of the solder joint regardless of anode location. Interestingly, as shown in Figure 13, anode side cracking and bismuth accumulation was observed in 120-day samples, but the accumulation did not appear to adversely affect drop performance relative to similarly aged control samples.

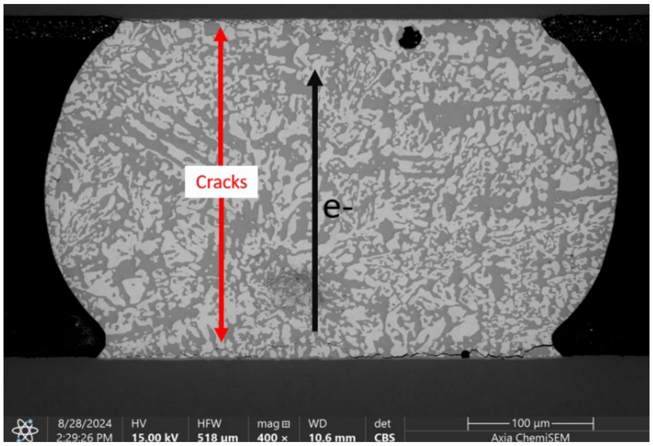


**Figure 11.** Cross-section of corner most solder joint subjected to drop testing after 120 days of 75°C 0.25A stressing. Note that the primary crack is located at the joint cathode, near the PCB.

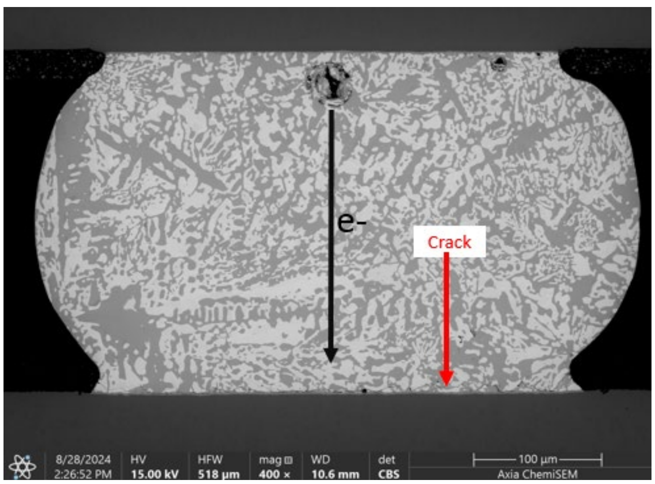


**Figure 12.** Cross-section of corner most solder joint subjected to drop testing after 120 days of 75°C 0.25A stressing. Note that the primary crack is located at the joint anode, near the PCB.

Upon initial inspection, bismuth migration or accumulation at the anodes was not observed in the 75ºC 0.80A samples and primary crack growth occurred near the PCB side of the joints with secondary cracking near the component side (Figure 14). However, variability in microstructure from joint to joint as well as the many non-uniform bismuth features found at the anodes led the authors to re-evaluate the samples. Ultimately, closer inspection of solder joints that had not cracked during drop test determined that bismuth density at the anodes was greater than the bismuth density at the cathodes at the 120-day milestone (Figure 15), providing the authors with convincing evidence for bismuth migration by day 120. As for the 60 and 90-day populations, no definitive instances of bismuth migration or accumulation at the anodes was observed.

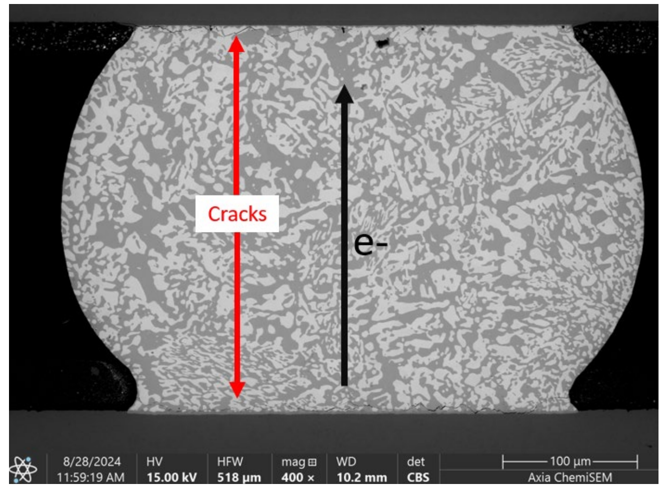


**Figure 13.** Cross-section of corner most solder joint subjected to drop testing after 120 days of 75°C 0.50A stressing. Bismuth accumulation at the anode is apparent. Note that the primary crack is located at the joint cathode, near the PCB.

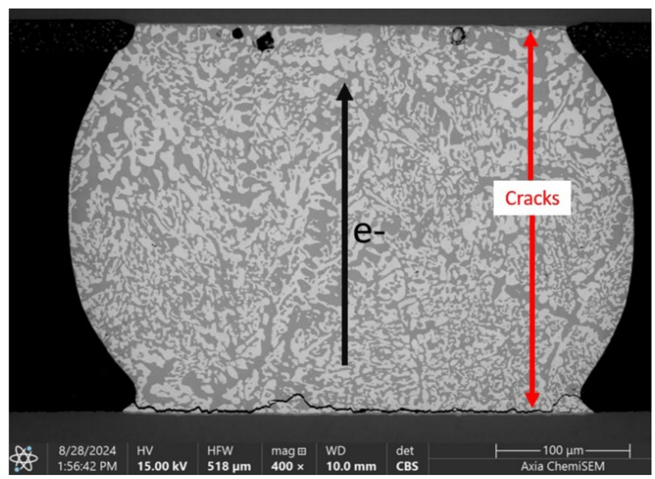


**Figure 14.** Cross-section of corner most solder joint subjected to drop testing after 120 days of 75°C 0.80A stressing. Note that the primary crack is located at the joint cathode, near the PCB.

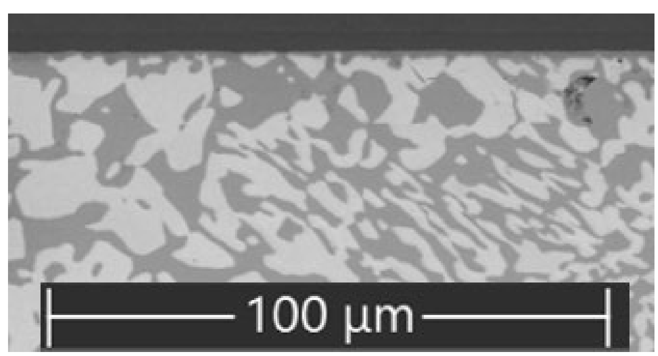


**Figure 15.** Cross-section showing solder joint anode region after 120 days of 75°C 0.80A stressing. Careful inspection indicates that bismuth has accumulated in this region.

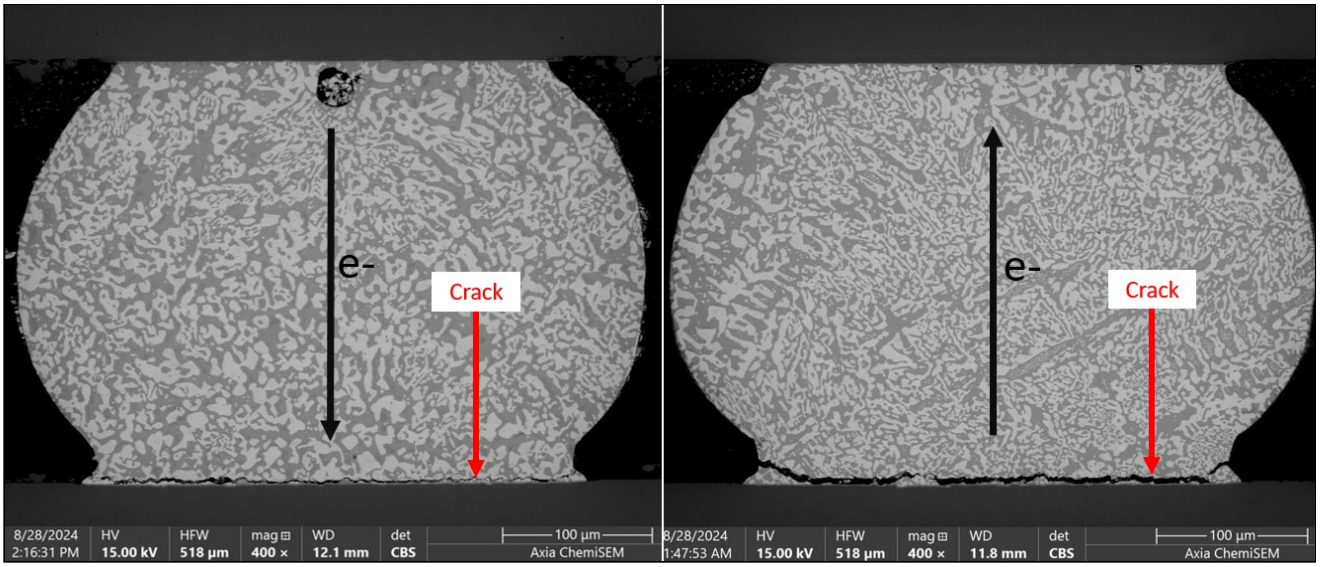


**Figure 16.** Cross-section of corner most solder joints subjected to drop testing after 30 days of 75°C 2.27A stressing. Note that the cracks are located at the joint anode (left) and joint cathode (right) near the PCB.

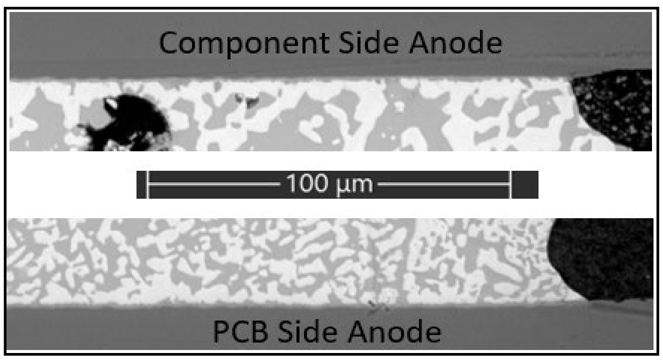


**Figure 17.** Comparison between component and PCB side anodes from 30 day 75°C 2.27A population. Bismuth density along the anodes was significantly greater than bismuth density at the cathodes.

Samples subjected to 30 days at 75°C and 2.27A preferentially failed at the PCB side of the solder joints regardless of the cathode/anode position as shown in Figure 16. Initially, it was observed that the 2.27A populations showed some evidence of bismuth migration in the cross-sections, not due to an accumulation at the anode side, but rather due to a lack of bismuth at the cathode side as may be inferred from the left image of Figure 16. After inspecting multiple parts, however, focusing on solder joints that did not crack, it was determined that bismuth density was greater at the anodes than the cathodes (Figure 17) indicating bismuth migration. The morphology of the bismuth located at the anodes could be described as blocky or irregularly shaped and similar in appearance to electromigrated bismuth examples with near-continuous or thin layers found in literature [5-7].

Importantly, the bismuth accumulation observed in the 75°C 2.27A samples did not negatively impact the drop performance of the population, however it is assumed that additional stress time beyond 30 days would ultimately result in weaker solder joints under this stress condition.

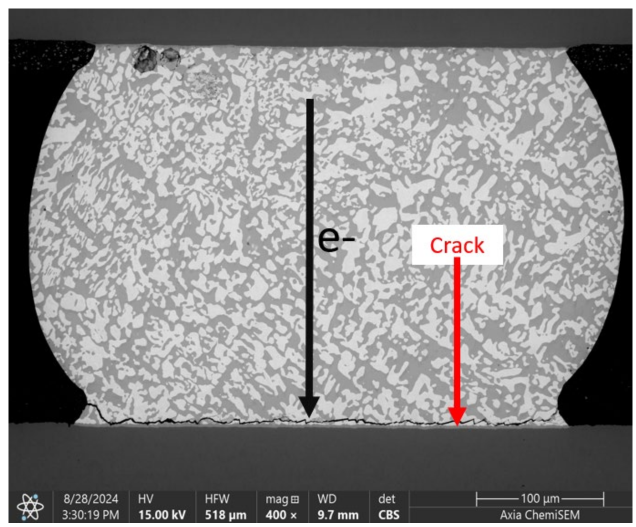


**Figure 18.** Cross-section of corner-most solder joint subjected to drop testing after 120 days of 85°C 0.50A stressing. Note that the primary crack is located at the joint anode near the PCB. All samples subjected to 85°C 0.50A for 120 days failed at "anode down" solder joint positions indicating a strong influence of bismuth migration on drop test performance.

**85ºC Stressing**

Samples subjected to the 85°C stress condition at 0.50A performed similarly to their control counterparts after 30 days but showed some degradation in drop performance at the 90 and 120-day milestones. When examined in cross- section, the samples demonstrated some bismuth accumulation at the anodes by day 90 with additional accumulation observed after day 120. However, the accumulation observed at these times was simply a thin

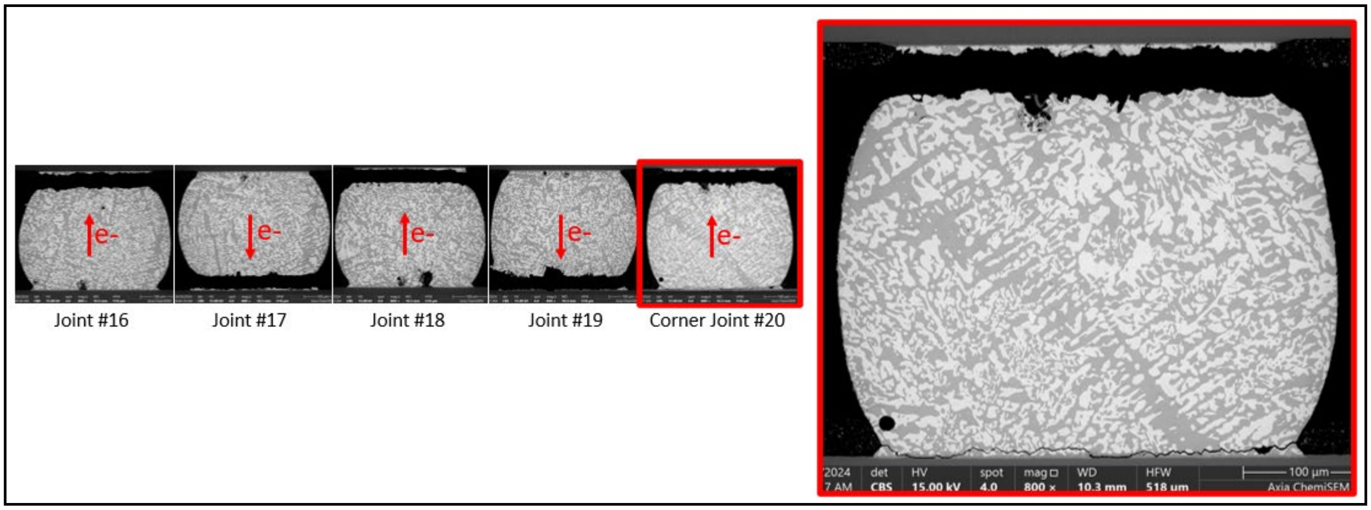


**Figure 19.** Cross-sectioned joints from 85°C 0.80A 75-day population showing complete cracking at the anode side of five sequential solder joints.

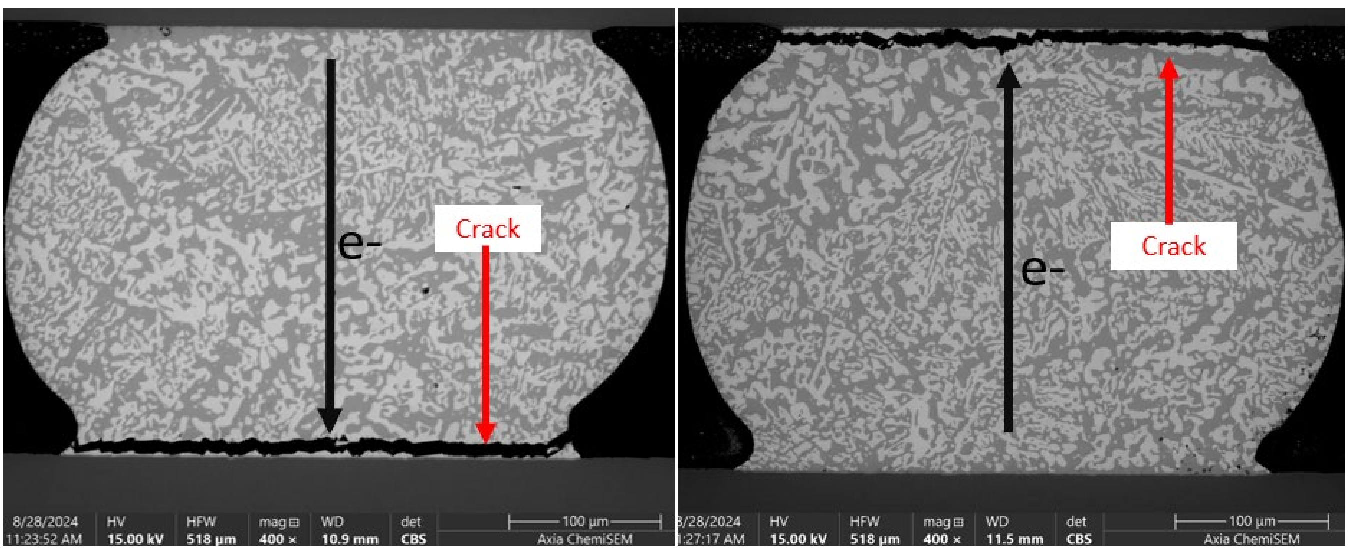


**Figure 20.** Cross-sectioned joints from 85°C 2.84A 45-day population showing complete cracking at the anode side of the solder joints. The left image shows a thin, solid layer of bismuth has formed at the anode. The right image shows a thin, incomplete layer of bismuth has formed at the anode.

layer of continuous or near-continuous bismuth at the anode intermetallic region. Estimating the bismuth thickness proved difficult due to the nature of the bismuth phases which were likely already present at the anode prior to stress testing. However, it was observed that the cracks which led to component failure were located at the bismuth accumulation region near the PCB pads in the "anode down" solder joint positions in all eight samples subjected to 120 days at 85°C and 0.50A – which was a strong indicator that bismuth migration had contributed to earlier failure (Figure 18).

85°C solder joints stressed at 0.80A and 2.84A were clearly affected by bismuth migration. In fact, over 90% of the samples failed at the corner-most solder joint positions with "anode down" configurations while the remaining samples failed at corner most solder joint positions with "anode up" configurations. However, the primary cracks that drove failure were almost always located at the anode side of the joints regardless of the joint's current flow direction. In some instances, failure was catastrophic, with all joints examined in cross-section containing anode side solder cracking. When inspected, the 0.80A samples showed some bismuth accumulation at the anodes while the 2.84A samples contained thin, but nearly complete bismuth layers at the anodes. Figures 19 and 20 show anode-side cracking for both 0.80A and 2.84A 85ºC populations.

**100ºC Stressing**

The 100°C populations stressed at 1.20A and 2.27A looked and behaved similarly to the 85°C populations in that the primary cracks formed at the corner-most solder joints near the anode side of the joints with "anode down" joints most likely to fail (Figure 21). In most cases, cross-sectioning indicated some degree of bismuth migration had occurred, resulting in a thin layer of bismuth at the anode (Figure 22).

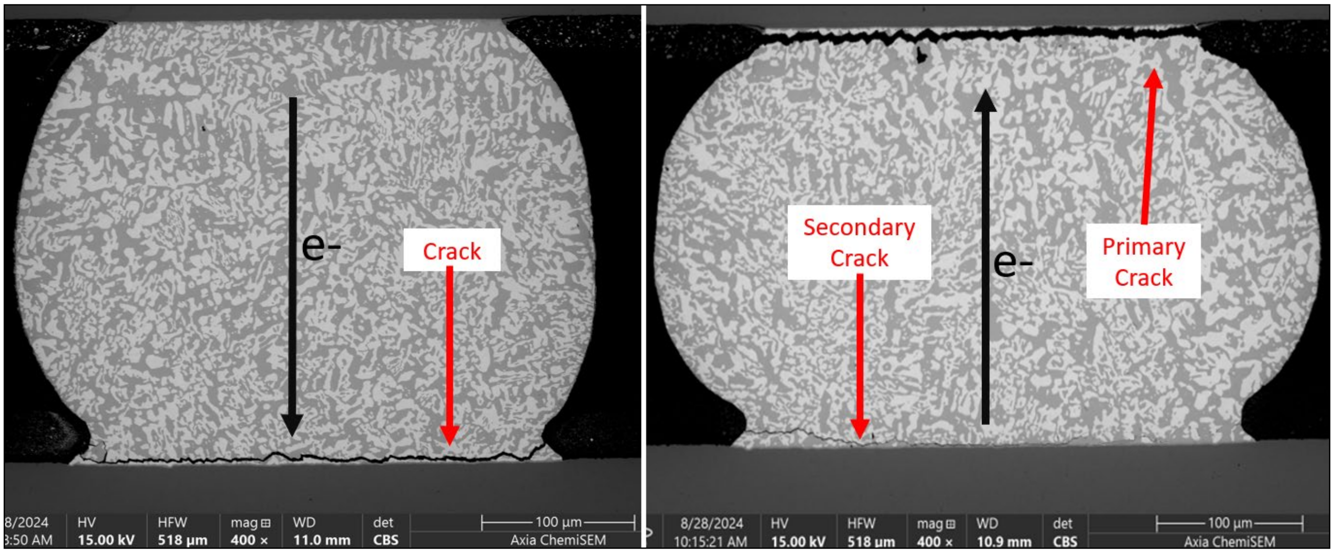


**Figure 21.** Cross-sectioned joints from 100°C 2.27A 20-day population showing corner joints with complete cracking at their anodes.

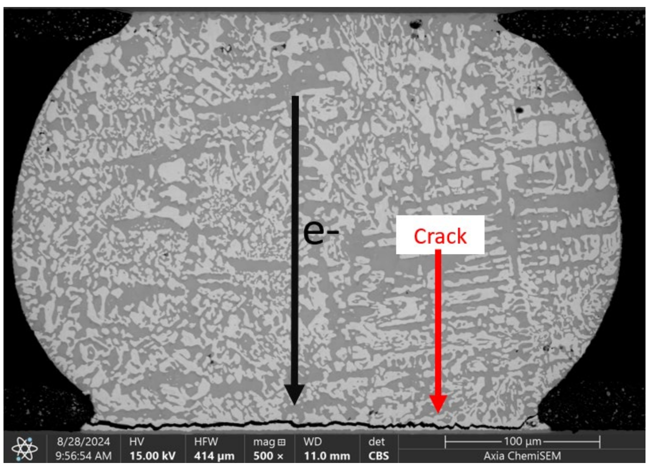


**Figure 22.** Cross-sectioned joint from 100°C 1.20A 30-day population showing complete cracking at the anode side.

Populations which were temperature / current stressed at a mild service-like condition of 0.25A with a solder joint temperature of 75ºC did not show obvious bismuth accumulation through 120 days. These samples failed due to solder fracturing near the PCB side of the corner-most joints regardless of anode and cathode position, which was similar to the Control population behavior.

The biggest take-away from the 100°C populations stressed at 1.20A and 2.27A is that the observable accumulated bismuth at the anode at 400X SEM magnification is relatively thin, perhaps on the order of 1 to 5µm, yet the BGA samples subjected to these conditions experienced significantly reduced drop test performance relative to the Control samples while showing a strong bias towards anode side failure. If one were to assume that the bismuth migration is the primary driver of reduced drops to failure, then these populations confirm that "thick" bismuth layers are not a pre-requisite for joint degradation, but instead show that "small" microstructural changes in joint morphology due to temperature / current stressing can significantly impact joint reliability. The result further implies/verifies that 100°C is a likely a "highly" accelerated condition for the LTS alloy, as lifetime reduction was observed after just 5 to 15 days for the current levels evaluated and thus LTS solder joints should not be allowed to reach such temperatures in service usage.

## CONCLUSIONS

Simultaneous temperature and current stressing affect the performance of LTS BGA solder joints in drop testing, with both increased temperature and current level showing larger impacts for the same stress duration.

Populations which were temperature / current stressed at a mild service-like conditions of 0.50A did not show obvious bismuth accumulation through 90 days but did show some degree of bismuth accumulation at day 120 which did not appear to significantly impact drop test performance relative to the benchmark criterion. These samples failed at corner joints due to solder cracking near the PCB pad regardless of the anode and cathode position.

Similarly, the slightly harsher 75°C 0.80A condition did not result in bismuth accumulation at the anodes by day 90, but did result in some accumulation by day 120. Importantly, the accumulation at day 120 did not appear to significantly impact the drop test performance relative to similarly aged Control samples and the benchmark criterion, and the primary failure mode was solder joint fracture near the PCB side of the joints regardless of anode and cathode position.

The mild conditions performed reasonably well in drop performance, with only the 75ºC 0.50A 30-day population failing the benchmark test, as all three populations ultimately showed improvement over time up to 120 days. It is possible that the mild temperature / current stress levels may have inhibited but did not reverse the improvement in drop performance that had been documented with the Control population through 120 days.

The current-accelerated populations with 75ºC joint temperature at 2.27A produced some degree of bismuth accumulation through 30 days of temperature / current stressing. These test specimens failed due to corner joint solder fracture along the PCB pad during drop testing and performed similarly to the comparable Control samples. It is believed that additional stress time would eventually have resulted in reduced drop performance under this stress condition.

85ºC populations showed a decrease in drop reliability over time, with the 85ºC 0.80A population performing slightly better than the 85ºC 2.84A samples, but with both populations failing the performance benchmark by day 30. The 0.50A population fared better, failing the benchmark requirement only after 120 days of temperature / current stress. Bismuth accumulation was observed after 90 days at 85ºC 0.50A and in all populations at both 0.80A and 2.84A, with failure occurring in "anode down" solder joints in most samples. These results indicate that 85ºC is an "accelerated condition" as this temperature is only 10ºC above peak service condition and yet drives relatively rapid joint degradation with modest current application.

The 100ºC populations performed similarly to each other in drop testing, with poor performance after only 5 days of temperature / current stress and decreasing performance over time. Most samples showed bismuth accumulation at the anode, and cracking occurred at the corner-most "anode down" solder joints. It is important to note that the bismuth layer thickness was relatively thin, on the order of 1 to 5µm and that all samples survived at least 12 drops prior to failure, indicating that there may be a limit on the impact of additional bismuth accumulation on drop performance (i.e., drop performance will not degrade significantly with increasing bismuth thickness once a thin layer of bismuth has formed).

Attempting to derive acceleration factors between the various test conditions is difficult due to the constantly evolving nature of the LTS solder joints which showed improvement over time at room temperature conditions and at 75°C stress conditions but fast degradation at 85°C and 100°C stress conditions. Further complicating the analysis is that the time between stress conditioning and drop testing was limited to 24 to 96 hours for the described experiment, and shorter or longer durations between stress conditioning and drop testing may potentially impact the results in an unknown manner. Similarly, the time between reflow soldering and the application of the stress conditioning may also affect the drop test results, and these "time factors" have not yet been evaluated.


## ACKNOWLEDGEMENTS
The authors would like to thank the following people for their invaluable contributions:

- Dr. James Wilcox; Universal Instruments Corporation
- Nithin Lakshminarayan and Dr. Martin Anselm; Rochester Institute of Technology
- Kevin Byrd; Intel Corporation
- Brian Roggeman; Qualcomm
- Issac Newton; Father of Modern Physics


## REFERENCES

[1] "ECO SOLDER alloys and their various forms," Senju Metal Industry Co, Ltd. Accessed September 2024. https://www.senju.com/en/products/ecosolder/alloy_form/

[2] "Properties of Chemical Elements" Periodic Table. Accessed September 2024. https://www.periodic-table.org/

[3] Meilunas, M. "Low Temperature Solder: BGA Drop/Shock Reliability After Current and Temperature Stressing (Phase 1)," AREA Consortium 2022.

[4] Tahat, S., S. Hamasha, M. Meilunas. "Drop/Shock Behavior of Low Temperature Solder BGA," *Proceedings of 2023 SMTA International*, pp. 379-386.

[5] Flores, J., F. Hadian, S. Panta, E. Cotts. "Kinetics of the Accumulation of a Layer of Bismuth at the Anode of a Sn-Bi Based Solder Joint During Current Stressing," *Proceedings of 2022 SMTA International,* pp. 393-398.

[6] Singh, P. et al. "In Situ Study of Electromigration in Eutectic Tin-Bismuth Planar Solder Joints," *Proceedings of SMTA Pan Pacific Strategic Electronics Symposium 2024*, pp. 77-82.

[7] Wang, F., L. Liu, D. Li, M. Wu. "Electromigration behaviors in Sn-58Bi solder joints under different current densities and temperatures," J. Mater. Sci.: Materials in Electronics. **29**, 21157-21169 (2018)