RELIABILITY ANALYSIS OF LOW-SILVER BGA SOLDER JOINTS USING
FOUR FAILURE CRITERIA

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Erin A. Kimura
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COMMITTEE MEMBERSHIP

TITLE: Reliability analysis of low-Ag BGA solder joints using four failure criteria

AUTHOR: Erin A. Kimura

DATE SUBMITTED: August 2012

COMMITTEE CHAIR: Dr. Jianbiao Pan, Professor of Industrial and Manufacturing Engineering

COMMITTEE MEMBER: Dr. Tao Yang, Professor of Industrial and Manufacturing Engineering

COMMITTEE MEMBER: Dr. Daniel Waldorf, Professor of Industrial and Manufacturing Engineering

ABSTRACT

Reliability analysis of low-Ag BGA solder joints using four failure criteria

Erin A. Kimura

The appropriate selection of failure criterion for solder joint studies is necessary to correctly estimate reliability life. The objective of this study is to compare the effect of different failure criteria on the reliability life estimation. The four failure criteria in this study are a 20% resistance increase defined in the IPC-9701A standard, a resistance beyond 500 Ω , an infinite resistance (hard open), and a failure criterion based on $\bar{X}$ and R control charts. Accelerated thermal cycling conditions of a low-silver BGA study included 0°C to 100 °C with ten minute dwell times and -40°C to 125°C with ten minute dwell times. The results show that the life estimation based on $\bar{X}$ and R failure criterion is very similar to the life estimation when a 20% resistance increase defined in the IPC-9701A failure criterion is used. The results also show that the reliability life would be overestimated if the failure criterion of a resistance threshold of 500 Ω or an infinite resistance (hard open) is used.

Keywords: Solder joint, failure criteria, $\bar{X}$ and R charts, statistical process control

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Chapter 1. Introduction

As the technologies of the microelectronics industry continue to advance, new solder alloy materials, manufacturing processes, and designs add to the complexity of microelectronics packaging. Although the implications of these new technologies on product reliability may not be fully understood, consumers expect these products to exhibit high performance and durability. In addition, microelectronics manufacturers may experience high costs of unreliability due to product warranties [1]. For many other industries, such as automotive, airline, and military, safety is contingent on product reliability as well.

Because the reliability of a product is heavily influenced by the design process, many products are engineered for high reliability during design. The design for reliability methodology is utilized to produce the highest level of product reliability, while minimizing the design process time. From an engineering perspective, reliability can be defined as:

The probability that an item will perform a required function without failure under stated conditions for a stated period of time [1].

In the microelectronics industry, reliability is largely dependent on the integrity of solder, which is used in different levels of the electronic assembly sequence. Solder

provides the electrical, thermal, and mechanical continuity in electronics assemblies. Solder alloys used in electronics manufacturing range from the once widely used SnPb solders to lead-free solders with additional micro-additives. For the lead-free SAC (SnAgCu) sphere alloys used in Ball Grid Array (BGA) assemblies, low-silver sphere alloys have become increasingly popular due to their improved drop shock performance over the more traditional SAC305 (3% Ag) and SAC405(4% Ag) spheres [2]-[5].

Microelectronics reliability studies are necessary for the understanding of thermal fatigue performance of solder joints, product qualification, and life estimation. However, the appropriate selection of failure criterion for solder joint studies is necessary to correctly estimate reliability life. Failure criteria can be categorized as an increase in resistance relative to the initial value, resistance threshold, or electrical discontinuities [6],[7]. Consequently, the use of many different solder joint failure criteria in industry results in reliability analyses which are difficult to compare.

The low-silver BGA study, an industry consortium study by G. Henshall et al., was undertaken to characterize the influence of solder alloy type and reflow parameters on the reliability life of the BGA assemblies [7]. The experiment included accelerated thermal cycling for reliability analysis of BGA assemblies. The IPC-9701A failure criterion was selected to identify cycles to failure for the accelerated thermal cycling data. The failure data was fit to the Weibull distribution to estimate the characteristic life (α) and slope (β) for each treatment.

In this study, the accelerated thermal cycling data from the low-silver BGA study was re-analyzed using four failure criteria. Because the results of the reliability life analysis depend on the failure criteria used, this study addresses the effect of failure

criteria selection on the reliability life low-silver BGA assemblies. The following four failure criteria were selected for the analysis: a 20% resistance increase defined in the IPC-9701A standard, a resistance beyond 500 Ω , an infinite resistance measurement (hard open), and a failure criterion based on $\bar{X}$ and R control chart developed by Pan and Silk [7]. The $\bar{X}$ and R failure criterion is based on the $\bar{X}$ and R charts of statistical process control, and is described in detail in the literature review section.

Chapter 2. Literature Review

By providing the electrical, thermal, and mechanical continuity in electronics assemblies, solder plays a vital role in the microelectronics industry. The functionality of these assemblies is dependent on the integrity of the solder, which is used throughout the electronic assembly process [9]**Error! Reference source not found.** A variety of advanced package types are used to meet consumer demands for the high performance and miniaturization of electronics. These include Ball Grid Array (BGA), Flip Chip Package, Chip Scale Package (CSP), Plastic Quad Flat Pack (PQFP), and Direct Chip Attach (DCA) [9]. The solder alloys used in electronics manufacturing range from the once widely used SnPb solders to lead-free solders with additional micro-additives.

2.1 Low-silver Ball Grid Array (BGA) Assemblies

Due to the toxicity of lead and environmental regulations which aim to eliminate its use in electronics, a variety of new solder joint alloys have been introduced to replace the once common SnPb alloys [9].

Low-silver SAC sphere alloys (1% or 2% Ag) have become an increasingly popular type of lead-free solder used in Ball Grid Array (BGA) electronic packages due to the improved drop shock performance over SAC305 (3% Ag) and SAC405 (4% Ag) [2]-[5]. The addition of micro-additives to low-silver BGA alloys can also have a significant effect on improving the drop shock performance of the packages as well [3].

The investigation of drop shock performance of electronics has become very important due to the popularity of handheld electronic devices [5].

2.2 Design for Reliability

The reliability of a product is heavily influenced by the design process. Because correcting design faults becomes more costly as the product development cycle progresses (See Figure 1), it is important to detect design faults as early as possible through reliability engineering [1]. The goal of design for reliability is to produce the highest level of product reliability, while minimizing the design process time.

The broad field of reliability engineering includes materials testing and modeling, finite element modeling and simulation, failure mode and effects analysis, reliability tests (such as accelerated life testing), and reliability life analysis [1,9]. The reliability life of a product can be determined from the statistical analysis of accelerated life testing data.

Figure 1. Cost of design change during the product development cycle [1].

Reliability engineering is oftentimes necessary for product qualification in the electronics industry.

2.3 Accelerated Life Testing

Accelerated tests utilize high stress levels to precipitate component failures in a relatively short time frame. In industry, they are performed to qualify a product for use and to evaluate product reliability. Accelerated tests are necessary when evaluating a component or product for failure under regular use that would not yield a sufficient amount of failures within a reasonable amount of time [11,12]. Due to the oftentimes short design process for microelectronics, this is almost always the case. Failures due to accelerated life testing are the result of the same failure mechanisms as failures with typical use, but in a much shorter (accelerated) time frame [13]. Accelerated test conditions must consider typical use conditions, anticipated failure modes, and available test approaches and techniques. The most common accelerated life tests include:

- high temperature (steady-state) dwell,
- low temperature storage,
- thermal cycling,
- power cycling,
- thermal shock,
- thermal gradients,
- fatigue tests,
- mechanical shock,
- drop shock,
- sinusoidal vibration,
- random vibration,
- creep/stress-relaxation,
- voltage extremes,
- high humidity, and
- radiation [12].

The reliability analyses from accelerated life testing data allow researchers to pinpoint weaknesses and to make improvements in the design of electronics, material selection, and the electronics manufacturing process [12].

The objective of accelerated life testing is to identify the failure modes and mechanisms, and to collect statistical information from the failure data collected [12]. The failure data collected from accelerated tests includes data (commonly cycles-to-failure or time-to-failure) from failed and not failed units. Units that survive the entire duration of the test are right-censored for the analysis. After the data is fit to a lifetime distribution, distribution parameters are estimated. Common lifetime distributions include the Weibull, Exponential, and Lognormal distributions.

2.3.1 Accelerated Thermal Cycling (ATC)

Microelectronics and their solder joints are subject to thermal stresses during typical use. Accelerated thermal cycling (ATC) is the type of accelerated test which mimics these thermal stresses. Accelerated thermal cycling is used to evaluate the thermal fatigue performance of electronic packages. The test is accelerated through increasing the rate of heating or cooling, increasing the difference between the peak (maximum and minimum) temperatures, and decreasing the dwell time at peak temperatures [13]. The data analyzed in this study is accelerated thermal cycling (ATC) data from the low-silver BGA data. The experimental setup and thermal cycling conditions for accelerated thermal cycling data from the low-silver BGA study are described in detail in the following section.

2.3.1.1 Accelerated Thermal Cycling Conditions

Because thermal cycling conditions mimic the thermal stresses from typical use, selection of thermal cycling conditions is important to the accuracy of component reliability evaluation. This could be from internal factors (such as power dissipation), or external factors (such as daily and seasonal temperature changes). Research has demonstrated that acceleration factors (ramp rate, dwell time, and temperature cycling range) affect fatigue life differently. The selection of these parameters should depend on the specific application of the device, and the conditions in which it will be used. These factors are shown below in Figure 2. During accelerated thermal cycling, failure begins with crack initiation followed by crack propagation. A larger temperature cycling range and increased dwell times will result in more creep strain, which reduces cycles-to-failure

Figure 2. Accelerated thermal cycling factors [24].

[13],[15]. The effect of ramp rate is not as clear. Although increasing the ramp rate will decrease the overall test time, some research has shown that increasing the ramp rate will not affect the cycles to failure [16]. Other research has shown that decreasing the ramp rate results in more creep strain, decreasing the cycles-to-failure [17,18].

For BGA assemblies, the SAC spheres showed a longer fatigue life than SnPb solder joints for 0–100 °C and –40 to 125 °C temperature cycling ranges [13]. Additional literature describes how Pb-free solder, such as SAC alloys, results in a longer fatigue life with greater cycles-to-failure [19]-[23].

Package size shows to have an influence on thermal fatigue as well. A study showed that increasing pitch size for BGA packages size results in lower cycles to failure for accelerated thermal cycling [24]. Other research has shown that the size of the component (including ball pitch and pad size) has a statistically significant effect on fatigue reliability of BGA packages as well [25,26].

2.3.2 Drop Shock Reliability

Due to the popularity of consumer handheld electronics, drop shock reliability has been an important area of study in microelectronics reliability. Although initially SAC305 and SAC405 (3% and 4% silver, respectively) were the most popular alternatives Pb solder alloys, there are drop shock reliability concerns with these alloys. Due to the higher strength and lower acoustic impedance, SAC305 and SAC405 transfer stress to the component more readily [3]. Low silver alloys (SAC105 and 205) have shown to have better drop shock performance than SAC305 and SAC405 [2]-[5].

This study includes reliability analysis of a variety of sphere alloys which include low-Ag SAC spheres as well as spheres with dopants, particularly bismuth (Bi) and nickel (Ni). Nickel has shown to increase drop shock reliability of SAC spheres, particularly in the F35 (Sn-1.2Ag-0.5Cu + 0.05Ni) solder alloy [27]. Research has shown that the addition of nickel to SAC solder alloys will improve thermal fatigue performance as well [28].

Bismuth added to lead-free solders as a micro-alloying agent has several benefits as well. These include to lower the solidus temperature, improve the strength of the solder, and to improve wetting and spread of the solder alloy [29]-[31]. However, the effect of Bi addition to SAC solder alloys on drop shock performance is inconclusive, but may improve or decrease drop shock performance depending on the alloy composition. The addition of Bi to SAC305 solder alloys reduces drop shock performance, while the addition of Bi to SACX (0.3Ag) has shown to improve its performance [3].

Figure 3. BGA solder joint crack resulting in electrical discontinuity and solder joint failure [17].

2.4 Solder Joint Failure

One of the most common failure modes for component is an open circuit resulting from solder joint fracture. This begins with an initiation of a crack in the joint, followed by propagation of the crack from cyclic loading. A cross-sectioned BGA solder joint with a complete fracture is seen in Figure 3. Solder joint fracture results from cyclic stresses and strains which damage the solder joint over time. However, these failures are extremely difficult to monitor and track due to the increased miniaturization of many types of electronic packages [32]. This miniaturization makes it very challenging to examine solder joint failures through non-destructive methods, such as X-ray. Instead, detecting solder joint failure is oftentimes done through monitoring resistance of the solder joint or daisy chain [7].

2.4.1 Solder Joint Failure Criteria

The proper failure criterion for accelerated life tests must be selected in order for reliability analyses to be accurate. For example, a failure criterion used which is not sensitive enough would result in overestimated reliability life. Societies such as IPC (Association Connecting Electronics Industries) and JEDEC (Solid State Technology Association) publish solder joint failure standards that are used extensively in industry. These standards, which specify solder joint criteria for temperature cycling tests, bend tests, and drop tests, are shown in Table 1. Results of a survey included in Qi et al. show that solder joint failure criteria used by major electronics companies are oftentimes adaptations of these standards as well (see Table 2) [6].

Regardless of the type of accelerated life test, solder joint failures are detected through data loggers or event detectors which monitor resistance of a solder joint or daisy chain. Solder joint failure criteria can be defined as either a resistance increase relative to the initial resistance, resistance beyond a specified threshold, or based on characteristics of electrical discontinuity in a solder joint. During thermal cycling, solder joint discontinuity is exhibited through high resistance spikes ($\geq 300 \Omega$) of a short duration ($\sim 1 \mu\text{s}$) [6].

Table 1. Solder joint failure criteria standards [7]

Standard	Test	Failure definition	
		Event Detector	Data Logger
IPC-SM-785 (1992)	Temperature cycling	The 1 st event of resistance exceeding 1000Ω for lasting $>1 \mu\text{s}$, followed by >9 events within 10% of the number of cycles to initial failure	
IPC-9701 (2002) & IPC-9701A (2006)	Temperature cycling	The 1 st event of resistance exceeding 1000Ω for lasting $>1 \mu\text{s}$, followed by >9 events within 10% of the cycles to initial failure	20% resistance increase in 5 consecutive readings
JESD22-B111 (2003)	Drop test	The 1 st event of resistance $> 1000 \Omega$ for a period of $>1 \mu\text{s}$, followed by 3 additional such events during 5 subsequent drops.	1 st detection of resistance value of 100Ω if initial resistance is $<85 \Omega$, or 20% increase in resistance if initial resistance is $>85 \Omega$, followed by 3 additional such events during 5 subsequent drops.
IPC/JEDEC-9702 (2004)	Bend test	20% resistance increase. A lower or higher threshold may be more appropriate, depending upon test equipment capability and specific daisy-chain design scheme.	

Table 2. Failure criteria used by major electronics companies [6]

Company/Organizaion	Criteria Used
A	IPC-SM and IPC-9701
B	IPC-9701
C	IPC-SM-785
D	IPC-SM-785
E	Internal standard, but refers to JESD22-B111
F	IPC-SM-785
G	IPC-9701
H	Similar to IPC-9701

A study by Henshall et al. evaluated the thermal fatigue performance of SAC105, Sn-3.5Ag, and SAC305 BGA spheres using three failure criteria: 20% resistance rise as specified by IPC-9701A, 500 Ω threshold, and infinite resistance (hard open). The study concluded that IPC-9701A was the most sensitive failure criterion of the three for the BGA packages in the study. When IPC-9701A was used, solder joint failure was detected 200 to 500 cycles sooner than for the other two criteria.

2.4.2 $\bar{X}$ and R Failure Criteria

The $\bar{X}$ and R solder joint failure criterion proposed by Pan and Silk defines solder joint failure as a resistance measurement exceeding k times the natural variation [7]. This methodology stems from the traditional $\bar{X}$ and R (range) control charts from statistical process control, originally developed by Walter Shewhart [33]. Other failure criteria used in industry do not consider the natural variation by random causes, such as the defined 20% resistance increase of IPC-9701A. Instead, the $\bar{X}$ and R solder joint failure criterion detects solder joint cracks by considering resistance increases exceeding threshold which is based on the natural variation.

The $\bar{X}$ chart monitors the process mean, while the R chart monitors the process variability. When applied to solder joint failure, a resistance measurement above the upper control limit (UCL) indicates solder joint failure. The control limits of $\bar{X}$ chart are defined as follows:

$$\text{Control Limits: } \bar{\bar{X}} \pm \frac{k\sigma}{\sqrt{n}}$$

Where $\bar{\bar{X}}$ is the average resistance,

σ = standard deviation of resistance due to natural variation,

n = rational subgroup size, and

k = desired number of standard deviations from the mean.

The recommended k value is 3 to 10. A smaller k value would detect solder joint failure as early as possible, while a larger k value would minimize false detection (Type II error). For the 3σ control chart which is standard in industry, k is set to 3. The control limits of R chart are defined as:

$$\text{Control Limits: } LCL_R = D_3 \bar{R} \text{ and } UCL_R = D_4 \bar{R}$$

Where $R = X_{max} - X_{min}$ (sample range), and

D_3 and D_4 are sample anti-biasing constants.

The study by Pan and Silk included an experiment which tested 39 components in three different package platforms. After cross-sectioning of the solder joints, the study concluded that a complete crack of an interconnection occurs when k is 10, which proves

the validity. However, using a smaller k value would result in more sensitive failure criteria, which would minimize “false positive” failure detection (Type I error).

Chapter 3. Low-Silver BGA Assembly Study

The low-silver BGA study, an industry consortium study by Henshall et al., was undertaken to characterize the influence of solder alloy type and reflow parameters on the reliability life of the BGA assemblies [8]. The first phase of the study focuses on the development of reflow profiles and their effect on mixing levels of the reflowed solder joint. The results of Phase I of the low-silver BGA study were used in the development of the experimental design for Phase II—the assessment of thermal fatigue performance of low-silver BGA components through accelerated thermal cycling.

3.1 Low-Silver BGA Experimental Setup: Accelerated Thermal Cycling

Accelerated thermal cycling data analyzed in this study is from the low-silver BGA study by Henshall et al. [8]. The experimental materials from the low-silver BGA and procedures necessary for the understanding of study are described in this section. Additional details from the ATC procedure, test vehicles, and board layouts are described in the sixth publication for the low-silver BGA study by Henshall, et al. [34]. The paste alloys used for the BGA assemblies were SnPb and SAC305. The following sphere alloys were investigated in the study:

- SACX 0307 (Sn-0.3Ag-0.7Cu+ Bi+X),
- SAC 105 (Sn-1.0Ag-0.5Cu),

- LF35 (Sn-1.2Ag-0.5Cu + 0.05Ni),
- SAC 205 (Sn-2.0Ag-0.5Cu),
- SAC 305 (Sn-3.0Ag-0.5Cu), the Pb-free baseline, and
- Sn-Pb (Sn-37Pb), Sn-Pb baseline.

Also, four different BGA package types were studied:

- 0.05 mm pitch ChipArray Thin Core BGA, 132 I/O; solder ball volume of 0.014 mm³.
- 0.80 mm pitch ChipArray BGA, 288 I/O; solder ball volume of 0.051 mm³,
- 1.00 mm pitch Plastic BGA, 324 I/O; solder ball volume of 0.131 mm³, and
- 1.27 mm pitch SuperBGA, 600 I/O; solder ball volume of 0.230 mm³.

Figure 4. BGA package types [37].

These package types are shown in Figure 4. From now on, these package types will be identified by their pitch. The accelerated thermal cycling (ATC) for the low-silver BGA study included two ATC conditions as specified by IPC-9701A [35]:

- IPC-9701A condition TC1: 0°C to 100°C with 10 minute ramps and dwells, and
- IPC-9701A condition TC3: -40°C to 125°C with 16.5 minute ramps and 10 minute dwells.

The test was terminated at 10,102 cycles for the 0°C to 100°C temperature cycling range (TCR), and at 3,556 for the -40°C to 125°C temperature cycling range (TCR) [36]. The full experimental matrix is seen in Table 3. A total of 20 packages were tested for each treatment, or “cell”.

Table 3. Accelerated thermal cycling (ATC) experimental matrix for the low-silver BGA study [36].

			0 to 100 °C (10,102 cycles) TCR				-40 to 125 °C (3,556 cycles) TCR			
			Pitch							
Paste Alloy	Ball Alloy	Peak Reflow Temp (°C)	0.50 mm	0.80 mm	1.00 mm	1.27 mm	0.50 mm	0.80 mm	1.00 mm	1.27 mm
SnPb	SnPb	215	20	20	20	20	20	20	20	20
SnPb	SAC105	215	20	20	20	20	20	20	20	20
SnPb	SAC105	220			20	20			20	20
SnPb	SAC205	215								
SnPb	SAC305	215	20	20	20	20			20	20
SnPb	SACx	215	20	20	20	20	20	20	20	20
SnPb	LF35	215	20				20			
SAC305	SAC105	235	20	20	20	20	20	20	20	20
SAC305	SAC205	235	20	20	20	20	20	20	20	20
SAC305	SAC305	235	20	20	20	10	20	20	20	20
SAC305	SACx	235	20	20	20	20	20	20	20	20
SAC305	LF35	235	20				20			

Chapter 4. Analysis and Results: Comparison of Four Failure Criteria

The accelerated thermal cycling data from the Low-Ag BGA Assembly Study were analyzed accordingly:

1. **Failure detection and failure criteria comparison using four failure criteria:** Cycles-to-failure for the low-Ag BGA accelerated thermal cycling data was determined using four failure criteria. The sensitivity of the four failure criteria was then compared.
2. **Reliability analysis of low-Ag BGA assembly accelerated thermal cycling (ATC) data:** The failure data for the $\bar{X}$ and R failure criteria was fit to the Weibull lifetime distribution in order to estimate the Weibull characteristic life (α) and slope (β) parameters. Analysis of variance (ANOVA) was used to see if package construction and solder joint composition had a statistically significant effect on the characteristic life and slope of the BGA assemblies.

This chapter includes the analysis and results for the failure detection and failure criteria comparison, while the following chapter includes the analysis and results of the reliability analysis.

4.1 Comparison of Four Failure Criteria

The objective of this study is to compare the effect of failure criteria in reliability life estimation for low-silver BGA data. The four failure criteria are:

1. $\bar{X}$ and R chart method
2. IPC-9701A: Cycle exceeding a 20% increase in resistance, where
$$R(T) > 1.2 \cdot R_0(T), \text{ and } R_0(T) = \text{resistance measured during the first cycle at temperature } T.$$
3. Resistance > 500 Ω : Cycle of first resistance reading greater than 500 Ω
4. Infinite Resistance: Cycle of first infinite resistance reading

4.1.1 Selection of Failure Criteria

The failure criteria selected to evaluate the low-silver BGA data were selected from the failure criteria used in the thermal fatigue study of SAC105, Sn-3.5Ag, and SAC305 BGA by Henshall et al.[35]. Henshall et al. used the IPC-9701A failure criteria, 500 Ω threshold, and infinite resistance (hard open) as failure criteria, and concluded that IPC-9701A was the most sensitive failure criterion of the three. The same failure criteria were selected for this study in order to compare this conclusion to a different and larger set of accelerated thermal cycling data (from the low-silver BGA study). These three failure criteria were compared with the $\bar{X}$ and R chart method proposed by Pan and Silk. Prior to this study, the $\bar{X}$ and R failure criterion had not been applied to any other accelerated testing data beyond the 39 packages evaluated in the study by Pan and Silk.

4.1.2 $\bar{X}$ and R chart Failure Criterion

The methodology for the $\bar{X}$ and R failure criterion proposed by Pan and Silk is described in the Literature Review. $\bar{X}$ and R charts were created for each component in the low-silver BGA study (total of 720 connections) using JMP software. The control limits of $\bar{X}$ chart are defined as:

$$\text{Control Limits: } \bar{\bar{X}} \pm \frac{k\sigma}{\sqrt{n}}$$

Where $\bar{\bar{X}}$ is the average resistance of the first 40 cycles,

σ = standard deviation of resistance due to natural variation, and

n = rational subgroup size (the average number of readings in each temperature cycle).

In this study, $k = 3$ is used, which minimizes “false positive” failure detection. A k value of 3 is the accepted industry standard for statistical process control. When $k=3$, the probability of an encountering an observation beyond three standard deviations from the center line is 0.3%. Therefore, a point outside the control limits indicates the process has shifted and is no longer in control [11]. The control limits of R chart are defined as:

$$\text{Control Limits: } LCL_R = D_3 \bar{R} \text{ and } UCL_R = D_4 \bar{R}$$

Where $R = X_{max} - X_{min}$ (sample range), and

D_3 and D_4 are sample anti-biasing constants.

A control chart for a single BGA package (SnPb ball alloy, SAC105 paste alloy, 1.0mm pitch, peak reflow temperature of 220°C, and temperature cycling range of 0 to 100°C) is shown in Figure 5. The $\bar{X}$ chart indicates failure 5375 cycles.

4.1.3 IPC-9701A, 500 Ohm, and Infinite Resistance Failure Criteria

Figure 5. $\bar{X}$ and R chart for a BGA package

Throughout the accelerated thermal cycling of the packages, the daisy chain resistance was monitored continuously. The data acquisition software detected failure from the IPC-9701A standard for a 20% increase in resistance from the initial value. The resistance was monitored for the remainder of the accelerated thermal cycling (10,102 cycles for the 0 to 100 °C temperature cycling range, and 3,556 cycles for the -40 to 125 °C temperature cycling range). From this data, the cycles to failure for the 500 Ohm and Infinite Resistance failure criteria were identified.

4.2 Results: Comparison of Failure Criteria

Failure data (cycles-to-failure) for the $\bar{X}$ and R, IPC-9701A, 500 Ω , and Infinite Resistance failure criteria are seen in Appendix A. The number of components meeting each failure criterion is shown in Table 4. A total of 720 components were analyzed for both temperature cycling ranges. Any package that did not meet a failure criterion was considered as right-censored for the reliability analysis. Appendix A includes this right-censored data, which are indicated by having no failure (n.f.).

Table 4. Number of components meeting each failure criterion with % out of 720 total components

	0°C to 100°C TCR (10,102 cycles)	-40°C to 125°C TCR (3,556 cycles)
$\bar{X}$ and R	687 (95%)	710 (99%)
IPC-9701A	687 (95%)	710 (99%)
500 Ohm	687 (95%)	710 (99%)
Infinite Resistance	629 (88%)	710 (99%)

A graph of the cycles of failure for a single package (SnPb ball alloy, SAC105 paste alloy, 1.0mm pitch, peak reflow temperature of 220°C, and temperature cycling range of 0 to 100°C) is shown in Figure 6 For this BGA package, both $\bar{X}$ and R failure

criterion and IPC-9701A detected solder joint failure at 5,375 cycles, while 500 Ω resistance threshold detected failure at 5,456 cycles and Infinite Resistance failure criteria detected failure at 5,504 cycles. Thus, the $\bar{X}$ and R and IPC-9701A failure criteria are more sensitive than the 500 Ω resistance threshold and Infinite Resistance failure criterion for this package. However, most packages exhibited this general relationship amongst the failure criterion. In general, the $\bar{X}$ and R and IPC-9701A criteria had very similar cycles to failure while being more sensitive than the 500 Ω resistance threshold and Infinite Resistance failure criteria.

Figure 6. Cycles to failure of four failure criteria for one package

Table 5 illustrates that $\bar{X}$ and R failure criterion and IPC-9701A detected solder joint failure at the same cycles-to-failure in most cases. The $\bar{X}$ and R failure criterion detected solder joint failure marginally sooner than IPC-9701A, with an average of 1.76 cycles earlier detection. Table 6 shows that $\bar{X}$ and R and IPC-9701A consistently detected failure sooner than 500 Ω resistance threshold and Infinite Resistance failure criteria. The $\bar{X}$ and R method detected failure on average 334 cycles or 12.9% of time-to-failure earlier than 500 Ω failure criterion for 0 to 100°C data, and 94 cycles or 10.4% of time-to-failure earlier for -40 to 125°C data. In addition, $\bar{X}$ and R failure criterion detected failure on average 822 cycles or 23.4% of time-to-failure earlier than Infinite Resistance failure criterion for 0 to 100°C data, and 227 cycles or 18.6% of time-to-failure earlier for -40 to 125°C data.

Table 5. $\bar{X}$ and R failure criterion compared to IPC-9701A

	% Earlier Detection	% Same Detection	% Later Detection
0°C to 100°C TCR	21.7	73.1	5.2
-40°C to 125°C TCR	38.2	61.1	0.7

Table 6. Average cycles to failure (% Total Cycles*) for four failure criteria

	$\bar{X}$ & R	IPC-9701A	500 Ω	Infinite Resistance
0 to 100°C TCR	3883 (38.4%)	3886 (38.4%)	4217 (41.7%)	4705 (46.6%)
-40 to 125°C TCR	1515 (42.6%)	1516 (42.6%)	1609 (45.2%)	1743 (49.0%)

Table 7 and Table 8 show the response values for Weibull characteristic life and slope parameter estimates for each treatment, respectively. Although there was no replication in the responses, each characteristic life and slope parameter was estimated from the failure data of 20 packages.

Table 7. Weibull characteristic life values for each treatment.

Ball/Paste	0 to 100 °C TCR (10,102 cycles)				-40 to 125 °C (3556 cycles) TCR			
	Pitch							
	0.5mm	0.8mm	1.0mm	1.27mm	0.5mm	0.8mm	1.0mm	1.27mm
SnPb	1825.77	1065.50	2162.69	3742.99	1326.73	1293.40	1818.73	2388.38
SAC305-SnPb	3176.21	2809.34	6485.70	10574.84	1449.72	1234.01	1657.65	2240.17
SAC105-SnPb	2866.70	1748.73	4856.77	7141.78	1474.99	1512.24	1517.76	2190.30
SACX-SnPb	3099.28	1601.68	3808.37	7672.22	1319.55	1272.37	1721.89	2605.52
SAC305	3671.79	3320.03	5660.81	11214.19	1235.30	1037.86	1735.66	2646.72
SAC105-SAC305	3105.33	2069.59	4022.67	7972.19	1498.92	1472.08	1525.58	2708.53
SACX-SAC305	2975.16	2088.34	3198.30	5109.12	1337.04	1131.00	1543.17	2237.56
SAC205-SAC305	3394.76	2583.50	4449.32	6348.58	1479.59	1546.13	1480.78	2753.35

Table 8. Weibull slope values for each treatment

Ball/Paste	0 to 100 °C (10,102 cycles)				-40 to 125 °C (3556 cycles)			
	Pitch							
	0.5mm	0.8mm	1.0mm	1.27mm	0.5mm	0.8mm	1.0mm	1.27mm
SnPb	9.62	10.85	5.93	3.35	4.24	1.83	4.03	3.57
SAC305-SnPb	2.89	6.39	5.35	4.70	3.38	2.07	3.67	3.11
SAC105-SnPb	9.55	4.72	6.88	4.46	2.34	2.73	2.79	2.50
SACX-SnPb	6.08	2.54	7.97	2.08	2.71	2.25	3.42	4.59
SAC305	9.35	5.66	7.73	3.60	3.59	3.12	5.70	3.26
SAC105-SAC305	9.69	7.27	8.30	2.24	2.87	2.60	2.55	3.25
SACX-SAC305	6.86	8.14	7.62	3.94	5.67	4.30	2.84	3.17
SAC205-SAC305	10.55	9.33	8.27	3.04	2.35	2.56	3.37	3.24

Chapter 5. Analysis and Results: Reliability analysis of low-Ag BGA ATC data

The reliability analysis of the low-Ag BGA data was performed using the $\bar{X}$ and R failure data. First, the Weibull life distribution was selected for the analysis from several distributions through the comparison of AIC values. The Weibull parameters (characteristic life α and slope β) were then estimated for each treatment. An analysis of variance (ANOVA) was performed to determine the significant factors which affect these Weibull parameters for the low-silver BGA solder joints.

5.1 Reliability Life Distribution Fitting

The failure data for each treatment “cell” was fit to every life distribution available on the life distribution platform using JMP statistical software. Components which did not fail by the end of the thermal cycling were right-censored. The appropriate life distribution for the failure data was selected through the comparison of the Akaike information criterion (AIC) values for the following goodness-of-fit measurement with the following equation: $AIC = 2k - 2\ln(L)$, where k is the number of parameters in the model and $\underline{L}$ is the maximum likelihood function of the model. For model selection from multiple models, the preferred model has the minimum AIC value.

The AIC values for all treatments were averaged for both temperature cycling ranges. The two lifetime distribution models with the minimum average AIC values were the two-parameter Weibull distribution and Lognormal distribution. The average AIC values were very close, with the Lognormal providing a slightly better fit for the 0 °C to

100 °C temperature cycling range and the Weibull distribution providing a slightly better fit for the -40 °C to 125 °C temperature cycling range (See Table 9). Although this indicates that either would have been suitable to model the data, the Weibull distribution was selected.

Table 9. Average AIC values for Weibull and Lognormal distributions for each temperature cycling range

Temperature Cycling Range	Distribution	Average AIC	Better Fit (Count)
0 °C to 100 °C	Weibull	293.89	13
	Lognormal	293.09	23
-40 °C to 125 °C	Weibull	303.8	20
	Lognormal	304.42	16

5.1.1 Weibull Parameter Estimation

Table 10 includes Weibull parameter estimates (the characteristic life α and slope β) for one “cell” treatment with a ball alloy of SnPb, paste alloy of SAC105 pitch of 1.0mm, peak reflow temperature of 220°C, and thermal cycling range of 0 to 100°C. Figure 7 shows the Weibull plots for each failure criterion of the treatment. The Weibull characteristic life and slope are used as response variables for the ANOVA analysis which is described in the next section.

Table 10. Weibull parameter estimation for one cell

Failure Criteria	Parameter	Parameter Est.
$\bar{X}$ and R	Weibull α	4646.78
	Weibull β	6.78
IPC-9701A	Weibull α	4649.71
	Weibull β	6.77
500 Ω	Weibull α	5362.38
	Weibull β	7.37
Infinite R	Weibull α	5455.45
	Weibull β	7.93

Figure 7. Weibull plot for one cell using four failure criteria

5.2 ANOVA using $\bar{X}$ and R Failure Criterion

Analysis of variance was used to determine the significant factors which affect the Weibull characteristic life and slope of the low-silver BGA solder joints for both temperature cycling ranges. Weibull parameter estimates from the $\bar{X}$ and R failure criterion were used in the ANOVA, because the $\bar{X}$ and R and IPC-9701A failure criteria were the most sensitive of the four studied, but provided very similar cycles to failure and Weibull parameter estimates.

5.2.1 Experimental Design

The original experimental matrix for the accelerated thermal cycling for the low-silver BGA study is described in the literature review. Varied in the original experimental matrix for the accelerated thermal cycling were ball alloy, paste alloy, peak reflow temperature, and pitch (see Table 3). Peak reflow temperature was removed as a factor for the analysis, and the ball alloy and paste alloy were consolidated into one factor. In addition, certain treatments were removed to create a balanced model. The resulting design was a two-way ANOVA for each of the four response variables: Weibull characteristic life (α) for 0 to 100 °C and -40 to 125 °C temperature cycling ranges and Weibull slope (β) for 0 to 100 °C and -40 to 125 °C temperature cycling ranges.

5.2.1.1 *Pitch (BGA package type)*

The other factor analyzed was BGA package type, which is identified by the pitch of the package type. To review, package types included in the accelerated thermal cycling experiment:

- 1.27 mm pitch SuperBGA, 600 I/O; solder ball volume of 0.230 mm³,
- mm pitch Plastic BGA, 324 I/O; solder ball volume of 0.131 mm³,
- 0.8 mm pitch ChipArray BGA, 288 I/O; solder ball volume of 0.051 mm³, and
- 0.5 mm pitch ChipArray Thin Core BGA, 132 I/O; solder ball volume of 0.014 mm³.

Both factors were considered nominal. The response variables were Weibull characteristic life (α) and slope (β). Significant factors were identified using a p-value

approach. Further, a Tukey's test of multiple comparisons was conducted for significant factors.

5.2.1.2 Paste Alloy and Ball Alloy Consolidation

The purpose of the reflow process for BGA assemblies is to melt the solder ball alloy into the solder paste, which attaches the surface mount components to a printed circuit board (PCB) and creates electrical continuity. Although complete mixing of the solder alloy and paste alloy is not necessary to create electrical continuity, the experiment in Phase I of the low-silver BGA study identified the factors which affect the level of mixing for the solder joint after reflow. The results of this experiment were used in the selection of peak reflow temperatures for the BGA assemblies used in the accelerated thermal cycling tests. Because it is assumed that appropriate levels of solder paste and solder ball mixing were achieved, the paste and ball alloy were consolidated into one factor (See Table 11) for ANOVA.

Table 11. Ball alloy and paste alloy consolidation

Ball Alloy	Paste Alloy	Ball/Paste
SnPb	SnPb	SnPb
SAC305	SnPb	SAC305-SnPb
SAC105	SnPb	SAC105-SnPb
SACX	SnPb	SACX-SnPb
SAC305	SAC305	SAC305
SAC105	SAC305	SAC105-SAC305
SACX	SAC305	SACX-SAC305
SAC205	SAC305	SAC205-SAC305

5.2.1.3 Peak Reflow Temperature

Because peak reflow temperature for the BGA assemblies were chosen based on the results of Phase I of the low-silver BGA study, peak reflow temperature was not

considered a factor for the ANOVA analysis. The peak reflow temperature for the solder joints with SAC305 paste alloy were consistent at 235°C. The peak reflow temperature for solder joints with SnPb paste alloy was 215°C with the exception of 1.0mm and 1.27mm pitch BGAs, which were also tested at 215°C and 220°C. However, failure data from these assemblies were ultimately removed for the purpose of this ANOVA (see next section).

5.2.1.4 Removal of Treatments for a Balanced ANOVA

In order to create a balanced model, treatments which included data for some BGA package types (itches) but not all were removed for the ANOVA. This includes the following treatments from both temperature cycling ranges:

- 1.0mm and 1.27 mm pitch, SnPb paste alloy, SAC105 ball alloy, and peak reflow temperature of 220°C,
- 0.5mm pitch, SnPb paste alloy, LF ball alloy, peak reflow temperature of 215°C, and
- 0.5mm pitch, SAC305 paste alloy, LF35ball alloy, peak reflow temperature of 215°C.

5.2.1.5 Final Experimental Matrix

One factor included in the ANOVA are Ball/Paste with the following levels: SnPb, SAC305-SnPb, SAC105-SnPb, SACX-SnPb, SAC305, SAC105-SAC305, SACX-SAC305, and SAC205-SAC305. The other factor included in the analysis was package construction (pitch) with the following levels: 0.5mm, 0.8mm, 1.0mm, 1.27mm.

Response variables are the Weibull characteristic life and slope for both temperature cycling ranges (0 to 100 °C and -40 to 125 °C).

Table 12 shows the final experimental matrix with the number of BGA packages used in the estimation of the Weibull α and Weibull β for ANOVA analysis. Although there was no replication in the responses for each treatment, each characteristic life and slope parameter was estimated from the failure data of 20 packages. The parameter estimates for each treatment are shown in the Results section.

5.2.1.6 ANOVA Hypotheses

The ANOVA will test the following hypotheses for the Weibull characteristic life for the 0 to 100 °C temperature cycling range:

Factor A (Ball/Paste)

$$H_{0(A)}: \mu_{A1} = \mu_{A2} = \mu_{A3} = \mu_{A4} = \mu_{A5} = \mu_{A6} = \mu_{A7} = \mu_{A8}$$

$H_{A(A)}$: at least one pair of the above is not equal

Table 12. Number of components for estimation of Weibull characteristic life and slope for each treatment

Ball/Paste	0 to 100 °C TCR (10,102 cycles)				-40 to 125 °C TCR (3556 cycles)			
	Pitch							
	0.5mm	0.8mm	1.0mm	1.27mm	0.5mm	0.8mm	1.0mm	1.27mm
SnPb	20	20	20	20	20	20	20	20
SAC305-SnPb	20	20	20	20	20	20	20	20
SAC105-SnPb	20	20	20	20	20	20	20	20
SACX-SnPb	20	20	20	20	20	20	20	20
SAC305	20	20	20	20	20	20	20	20
SAC105-SAC305	20	20	20	20	20	20	20	20
SACX-SAC305	20	20	20	20	20	20	20	20
SAC205-SAC305	20	20	20	20	20	20	20	20

Where μ_{A1} is the population mean characteristic life for packages with ball/paste SnPb, μ_{A2} is the population mean characteristic life for packages with ball/paste SAC305-SnPb, [...], and μ_{A8} is the population mean characteristic life for packages with ball/paste SnPbSAC205-SAC305.

Factor B (Pitch)

$H_{0(B)}: \mu_{B1} = \mu_{B2} = \mu_{B3} = \mu_{B4}$

$H_{A(B)}: \text{at least one pair of the above is not equal}$

Where μ_{B1} is the population mean characteristic life for packages with pitch 0.50mm, μ_{B2} is the population mean characteristic life for packages with pitch 0.80mm, μ_{B3} is the population mean characteristic life for packages with pitch 1.00mm, μ_{B4} is the population mean characteristic life for packages with pitch 1.27mm.

The hypotheses for the remaining two-way ANOVAs also include ball/paste and pitch as factors. The remaining three response variables for these ANOVAs are the Weibull characteristic life (α) for the 0 to 100°C temperature cycling range, Weibull slope (β) for the -40 to 125°C and 0 to 100 °C temperature cycling range. This results in a total of four sets of hypotheses (one for each response variable).

5.3 ANOVA Results

The results of the ANOVA reveal whether package construction and ball/paste has a significant effect on the characteristic life and slope of the low-Ag BGA assembly ATC data for both temperature ranges. The differentiation of the temperature ranges is important because the 40°C to 125 °C temperature cycling range represents harsher thermal conditions from normal component use than the 0°C to 100 °C temperature cycling range. Determining whether ball/paste alloys and pitch sizes will have a statistically significant effect on Weibull characteristic life has the potential to be applied to BGA package and alloy selection. Similar Weibull slopes indicate the same failure mode, while Weibull slopes which are not similar can indicate multiple failure modes. Because the failure mode of interest is a crack from thermal fatigue, it is necessary see whether other failure modes may be present.

5.3.1 ANOVA Results: Weibull Characteristic Life: 0°C to 100 °C TCR

Characteristic life for both temperature cycling ranges was examined. For 0 to 100°C temperature cycling range, ball/paste and pitch were both significant factors with p-values of 0.001 and <0.0001, respectively, as shown in Table 13. The LS Means plot for pitch in Figure 8 shows that the characteristic life for 0.8 mm pitch is the lowest. The Tukey's test of multiple comparisons shown in Table 14 indicates that the characteristic life for 0.8 mm pitch is statistically significantly different from that for 1.0 mm and 1.27 mm pitch. In addition, the characteristic life for 1.27mm pitch is statistically significant longer than that for other pitches.

Table 13. ANOVA Table for Weibull characteristic life (0 to 100 °C)

Source	DF	SS	F Ratio	p-value
pitch	3	130,231,567	40.95	<.0001

ball/paste	7	41,265,630	5.56	0.001
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Table 14. Tukey's multiple comparisons for Weibull characteristic life of different package constructions (0 to 100 °C)

Pitch Level	Group			Least Sq Mean (cycles)
1.27 mm	A			7471.99
1.0 mm		B		4330.58
0.5 mm		B	C	3014.37
0.8 mm			C	2160.84

Figure 8. Weibull characteristic life LS Means for pitch (0 to 100 °C)

The LS Means plot for ball/paste in Figure 9 shows that ball/paste has statistically significant effect on the characteristic life of solder joints. Table 15 shows the Tukey's multiple comparisons for Weibull characteristic life of different ball/paste (0 to 100 °C).

5.3.2 ANOVA Results: Weibull Characteristic Life: -40°C to 125 °C TCR

For the -40 to 125°C temperature cycling range, Table 16 shows that package construction or pitch was a significant factor for Weibull characteristic life while ball/paste was not. The LS means plot for pitch in Figure 6 shows a very similar result as the 0 to 100 °C temperature cycling range. Table 10 is the Tukey's multiple comparisons for Weibull characteristic life of different ball/paste (-40 to 125 °C).

Figure 9. Weibull characteristic life LS Means for ball/paste (0 to 100 °C)

Table 15. Tukey's Test for Weibull characteristic life α for different ball/paste (0 to 100 °C)

Level	Group			Least Sq Mean (cycles)
SAC305	A			5966.71
SAC305-SnPb	A	B		5761.52
SAC105-SAC305	A	B	C	4292.45
SAC205-SAC305	A	B	C	4194.04
SAC105-SnPb	A	B	C	4153.49
SACX-SnPb	A	B	C	4045.39
SACX-SAC305		B	C	3342.73
SnPb			C	2199.24

Table 16. ANOVA Table for Weibull characteristic life α (-40 to 125°C)

Source	DF	SS	F Ratio	p-value
pitch (mm)	3	6773844	79.43	<.0001
ball/paste	7	193486	0.97	0.4762

Figure 10. Weibull characteristic life LS Means for pitch (-40 to 125 °C)

Table 17. Tukey's Test for Weibull characteristic life for different package constructions (-40 to 125°C)

Pitch Level	Group			Least Sq Mean (cycles)
1.27 mm	A			2471.31
1.0 mm		B		1625.15
0.5 mm		B	C	1390.23
0.8 mm			C	1312.39

5.3.3 ANOVA Results: Weibull Slope: 0°C to 100 °C TCR

Table 18 shows that package construction or pitch has a statistically significant effect on the Weibull slope for the 0 to 100 °C temperature cycling range, while ball/paste does not have a significant effect. Tukey's test in Table 19 and the LS means plot in Figure 11.

Weibull slope β LS Means for pitch (0 to 100 °C) shows that Weibull slope for package types with a 1.27 mm pitch is statistically significant lower than those with any other pitch size, which indicates that the failure mode of solder joints with a 1.27 mm pitch may be different from that packages with a 0.5mm, 0.8mm, and 1.0mm pitch.

Table 18. ANOVA Table for Weibull slope β (0 to 100 °C)

Source	DF	SS	F Ratio	p-value
pitch	3	100.76	9.31	0.0004
ball/paste	7	35.26	1.49	0.2583

Table 19. Weibull β Tukey's Test for pitch (0 to 100 °C)

Pitch Level	Group	Least Sq Mean
0.5 mm	A	8.07
1.0 mm	A	7.26
0.8 mm	A	6.86
1.27 mm	B	3.43

Figure 11. Weibull slope β LS Means for pitch (0 to 100 °C)

5.3.4 ANOVA Results: Weibull Slope -40°C to 125 °C TCR

For the -40 to 125 °C temperature cycling range, the ANOVA shown in Table 20 shows that neither pitch nor ball/paste was significant factor for the Weibull slope. Because there is no difference in the Weibull slope due to the solder joint package type or alloy

type, this implies that the failure mode for the solder joints is the same for the solder joints with the -40 to 125 °C temperature cycling condition.

Table 20. ANOVA Table for Weibull characteristic life β (-40 to 125°C)

Source	DF	SS	F Ratio	p-value
pitch	3	3.52	1.63	0.2117
ball/paste	7	7.26	1.44	0.2409

Chapter 6. Conclusions and Discussions

Four failure criteria were compared in solder joint reliability life estimation. These failure criteria include a failure criterion based on $\bar{X}$ and R control charts, a 20% resistance increase defined in the IPC-9701A, 500 Ω resistance threshold, and Infinite Resistance. Results show that $\bar{X}$ and R failure criterion has very similar cycles to failure as the IPC-9701A failure criterion for both temperature cycling ranges. The $\bar{X}$ and R failure criterion detects failures marginally sooner than IPC-9701A. Both the $\bar{X}$ and R failure criterion and IPC-9701A detected failure earlier than 500 Ω resistance threshold and Infinite Resistance failure criteria. In addition, when Infinite Resistance failure criterion is used, more failure data are right-censored compared to when other failure criteria are used.

The reliability of the solder joints was assessed using the $\bar{X}$ and R failure criterion. Pitch (package structure) had a statistically significant effect on Weibull characteristic life of low-silver BGA solder joints for data from both temperature cycling ranges, with 0.8mm pitch packages having the lowest characteristic life.

Ball/paste (solder joint composition) had a statistically significant effect on Weibull characteristic life of low-silver BGA solder joints for 0 to 100°C thermal cycling data, but not for -40 to 125°C thermal cycling data. This indicates that there is no statistically significant difference in reliability life among ball/paste alloys for -40 to 125°C thermal cycling range data.

Both pitch (package structure) and ball/paste (solder joint compositions) have no statistically significant effect on Weibull slope for both temperature ranges, with the exception of pitch for 0 to 100°C data. This indicates that the failure mode for all treatments may be the same.

6.1 Package Construction and Weibull Characteristic Life Relationship

A significant relationship between package construction and Weibull characteristic life is seen in both temperature ranges. Although it is known that finer pitch BGA assemblies result in fewer cycles-to-failure, the 0.8mm pitch BGA joints showed the lowest Weibull characteristic life for both temperature ranges. Although pitch varied for each BGA package studied, the BGA assemblies were not of the same package construction regardless of pitch. There are other factors which could have resulted in the lowest characteristic life for 0.8mm pitch BGA assemblies, which are unknown. If the BGA assemblies had the same package construction of the BGA assemblies with the exception of pitch, there would have likely been an increase in characteristic life with an increase in ball pitch.

6.2 Effect of Temperature Cycling Range on Weibull Characteristic Life

As expected, the larger temperature cycling range resulted in a lower characteristic life for BGA packages thermally cycled at -40 to 125°C when compared to the packages subject to the 0 to 100°C temperature cycling range. The effect of ball/paste composition

on Weibull characteristic life differed for the temperature cycling range. Ball/paste did not have a statistically significant effect on Weibull characteristic life for the -40 to 125°C, which indicates that for BGA assemblies used for applications in which there are harsher thermal conditions, many alloys can be used without affecting the reliability life of the device. However, for less extreme conditions, which are represented at the 0 to 100°C temperature cycling range, solder alloy selection is important. In these cases, SAC305 would be a better solder alloy choice than SnPb.

6.3 Possible Further Work

The results and conclusions from this study show the applicability of the $\bar{X}$ and R failure criterion to the low-silver BGA assembly ATC data. However, the $\bar{X}$ and R failure criterion has not been applied to any other failure data with the exception of the data from the initial proposal by Pan and Silk. It would be interesting to if the $\bar{X}$ and R failure criterion would yield similar results as the IPC-9701A failure criterion when applied to other types of accelerated tests.

Although the low-Ag BGA assembly study included accelerated thermal cycling, the drop-shock performance of the BGA assemblies was not evaluated in the study. Although the benefits of low-Ag alloys for drop shock performance has already been documented in previous, relationships between the other factors which were examined in the low-Ag BGA assembly study (peak reflow temperature, temperature cycling range, package construction, etc.) could have been evaluated in another design of experiment.

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Appendix A

Cycles to failure for low-silver BGA data for each failure criteria

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.50	SAC305	SAC305	235	3793	3794	4095	4095	1253	1253	1310	1363
0.50	SAC305	SAC305	235	3842	3842	4341	4341	1705	1705	1722	1722
0.50	SAC305	SAC305	235	2881	2891	3459	3670	1943	1943	1945	1945
0.50	SAC305	SAC305	235	3195	3195	3240	3240	1661	1661	1691	1691
0.50	SAC305	SAC305	235	3441	3441	3766	3766	1637	1637	1643	1867
0.50	SAC305	SAC305	235	3692	3697	4360	4360	1101	1101	1112	1112
0.50	SAC305	SAC305	235	3540	3540	3748	3748	1334	1334	1355	1355
0.50	SAC305	SAC305	235	3512	3512	3965	3965	1202	1202	1550	1550
0.50	SAC305	SAC305	235	3182	3235	3468	3468	1828	1828	1837	1839
0.50	SAC305	SAC305	235	3542	3542	3778	3779	1222	1222	1243	1603
0.50	SAC305	SAC305	235	3647	3654	4084	4084	1651	1651	1660	1660
0.50	SAC305	SAC305	235	3764	3764	3897	3897	1430	1429	1510	1510
0.50	SAC305	SAC305	235	3558	3559	4094	4094	975	975	1082	1082
0.50	SAC305	SAC305	235	3446	3446	3593	3593	1232	1232	1429	1471
0.50	SAC305	SAC305	235	3466	3465	3918	3918	1222	1221	1309	1309
0.50	SAC305	SAC305	235	3646	3647	4293	4293	1548	1548	1642	1642
0.50	SAC305	SAC305	235	3915	3915	4188	4188	1417	1417	1676	1998
0.50	SAC305	SAC305	235	2500	2500	2515	2515	1244	1244	1406	1406
0.50	SAC305	SAC305	235	4433	4434	4975	4975	1461	1461	1467	1467
0.50	SAC305	SAC305	235	2899	2900	3515	3515	1360	1360	1414	1587
0.50	SAC305	SAC105	235	2905	2915	3609	3609	860	860	971	971
0.50	SAC305	SAC105	235	3389	3392	3684	3684	1274	1274	1347	1347
0.50	SAC305	SAC105	235	2701	2704	3587	3587	1240	1240	1373	1408
0.50	SAC305	SAC105	235	3456	3456	3764	3764	1199	1199	1223	1223
0.50	SAC305	SAC105	235	3172	3174	3402	3402	751	752	765	765
0.50	SAC305	SAC105	235	3293	3299	3375	3375	818	837	864	1144
0.50	SAC305	SAC105	235	2910	2911	2940	2940	742	742	752	1041
0.50	SAC305	SAC105	235	2645	2648	2651	2651	1324	1324	1496	1496
0.50	SAC305	SAC105	235	2448	2448	2501	2501	1276	1277	1331	1331
0.50	SAC305	SAC105	235	2733	2733	2944	2944	844	843	848	848
0.50	SAC305	SAC105	235	2673	2697	3063	3063	1266	1266	1273	1273
0.50	SAC305	SAC105	235	2757	2757	2992	2992	930	930	940	940

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.50	SAC305	SAC105	235	3102	3102	3483	3483	1390	1390	1415	1420
0.50	SAC305	SAC105	235	2216	2216	3140	3140	1017	1017	1048	1048
0.50	SAC305	SAC105	235	3232	3232	3495	3495	1527	1527	1534	1534
0.50	SAC305	SAC105	235	3170	3171	3797	3797	1534	1535	1602	1602
0.50	SAC305	SAC105	235	2599	2599	2978	2978	1326	1326	1728	1728
0.50	SAC305	SAC105	235	3512	3514	3911	4087	1036	1036	1046	1156
0.50	SAC305	SAC105	235	3310	3310	3648	3648	1435	1435	1444	1446
0.50	SAC305	SAC105	235	2770	2770	3033	3033	973	973	1055	1055
0.50	SAC305	SACX	235	3069	3070	3229	3229	1016	1016	1202	1357
0.50	SAC305	SACX	235	2267	2267	2545	2545	1566	1567	1603	1603
0.50	SAC305	SACX	235	2896	2899	2978	2978	1183	1183	1367	1367
0.50	SAC305	SACX	235	3384	3384	3602	3602	1368	1368	1410	1410
0.50	SAC305	SACX	235	2463	2463	3083	3083	1304	1307	1312	1314
0.50	SAC305	SACX	235	3752	3752	4033	4033	1187	1196	1216	1216
0.50	SAC305	SACX	235	2954	2968	3498	3498	1551	1551	1577	1593
0.50	SAC305	SACX	235	2572	2572	3142	3142	1568	1568	1577	1599
0.50	SAC305	SACX	235	2694	2694	2981	3263	1294	1295	1365	1451
0.50	SAC305	SACX	235	2398	2398	3033	3033	1247	1247	1261	1262
0.50	SAC305	SACX	235	3235	3235	3274	3592	1090	1090	1111	1111
0.50	SAC305	SACX	235	1811	1829	2830	3335	1059	1060	1060	1061
0.50	SAC305	SACX	235	2676	2677	2704	2704	1204	1204	1255	1273
0.50	SAC305	SACX	235	2820	2820	3679	3850	1282	1282	1283	1334
0.50	SAC305	SACX	235	2720	2721	2880	2880	1389	1389	1389	1389
0.50	SAC305	SACX	235	3332	3332	3458	3458	1534	1534	1627	1627
0.50	SAC305	SACX	235	2183	2201	2991	3023	846	846	1242	1311
0.50	SAC305	SACX	235	2626	2632	3224	3224	1117	1117	1344	1344
0.50	SAC305	SACX	235	2910	2910	3447	3447	1314	1314	1455	1471
0.50	SAC305	SACX	235	2981	2982	3277	3277	1219	1219	1271	1300
0.50	SAC305	SAC205	235	2757	2757	2558	3190	1294	1294	1303	1303
0.50	SAC305	SAC205	235	3393	3393	4093	4093	1301	1301	1328	1328
0.50	SAC305	SAC205	235	2457	2458	3378	3378	1416	1416	1429	1448
0.50	SAC305	SAC205	235	3919	3919	4391	4391	1411	1442	1471	1471
0.50	SAC305	SAC205	235	3532	3532	4291	4291	1485	1485	1486	1488
0.50	SAC305	SAC205	235	3578	3578	3580	4291	1051	1052	1077	1436
0.50	SAC305	SAC205	235	2861	2861	3156	3156	1439	1439	1460	1461
0.50	SAC305	SAC205	235	3398	3398	3798	3798	1415	1415	1420	1420

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.50	SAC305	SAC205	235	3165	3165	3319	3319	1507	1507	1526	1526
0.50	SAC305	SAC205	235	3791	3793	4130	4130	1273	1273	1290	1290
0.50	SAC305	SAC205	235	3367	3368	4422	4422	1461	1462	1551	1575
0.50	SAC305	SAC205	235	3281	3289	3495	3495	967	967	1030	1030
0.50	SAC305	SAC205	235	3437	3438	3759	3759	1236	1236	1251	1251
0.50	SAC305	SAC205	235	3336	3342	3866	3866	1060	1060	1095	1158
0.50	SAC305	SAC205	235	3107	3108	3369	3369	1260	1260	1520	1520
0.50	SAC305	SAC205	235	3309	3309	3965	3965	1677	1676	1712	1752
0.50	SAC305	SAC205	235	3200	3200	3980	4059	1295	1295	1381	1381
0.50	SAC305	SAC205	235	3224	3225	4061	4061	1361	1361	1366	1366
0.50	SAC305	SAC205	235	2864	2865	3175	3175	1617	1617	1638	1680
0.50	SAC305	SAC205	235	2869	2869	3454	3454	1481	1481	1500	1501
0.50	SAC305	LF35	235	2811	2811	3000	3000	1555	1555	1555	1555
0.50	SAC305	LF35	235	3375	3376	3906	3960	1409	1409	1452	1452
0.50	SAC305	LF35	235	3457	3457	4030	4083	1447	1447	1453	1455
0.50	SAC305	LF35	235	3020	3020	3788	3788	1353	1353	1353	1353
0.50	SAC305	LF35	235	3194	3194	3533	3533	1168	1168	1177	1177
0.50	SAC305	LF35	235	2834	2834	2733	2733	1077	1078	1104	1478
0.50	SAC305	LF35	235	3482	3482	3634	3674	1748	1748	1749	1755
0.50	SAC305	LF35	235	3229	3229	3695	3695	1677	1678	1681	1736
0.50	SAC305	LF35	235	3069	3071	3685	3685	1709	1709	1726	1969
0.50	SAC305	LF35	235	3237	3238	3742	3759	1420	1421	1428	1428
0.50	SAC305	LF35	235	2819	2835	3073	3073	1402	1402	1427	1427
0.50	SAC305	LF35	235	3200	3200	3771	3771	1288	1288	1336	1362
0.50	SAC305	LF35	235	3259	3259	3500	3500	1455	1455	1468	1514
0.50	SAC305	LF35	235	3931	3932	4042	4067	1028	1029	1032	1427
0.50	SAC305	LF35	235	3205	3205	3354	3406	1386	1386	1389	1389
0.50	SAC305	LF35	235	2948	2948	3557	3557	1167	1167	1183	1183
0.50	SAC305	LF35	235	3331	3331	3473	3473	1352	1352	1370	1566
0.50	SAC305	LF35	235	2669	2669	2779	2779	1376	1376	1378	1378
0.50	SAC305	LF35	235	3334	3360	3507	3717	1595	1595	1599	1603
0.50	SAC305	LF35	235	3009	3009	3654	3777	1375	1375	1536	1610
0.80	SAC305	SAC305	235	3328	3328	3778	3778	664	667	780	1564
0.80	SAC305	SAC305	235	2837	2838	3089	3364	1133	1133	1146	1389
0.80	SAC305	SAC305	235	3127	3128	3662	4138	1697	1697	1789	1789
0.80	SAC305	SAC305	235	3746	3746	3753	4387	927	927	960	1691

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.80	SAC305	SAC305	235	3717	3718	3918	4110	1137	1137	1141	1533
0.80	SAC305	SAC305	235	4430	4430	4590	4954	1531	1531	1579	1881
0.80	SAC305	SAC305	235	2456	2458	3273	3717	1255	1255	1298	1590
0.80	SAC305	SAC305	235	1698	1698	2109	2905	999	999	1048	1692
0.80	SAC305	SAC305	235	3114	3114	3445	3445	1530	1530	1647	1647
0.80	SAC305	SAC305	235	2385	2385	2590	3782	1278	1278	1355	1364
0.80	SAC305	SAC305	235	2766	2776	2846	3556	985	985	1257	1587
0.80	SAC305	SAC305	235	3128	3128	3532	4025	1809	1807	1818	1818
0.80	SAC305	SAC305	235	2804	2804	3540	3540	1356	1356	1366	1504
0.80	SAC305	SAC305	235	3593	3593	4115	4316	1291	1290	1348	1403
0.80	SAC305	SAC305	235	3086	3086	3486	3722	1398	1398	1588	1778
0.80	SAC305	SAC305	235	2869	2869	3347	3428	1499	1499	1699	1699
0.80	SAC305	SAC305	235	2927	2927	3748	3748	1440	1439	1765	1765
0.80	SAC305	SAC305	235	2962	2962	2998	3285	1370	1370	1404	1404
0.80	SAC305	SAC305	235	2783	2783	3474	3739	785	784	885	1528
0.80	SAC305	SAC305	235	3852	3852	3938	4268	1716	1716	1779	1805
0.80	SAC305	SAC105	235	2101	2101	2158	2158	708	708	720	720
0.80	SAC305	SAC105	235	1921	1921	2058	2058	736	736	753	753
0.80	SAC305	SAC105	235	2206	2207	2660	2684	831	831	841	841
0.80	SAC305	SAC105	235	2178	2178	2417	2417	589	589	591	591
0.80	SAC305	SAC105	235	1324	1324	1853	1853	1416	1416	1428	1428
0.80	SAC305	SAC105	235	2603	2603	3024	3034	775	775	782	782
0.80	SAC305	SAC105	235	1997	1997	2060	2060	585	585	637	757
0.80	SAC305	SAC105	235	1686	1686	1777	1777	619	618	709	709
0.80	SAC305	SAC105	235	1742	1742	2123	2123	792	792	794	794
0.80	SAC305	SAC105	235	1974	1974	2271	2271	668	668	677	677
0.80	SAC305	SAC105	235	1439	1439	1564	1564	679	679	682	682
0.80	SAC305	SAC105	235	2050	2050	2094	2094	673	673	724	724
0.80	SAC305	SAC105	235	1528	1528	1886	1886	689	689	740	748
0.80	SAC305	SAC105	235	2285	2285	2619	2619	673	673	697	697
0.80	SAC305	SAC105	235	1933	1933	2312	2312	661	661	688	688
0.80	SAC305	SAC105	235	1928	1928	2457	2457	812	812	966	966
0.80	SAC305	SAC105	235	2247	2247	2340	2340	816	816	937	937
0.80	SAC305	SAC105	235	1866	1866	1969	2005	671	671	682	682
0.80	SAC305	SAC105	235	1987	1987	2010	2010	631	631	635	635
0.80	SAC305	SAC105	235	1897	1897	2292	2292	702	702	729	729

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.80	SAC305	SACX	235	1726	1726	1776	1776	735	734	779	779
0.80	SAC305	SACX	235	1785	1785	1914	1914	863	863	881	887
0.80	SAC305	SACX	235	1852	1852	2035	2035	833	833	838	838
0.80	SAC305	SACX	235	2482	2482	2577	2577	675	675	679	679
0.80	SAC305	SACX	235	1882	1882	1923	1923	783	783	784	784
0.80	SAC305	SACX	235	2202	2202	2679	2679	788	787	809	809
0.80	SAC305	SACX	235	2263	2263	2506	2506	603	603	824	824
0.80	SAC305	SACX	235	2024	2024	2311	2311	697	697	706	706
0.80	SAC305	SACX	235	1887	1887	2264	2264	934	934	975	1049
0.80	SAC305	SACX	235	1781	1781	2168	2205	720	720	729	729
0.80	SAC305	SACX	235	1968	1968	2024	2024	629	629	701	701
0.80	SAC305	SACX	235	1799	1799	2080	2080	849	858	944	945
0.80	SAC305	SACX	235	1680	1682	2124	2124	586	586	590	591
0.80	SAC305	SACX	235	2499	2499	2695	2695	710	710	732	732
0.80	SAC305	SACX	235	1978	1979	2312	2312	833	833	948	948
0.80	SAC305	SACX	235	2020	2020	2143	2143	884	884	898	901
0.80	SAC305	SACX	235	2215	2216	2541	2541	950	950	1023	1077
0.80	SAC305	SACX	235	1812	1812	2072	2072	602	602	608	613
0.80	SAC305	SACX	235	1695	1696	2180	2180	644	644	653	653
0.80	SAC305	SACX	235	2018	2018	2297	2297	866	865	885	885
0.80	SAC305	SAC205	235	2464	2464	4196	2979	663	662	718	718
0.80	SAC305	SAC205	235	2243	2245	2709	2717	679	679	716	716
0.80	SAC305	SAC205	235	2677	2677	3017	3181	858	858	897	930
0.80	SAC305	SAC205	235	1850	1850	3327	3327	769	769	770	803
0.80	SAC305	SAC205	235	2520	2520	2684	4423	874	874	880	904
0.80	SAC305	SAC205	235	1992	1992	2002	2098	689	689	702	702
0.80	SAC305	SAC205	235	2486	2486	2593	2593	752	752	817	817
0.80	SAC305	SAC205	235	2129	2130	2525	2582	913	913	948	966
0.80	SAC305	SAC205	235	2416	2416	2622	2622	1028	1028	1065	1066
0.80	SAC305	SAC205	235	2886	2886	2988	2988	674	764	829	840
0.80	SAC305	SAC205	235	2106	2106	2189	2565	883	883	885	892
0.80	SAC305	SAC205	235	2511	2511	3097	3166	956	956	971	1162
0.80	SAC305	SAC205	235	2873	2875	3175	3175	680	680	695	695
0.80	SAC305	SAC205	235	2971	2971	3429	3429	830	830	869	869
0.80	SAC305	SAC205	235	2214	2215	2451	2451	807	807	862	862
0.80	SAC305	SAC205	235	2760	2761	2984	2984	852	852	892	915

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.80	SAC305	SAC205	235	2591	2591	3230	3230	715	714	733	733
0.80	SAC305	SAC205	235	2551	2554	2651	2954	601	600	668	676
0.80	SAC305	SAC205	235	2185	2186	2958	2958	750	750	754	779
0.80	SAC305	SAC205	235	2599	2599	3394	3394	769	767	789	793
1.00	SAC305	SAC305	235	6030	6031	6371	6708	1967	1967	1972	2008
1.00	SAC305	SAC305	235	6288	6288	6323	7080	2182	2182	2191	2348
1.00	SAC305	SAC305	235	6323	6325	6386	6885	2084	2085	2086	2136
1.00	SAC305	SAC305	235	6684	6684	6738	7493	2034	2034	2035	2117
1.00	SAC305	SAC305	235	5447	5452	5902	7340	1497	1497	1516	1781
1.00	SAC305	SAC305	235	5792	5795	6366	7284	2093	2093	2097	2232
1.00	SAC305	SAC305	235	5494	5494	5579	5757	2021	2021	2077	2235
1.00	SAC305	SAC305	235	4557	4557	4661	5173	2024	2024	2048	2263
1.00	SAC305	SAC305	235	3999	3999	4807	4807	1955	1955	2031	2031
1.00	SAC305	SAC305	235	4282	4282	4406	4598	2123	2123	2123	2174
1.00	SAC305	SAC305	235	5470	5471	5621	6012	2036	2036	2067	2423
1.00	SAC305	SAC305	235	3715	3715	4650	5118	2333	2333	2406	2406
1.00	SAC305	SAC305	235	5872	5873	5987	6311	1876	1876	1915	2133
1.00	SAC305	SAC305	235	4831	4831	5515	5515	1772	1773	1785	1785
1.00	SAC305	SAC305	235	5339	5339	5727	6912	2394	2394	2517	2564
1.00	SAC305	SAC305	235	4425	4425	5157	6122	1861	1862	2073	2309
1.00	SAC305	SAC305	235	4651	4652	6065	6702	1505	1505	1928	2290
1.00	SAC305	SAC305	235	6220	6222	6290	7201	2152	2152	2166	2256
1.00	SAC305	SAC305	235	5688	5689	6368	6864	1839	1839	1916	2420
1.00	SAC305	SAC305	235	5192	5192	5843	5849	1859	1859	1979	2066
1.00	SAC305	SAC105	235	2967	2967	2990	5055	1867	1867	1870	2113
1.00	SAC305	SAC105	235	4846	4846	4933	5091	1437	1437	1439	1689
1.00	SAC305	SAC105	235	4021	4021	4137	4658	1798	1798	1823	1873
1.00	SAC305	SAC105	235	3790	3790	3821	5503	1052	1052	1057	1726
1.00	SAC305	SAC105	235	3827	3827	3891	4370	1307	1307	1477	1547
1.00	SAC305	SAC105	235	4437	4437	4943	5207	1480	1480	1504	1516
1.00	SAC305	SAC105	235	4242	4242	4283	4847	1872	1872	1889	2036
1.00	SAC305	SAC105	235	3581	3581	3727	3727	1587	1588	1679	1726
1.00	SAC305	SAC105	235	2764	2764	3416	3661	1535	1535	1563	1563
1.00	SAC305	SAC105	235	3867	3867	3880	4082	1822	1823	1837	2101
1.00	SAC305	SAC105	235	3259	3260	3761	3761	1599	1599	1611	1735
1.00	SAC305	SAC105	235	3590	3590	3830	3830	1238	1237	1301	1483

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.00	SAC305	SAC105	235	3396	3396	3769	4187	1649	1649	1690	1787
1.00	SAC305	SAC105	235	3977	3977	4268	4578	1471	1471	1481	1610
1.00	SAC305	SAC105	235	3421	3421	3586	4669	1721	1721	1726	1913
1.00	SAC305	SAC105	235	3795	3795	3982	5050	1721	1727	1763	2065
1.00	SAC305	SAC105	235	3829	3829	4082	4272	1751	1751	1848	1891
1.00	SAC305	SAC105	235	4418	4419	4419	4673	1673	1673	1678	1820
1.00	SAC305	SAC105	235	3622	3622	3719	4957	1741	1741	1742	1826
1.00	SAC305	SAC105	235	4412	4412	4721	4837	1399	1399	1428	1585
1.00	SAC305	SACX	235	3625	3625	3629	3783	1420	1420	1441	1521
1.00	SAC305	SACX	235	2484	2484	2551	2551	1111	1111	1281	1335
1.00	SAC305	SACX	235	3071	3071	3395	3395	1177	1177	1231	1343
1.00	SAC305	SACX	235	3957	3957	4027	4233	697	697	699	754
1.00	SAC305	SACX	235	3439	3440	4653	4653	1048	1048	1065	1097
1.00	SAC305	SACX	235	3571	3571	4071	4071	888	888	1036	1054
1.00	SAC305	SACX	235	3106	3106	3255	3562	1031	1031	1046	1413
1.00	SAC305	SACX	235	3023	3023	3157	3636	1117	1117	1144	1342
1.00	SAC305	SACX	235	2595	2595	2855	2855	995	995	1078	1273
1.00	SAC305	SACX	235	2783	2786	2839	3278	1248	1248	1254	1279
1.00	SAC305	SACX	235	2718	2719	2808	2808	1382	1383	1388	1437
1.00	SAC305	SACX	235	2680	2680	2736	2736	926	926	960	960
1.00	SAC305	SACX	235	3124	3125	3213	3551	1283	1287	1306	1410
1.00	SAC305	SACX	235	2965	2965	3545	3545	1179	1179	1185	1191
1.00	SAC305	SACX	235	2217	2217	2454	3317	1263	1263	1285	1429
1.00	SAC305	SACX	235	3326	3326	3571	3571	1178	1177	1306	1375
1.00	SAC305	SACX	235	2802	2802	2893	2893	1278	1278	1442	1442
1.00	SAC305	SACX	235	2814	2814	2900	3927	1248	1248	1263	1319
1.00	SAC305	SACX	235	3087	3087	3809	3861	1160	1160	1189	1198
1.00	SAC305	SACX	235	2951	2952	3373	3373	1158	1158	1202	1262
1.00	SAC305	SAC205	235	4159	4164	4622	5271	1735	1735	1761	1998
1.00	SAC305	SAC205	235	4455	4456	4586	5229	1700	1700	1706	1792
1.00	SAC305	SAC205	235	3656	3659	4406	4406	1243	1243	1273	1424
1.00	SAC305	SAC205	235	5018	5018	5608	5849	1822	1822	1823	2130
1.00	SAC305	SAC205	235	128	129	139	223	1630	1630	1674	1839
1.00	SAC305	SAC205	235	4297	4297	4321	6880	1392	1392	1394	1508
1.00	SAC305	SAC205	235	3979	3979	4066	4422	1060	1060	1149	2098
1.00	SAC305	SAC205	235	3335	3336	3630	4115	1716	1717	1749	2202

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.00	SAC305	SAC205	235	3436	3436	3956	4094	1414	1416	1474	1834
1.00	SAC305	SAC205	235	4257	4257	4361	5102	1682	1682	1686	1860
1.00	SAC305	SAC205	235	4015	4015	4085	5119	1701	1702	1773	2075
1.00	SAC305	SAC205	235	4182	4182	4457	4458	1787	1787	1854	1863
1.00	SAC305	SAC205	235	3911	3912	4382	5270	1199	1199	1207	1560
1.00	SAC305	SAC205	235	4041	4042	4383	4791	1448	1448	1460	1583
1.00	SAC305	SAC205	235	4898	4898	5087	5229	2075	2075	2076	2229
1.00	SAC305	SAC205	235	5185	5185	5237	5467	1584	1585	1606	1609
1.00	SAC305	SAC205	235	3717	3717	3892	4515	1391	1391	1405	1635
1.00	SAC305	SAC205	235	4507	4507	4549	5087	1923	1923	1923	2078
1.00	SAC305	SAC205	235	5139	5145	5630	5630	1748	1748	1750	1897
1.00	SAC305	SAC205	235	3761	3761	4821	4905	1485	1485	1502	1727
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	2497	2496	2497	2497
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	2699	2698	2699	3497
1.27	SAC305	SAC305	235	5178	5178	5208	n.f.	1447	1447	1454	2807
1.27	SAC305	SAC305	235	9390	9390	9407	n.f.	3333	3333	3357	3365
1.27	SAC305	SAC305	235	7059	7059	7059	n.f.	2333	2333	2340	2764
1.27	SAC305	SAC305	235	7215	7215	7344	n.f.	3444	3444	3481	3513
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	3401	3402	3402	3529
1.27	SAC305	SAC305	235	10019	10022	10023	n.f.	2906	2906	2906	3508
1.27	SAC305	SAC305	235	9444	9444	9484	n.f.	n.f.	n.f.	n.f.	n.f.
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	1997	1999	2010	3281
1.27	SAC305	SAC305	235	5558	5558	5601	n.f.	1919	1919	1946	3076
1.27	SAC305	SAC305	235	5768	5768	5907	n.f.	3327	3327	3340	3521
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	2741	2741	2770	3550
1.27	SAC305	SAC305	235	10012	10016	10076	n.f.	2342	2342	2349	3531
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	3378	3378	3489	3489
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	2012	2012	2109	2882
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	2630	2630	2718	3357
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	3117	3117	3117	3482
1.27	SAC305	SAC305	235	6008	6014	6074	n.f.	1939	1939	1942	3457
1.27	SAC305	SAC305	235	n.f.	n.f.	n.f.	n.f.	2750	2750	2750	3090
1.27	SAC305	SAC105	235	6525	6527	6534	n.f.	3464	3464	3467	3548
1.27	SAC305	SAC105	235	4347	4347	4365	4785	654	654	664	1567
1.27	SAC305	SAC105	235	4239	4239	4277	n.f.	2050	2050	2058	3007
1.27	SAC305	SAC105	235	7434	7434	7436	n.f.	2405	2405	2413	3555

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.27	SAC305	SAC105	235	5386	5386	5388	9174	n.f.	n.f.	n.f.	n.f.
1.27	SAC305	SAC105	235	8789	8789	8789	n.f.	n.f.	n.f.	n.f.	n.f.
1.27	SAC305	SAC105	235	5326	5326	5326	n.f.	2868	2868	2888	3551
1.27	SAC305	SAC105	235	4990	4990	4991	n.f.	1873	1873	1876	1884
1.27	SAC305	SAC105	235	5071	5071	5073	n.f.	2528	2529	2532	3488
1.27	SAC305	SAC105	235	n.f.	n.f.	n.f.	n.f.	2590	2591	2591	3138
1.27	SAC305	SAC105	235	4953	4953	4964	n.f.	2170	2170	2173	3247
1.27	SAC305	SAC105	235	5013	5013	5095	n.f.	1379	1379	1384	3295
1.27	SAC305	SAC105	235	4243	4242	4253	n.f.	1907	1907	1908	3235
1.27	SAC305	SAC105	235	3465	3465	3502	n.f.	945	945	948	967
1.27	SAC305	SAC105	235	n.f.	n.f.	n.f.	n.f.	1976	1976	1984	3327
1.27	SAC305	SAC105	235	3939	3939	3968	4999	1961	1961	1964	3428
1.27	SAC305	SAC105	235	n.f.	n.f.	n.f.	n.f.	1435	1435	1436	1616
1.27	SAC305	SAC105	235	n.f.	n.f.	n.f.	n.f.	2032	2033	2033	3542
1.27	SAC305	SAC105	235	5459	5459	5579	n.f.	1291	1290	1300	1357
1.27	SAC305	SAC105	235	n.f.	n.f.	n.f.	n.f.	2207	2207	2207	3387
1.27	SAC305	SACX	235	6113	6113	6113	n.f.	1208	1208	1209	2794
1.27	SAC305	SACX	235	2891	2890	2910	3021	1547	1547	1548	1591
1.27	SAC305	SACX	235	3634	3634	3639	3891	1219	1219	1220	1616
1.27	SAC305	SACX	235	n.f.	n.f.	n.f.	n.f.	1620	1620	1621	1754
1.27	SAC305	SACX	235	5110	5110	5114	n.f.	1375	1375	1377	1694
1.27	SAC305	SACX	235	6366	6397	6404	n.f.	1957	1957	1961	2251
1.27	SAC305	SACX	235	3889	3889	3891	n.f.	2955	2954	2955	3003
1.27	SAC305	SACX	235	4443	4443	4447	7414	1608	1608	1608	2360
1.27	SAC305	SACX	235	4050	4050	4065	5005	1047	1047	1058	1926
1.27	SAC305	SACX	235	6159	6159	6159	8437	2100	2100	2104	2477
1.27	SAC305	SACX	235	3719	3719	3730	6092	1932	1933	1933	2674
1.27	SAC305	SACX	235	4720	4720	4794	4873	1115	1116	1116	1322
1.27	SAC305	SACX	235	4533	4533	4533	7622	823	823	823	1545
1.27	SAC305	SACX	235	5351	5351	5367	5675	1242	1242	1243	2259
1.27	SAC305	SACX	235	7553	7553	7605	10046	1674	1674	1690	2872
1.27	SAC305	SACX	235	3754	3754	3758	4203	1341	1341	1366	1482
1.27	SAC305	SACX	235	3809	3809	3092	3410	1973	1973	1980	2101
1.27	SAC305	SACX	235	5516	5516	5516	6340	1759	1760	1760	3310
1.27	SAC305	SACX	235	2733	2733	2745	3505	1551	1551	1552	1676
1.27	SAC305	SACX	235	3656	3656	3683	6361	1021	1020	1023	1149

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.27	SAC305	SAC205	235	6005	6005	6005	n.f.	3348	3348	3349	3379
1.27	SAC305	SAC205	235	4616	4616	4622	n.f.	3059	3059	3059	3059
1.27	SAC305	SAC205	235	4968	4970	4980	n.f.	2975	2976	3002	3112
1.27	SAC305	SAC205	235	6123	6123	6125	n.f.	2877	2877	2877	3541
1.27	SAC305	SAC205	235	3619	3619	3638	n.f.	1738	1738	1743	3118
1.27	SAC305	SAC205	235	3789	3789	3799	9170	2154	2154	2154	2796
1.27	SAC305	SAC205	235	n.f.	n.f.	n.f.	n.f.	3498	3499	3504	3542
1.27	SAC305	SAC205	235	3945	3945	3950	n.f.	1352	1352	1355	2949
1.27	SAC305	SAC205	235	9624	9627	9649	n.f.	1233	1233	1233	1264
1.27	SAC305	SAC205	235	5389	5390	5428	n.f.	3183	3184	3184	3518
1.27	SAC305	SAC205	235	5004	5004	5007	n.f.	1754	1754	1755	3534
1.27	SAC305	SAC205	235	6697	6697	6711	n.f.	3061	3061	3069	3522
1.27	SAC305	SAC205	235	8041	8042	8101	n.f.	2656	2654	2671	2803
1.27	SAC305	SAC205	235	4482	4482	4563	6736	1481	1481	1483	3546
1.27	SAC305	SAC205	235	6574	6574	6584	7582	3364	3364	3364	3550
1.27	SAC305	SAC205	235	5100	5100	5179	6279	2716	2717	2722	3512
1.27	SAC305	SAC205	235	3145	3145	3148	3346	3130	3130	3132	3525
1.27	SAC305	SAC205	235	4835	4835	4847	n.f.	3072	3072	3073	3543
1.27	SAC305	SAC205	235	6111	6111	6119	n.f.	2282	2282	2285	2765
1.27	SAC305	SAC205	235	4726	4726	4734	5719	1757	1757	1758	2599
0.50	SnPb	SnPb	215	1581	1582	1743	1743	915	915	928	928
0.50	SnPb	SnPb	215	1688	1688	1996	1996	989	989	1062	1062
0.50	SnPb	SnPb	215	1410	1411	1453	1453	724	724	735	735
0.50	SnPb	SnPb	215	1774	1774	1867	1867	956	955	972	972
0.50	SnPb	SnPb	215	1843	1844	1970	1970	1094	1094	1163	1163
0.50	SnPb	SnPb	215	n.f.	n.f.	n.f.	n.f.	689	689	739	739
0.50	SnPb	SnPb	215	1847	1847	1983	1983	957	957	1006	1006
0.50	SnPb	SnPb	215	1900	1900	2075	2075	885	886	895	895
0.50	SnPb	SnPb	215	1542	1542	1733	1733	840	840	868	868
0.50	SnPb	SnPb	215	2071	2071	2224	2224	946	946	966	966
0.50	SnPb	SnPb	215	1721	1722	1769	1769	989	989	1004	1004
0.50	SnPb	SnPb	215	1547	1548	1647	1647	956	955	998	998
0.50	SnPb	SnPb	215	1770	1770	1813	1813	1257	1257	1325	1325
0.50	SnPb	SnPb	215	1355	1355	1471	1471	1059	1059	1075	1075
0.50	SnPb	SnPb	215	1709	1709	1766	1766	972	972	1042	1042
0.50	SnPb	SnPb	215	2072	2072	2235	2235	1173	1173	1223	1223

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.50	SnPb	SnPb	215	1639	1639	1848	1848	901	901	985	985
0.50	SnPb	SnPb	215	2008	2008	2172	2172	950	950	1003	1003
0.50	SnPb	SnPb	215	1919	1919	2038	2038	1083	1084	1109	1109
0.50	SnPb	SnPb	215	1585	1585	1731	1731	717	717	740	740
0.50	SnPb	SAC305	215	2581	2581	3210	3210	861	867	1416	1416
0.50	SnPb	SAC305	215	3019	3025	3777	3777	1401	1401	1523	1523
0.50	SnPb	SAC305	215	2653	2658	3706	3706	509	509	928	928
0.50	SnPb	SAC305	215	2586	2590	3282	3282	1166	1167	1710	1710
0.50	SnPb	SAC305	215	2750	2751	3499	3499	623	629	1393	1393
0.50	SnPb	SAC305	215	2394	2406	3448	3448	933	933	1606	1606
0.50	SnPb	SAC305	215	2590	2596	3488	3488	1120	1121	1488	1488
0.50	SnPb	SAC305	215	3493	3493	3500	4291	628	641	938	938
0.50	SnPb	SAC305	215	2724	2725	2727	4423	1066	1066	1255	1255
0.50	SnPb	SAC305	215	2714	2714	3477	3477	997	998	1511	1511
0.50	SnPb	SAC305	215	2861	2861	3881	3881	1532	1552	1939	1939
0.50	SnPb	SAC305	215	2214	2214	3454	3454	1266	1266	1728	1728
0.50	SnPb	SAC305	215	2125	2127	3082	3082	985	985	1035	1035
0.50	SnPb	SAC305	215	2103	2103	3092	3092	944	950	1304	1304
0.50	SnPb	SAC305	215	2647	2723	3012	3012	1156	1156	1460	1460
0.50	SnPb	SAC305	215	6524	6525	6888	7528	1127	1127	1194	1194
0.50	SnPb	SAC305	215	3263	3264	3777	3777	1182	1182	1377	1377
0.50	SnPb	SAC305	215	2811	2814	3353	3353	1674	1675	1880	2020
0.50	SnPb	SAC305	215	2920	2922	3326	3467	1668	1668	1784	1784
0.50	SnPb	SAC305	215	2184	2185	3358	3358	1241	1242	1488	1488
0.50	SnPb	SAC105	215	2738	2745	2959	2959	1003	1005	1786	1786
0.50	SnPb	SAC105	215	3069	3069	3424	3424	1251	1251	1634	1634
0.50	SnPb	SAC105	215	2762	2763	3157	3157	1512	1512	1724	1724
0.50	SnPb	SAC105	215	2247	2247	2804	2804	1183	1184	1472	1472
0.50	SnPb	SAC105	215	2650	2654	3156	3156	1287	1290	1430	1430
0.50	SnPb	SAC105	215	2907	2907	3499	3499	991	992	1499	1499
0.50	SnPb	SAC105	215	3060	3061	3619	3619	852	852	1115	1115
0.50	SnPb	SAC105	215	3028	3050	3648	3648	671	692	1553	1553
0.50	SnPb	SAC105	215	2513	2513	2983	2983	1302	1308	1677	1694
0.50	SnPb	SAC105	215	2552	2552	3167	3167	1437	1437	1528	1528
0.50	SnPb	SAC105	215	2351	2352	2714	2714	1243	1243	1590	1590
0.50	SnPb	SAC105	215	2736	2736	3370	3370	737	744	1255	1255

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.50	SnPb	SAC105	215	2771	2848	3017	3017	1294	1294	1429	1576
0.50	SnPb	SAC105	215	2725	2725	3394	3394	994	994	1161	1161
0.50	SnPb	SAC105	215	3432	3432	4139	4139	1096	1096	1617	1617
0.50	SnPb	SAC105	215	2790	2813	3500	3500	1245	1245	1377	1377
0.50	SnPb	SAC105	215	2478	2479	2927	2927	714	720	1157	1157
0.50	SnPb	SAC105	215	2805	2805	3454	3454	1885	1886	2102	2102
0.50	SnPb	SAC105	215	2941	2943	3467	3467	1239	1239	1638	1638
0.50	SnPb	SAC105	215	2069	2070	3081	3081	1208	1208	1318	1318
0.50	SnPb	SACX	215	3176	3176	4175	4175	1443	1444	1722	1997
0.50	SnPb	SACX	215	3316	3324	3827	4266	1062	1063	1805	1805
0.50	SnPb	SACX	215	2570	2571	3504	3504	241	246	635	635
0.50	SnPb	SACX	215	3852	3854	4652	4652	1166	1170	1855	1855
0.50	SnPb	SACX	215	3623	3627	4618	4618	979	981	1925	2034
0.50	SnPb	SACX	215	2811	2839	3666	3666	223	231	643	643
0.50	SnPb	SACX	215	2802	2802	3363	3363	1176	1190	1894	1894
0.50	SnPb	SACX	215	2735	2738	3777	3777	1441	1457	1913	1957
0.50	SnPb	SACX	215	2249	2249	3528	3528	668	668	2064	2064
0.50	SnPb	SACX	215	2887	2893	3514	3514	1846	1848	2212	2212
0.50	SnPb	SACX	215	3289	3289	3381	3706	1614	1614	1846	1846
0.50	SnPb	SACX	215	2131	2193	3219	3219	753	753	1657	1657
0.50	SnPb	SACX	215	2460	2465	3300	3300	997	997	1364	1364
0.50	SnPb	SACX	215	2476	2476	3289	3289	1083	1085	1377	1377
0.50	SnPb	SACX	215	3406	3413	3747	3747	1677	1682	1984	1984
0.50	SnPb	SACX	215	2825	2826	4100	4100	593	597	1626	1827
0.50	SnPb	SACX	215	2014	2125	4473	4473	1477	1489	1861	1923
0.50	SnPb	SACX	215	3488	3492	4083	4083	1892	1892	2179	2179
0.50	SnPb	SACX	215	3400	3410	4596	4596	1989	1992	2189	2402
0.50	SnPb	SACX	215	1985	1994	3660	3660	535	536	1135	1135
0.50	SnPb	LF35	215	3456	3459	3589	3738	1177	1180	1470	1618
0.50	SnPb	LF35	215	2568	2573	4433	4433	645	646	1683	1683
0.50	SnPb	LF35	215	2812	2812	3737	3737	1358	1362	1839	1839
0.50	SnPb	LF35	215	2517	2518	3934	4382	1252	1252	1608	1608
0.50	SnPb	LF35	215	3380	3393	4382	4382	1711	1719	1810	1810
0.50	SnPb	LF35	215	3009	3133	4462	4462	1451	1453	2069	2069
0.50	SnPb	LF35	215	2542	2543	3510	3510	735	739	1418	1478
0.50	SnPb	LF35	215	3205	3206	3928	4482	1124	1124	1166	1166

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.50	SnPb	LF35	215	3608	3636	4770	4882	1019	1024	1326	1326
0.50	SnPb	LF35	215	3599	3601	3844	4049	1554	1556	1738	1906
0.50	SnPb	LF35	215	3693	3693	3885	4567	1430	1430	1624	1624
0.50	SnPb	LF35	215	2621	2632	3972	3972	998	998	1548	1548
0.50	SnPb	LF35	215	1579	1579	2772	2772	1418	1418	1799	1875
0.50	SnPb	LF35	215	2802	2804	3188	3188	1029	1030	1280	1280
0.50	SnPb	LF35	215	2278	2280	3223	3223	1062	1063	1587	1819
0.50	SnPb	SAC105	220	8799	8800	8800	n.f.	1956	1956	1959	2027
0.50	SnPb	SAC105	220	8427	8427	8430	n.f.	2079	2079	2154	2363
0.80	SnPb	SnPb	215	1025	1025	1100	1100	618	618	629	629
0.80	SnPb	SnPb	215	1049	1050	1113	1113	637	638	647	647
0.80	SnPb	SnPb	215	1128	1130	1211	1211	699	699	708	708
0.80	SnPb	SnPb	215	1005	1005	1159	1159	609	609	627	627
0.80	SnPb	SnPb	215	1172	1172	1194	1194	576	576	602	602
0.80	SnPb	SnPb	215	1242	1242	1305	1305	542	542	575	575
0.80	SnPb	SnPb	215	1085	1086	1114	1114	611	611	665	665
0.80	SnPb	SnPb	215	1000	1000	1080	1080	593	594	595	595
0.80	SnPb	SnPb	215	1055	1055	1251	1251	692	697	780	780
0.80	SnPb	SnPb	215	888	888	966	966	646	646	665	665
0.80	SnPb	SnPb	215	941	942	1065	1065	534	534	566	566
0.80	SnPb	SnPb	215	1044	1058	1118	1118	711	711	780	780
0.80	SnPb	SnPb	215	958	966	1015	1015	778	778	788	788
0.80	SnPb	SnPb	215	1102	1102	1125	1125	688	687	761	761
0.80	SnPb	SnPb	215	901	901	919	919	609	609	621	621
0.80	SnPb	SnPb	215	1036	1036	1110	1110	608	608	618	618
0.80	SnPb	SnPb	215	1061	1069	1159	1159	714	714	724	724
0.80	SnPb	SnPb	215	950	950	1016	1016	463	463	476	476
0.80	SnPb	SnPb	215	851	860	927	927	639	639	645	645
0.80	SnPb	SnPb	215	926	927	1026	1026	610	610	624	624
0.80	SnPb	SAC305	215	2660	2664	3131	3131	530	530	856	856
0.80	SnPb	SAC305	215	1841	1842	2665	2665	959	959	1086	1086
0.80	SnPb	SAC305	215	2992	2993	3119	3119	1370	1370	1522	1649
0.80	SnPb	SAC305	215	2756	2759	3432	3497	746	746	905	905
0.80	SnPb	SAC305	215	2245	2245	3537	3632	887	887	1047	1047
0.80	SnPb	SAC305	215	3088	3088	3716	3716	1001	1009	1371	1371
0.80	SnPb	SAC305	215	2915	2922	3402	3402	571	571	643	643

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.80	SnPb	SAC305	215	1907	1912	1930	4291	1114	1115	1173	1173
0.80	SnPb	SAC305	215	3303	3303	3322	4423	1214	1221	1367	1367
0.80	SnPb	SAC305	215	2073	2076	3379	3379	1192	1192	1230	1230
0.80	SnPb	SAC305	215	2512	2515	3106	3106	989	996	1308	1308
0.80	SnPb	SAC305	215	2937	2938	3369	3369	1333	1333	1523	1523
0.80	SnPb	SAC305	215	1532	1534	2415	2415	955	955	1118	1272
0.80	SnPb	SAC305	215	2082	2082	3294	3294	1191	1194	1284	1284
0.80	SnPb	SAC305	215	3314	3314	3348	3348	651	651	949	949
0.80	SnPb	SAC305	215	2808	2808	3166	3166	1483	1483	1532	1532
0.80	SnPb	SAC305	215	3055	3055	3530	3530	952	952	1211	1211
0.80	SnPb	SAC305	215	2365	2371	2550	2550	1331	1331	1448	1448
0.80	SnPb	SAC305	215	2630	2630	2822	2822	878	878	1246	1246
0.80	SnPb	SAC305	215	3112	3113	3463	3463	784	787	1522	1522
0.80	SnPb	SAC105	215	1132	1132	1875	1875	708	708	718	718
0.80	SnPb	SAC105	215	1126	1127	1740	1740	688	688	708	708
0.80	SnPb	SAC105	215	1784	1784	2076	2076	821	821	831	831
0.80	SnPb	SAC105	215	1320	1323	1786	1786	330	333	403	403
0.80	SnPb	SAC105	215	1139	1148	1729	1729	481	481	513	513
0.80	SnPb	SAC105	215	1920	1920	1996	1996	641	641	670	670
0.80	SnPb	SAC105	215	1685	1690	2158	2158	657	657	941	941
0.80	SnPb	SAC105	215	1824	1824	2138	2138	370	370	546	754
0.80	SnPb	SAC105	215	2232	2232	2315	2315	902	902	967	967
0.80	SnPb	SAC105	215	1475	1479	1733	1733	567	567	676	676
0.80	SnPb	SAC105	215	1803	1804	1854	1854	671	673	725	725
0.80	SnPb	SAC105	215	2010	2010	2180	2180	852	852	872	872
0.80	SnPb	SAC105	215	1332	1332	1806	1806	222	222	636	636
0.80	SnPb	SAC105	215	2267	2267	2421	2421	800	802	838	838
0.80	SnPb	SAC105	215	1381	1382	1705	1705	524	524	622	622
0.80	SnPb	SAC105	215	1508	1511	2052	2052	472	476	754	754
0.80	SnPb	SAC105	215	1922	1922	2220	2220	998	998	1004	1004
0.80	SnPb	SAC105	215	851	851	1490	1490	362	362	563	563
0.80	SnPb	SAC105	215	1311	1311	1606	1606	625	625	705	705
0.80	SnPb	SAC105	215	1929	1929	2079	2079	824	824	868	868
0.80	SnPb	SACX	215	957	957	1502	1502	406	407	742	742
0.80	SnPb	SACX	215	1398	1400	2101	2101	543	543	793	793
0.80	SnPb	SACX	215	2233	2233	2693	2693	532	535	877	877

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
0.80	SnPb	SACX	215	1366	1366	2466	2466	546	546	839	839
0.80	SnPb	SACX	215	915	915	1544	1544	535	535	817	817
0.80	SnPb	SACX	215	2848	2848	2933	2933	832	832	929	933
0.80	SnPb	SACX	215	1381	1383	2447	2447	519	520	813	813
0.80	SnPb	SACX	215	808	809	1500	1500	810	810	909	909
0.80	SnPb	SACX	215	2255	2255	2819	2819	1182	1182	1350	1350
0.80	SnPb	SACX	215	882	882	1233	1233	256	255	428	428
0.80	SnPb	SACX	215	871	872	1593	1593	762	766	866	866
0.80	SnPb	SACX	215	1862	1862	2408	2408	886	887	920	920
0.80	SnPb	SACX	215	1311	1314	2120	2120	762	762	1081	1081
0.80	SnPb	SACX	215	1970	1970	2393	2393	1248	1248	1396	1396
0.80	SnPb	SACX	215	777	782	1876	1876	372	372	474	474
0.80	SnPb	SACX	215	789	831	1765	1765	436	436	732	732
0.80	SnPb	SACX	215	1940	1943	2680	2680	998	999	1232	1232
0.80	SnPb	SACX	215	873	873	1577	1577	493	493	898	898
0.80	SnPb	SACX	215	953	953	1813	1813	372	374	791	791
0.80	SnPb	SACX	215	1920	1924	2897	2897	692	692	1113	1113
0.80	SnPb	LF35	215	3334	3337	4281	4443	1062	1066	1645	1781
0.80	SnPb	SAC105	220	4203	4203	4442	4442	2052	2052	2133	2147
0.80	SnPb	SAC105	220	3495	3495	4302	4306	1585	1585	1638	1638
1.00	SnPb	SnPb	215	2806	2809	2960	3036	1232	1233	1248	1248
1.00	SnPb	SnPb	215	2088	2090	2747	2747	1313	1313	1336	1336
1.00	SnPb	SnPb	215	1388	1389	1390	1390	1388	1389	1390	1390
1.00	SnPb	SnPb	215	1690	1690	1866	1866	1258	1258	1270	1281
1.00	SnPb	SnPb	215	2705	2706	2810	2810	1339	1340	1372	1372
1.00	SnPb	SnPb	215	2480	2480	2765	2765	1440	1440	1644	1644
1.00	SnPb	SnPb	215	2210	2210	2300	2300	1366	1366	1379	1391
1.00	SnPb	SnPb	215	1801	1801	2020	2020	1299	1300	1322	1322
1.00	SnPb	SnPb	215	1882	1887	2098	2098	1328	1328	1356	1356
1.00	SnPb	SnPb	215	1812	1812	1962	1962	1261	1261	1264	1264
1.00	SnPb	SnPb	215	2225	2226	2269	2269	1469	1479	1561	1561
1.00	SnPb	SnPb	215	1753	1753	2015	2015	1090	1090	1198	1198
1.00	SnPb	SnPb	215	1840	1842	2077	2077	1605	1605	1663	1663
1.00	SnPb	SnPb	215	1980	1985	2172	2172	1538	1540	1622	1622
1.00	SnPb	SnPb	215	2102	2102	2126	2260	1420	1425	1459	1459
1.00	SnPb	SnPb	215	1975	1975	2439	2439	1396	1396	1485	1485

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.00	SnPb	SnPb	215	1639	1640	1818	1818	974	981	1442	1442
1.00	SnPb	SnPb	215	2125	2125	2161	2292	1307	1307	1315	1315
1.00	SnPb	SnPb	215	1936	1968	2292	2292	1353	1353	1379	1379
1.00	SnPb	SnPb	215	1871	1871	2152	2152	1050	1051	1123	1123
1.00	SnPb	SAC305	215	6747	6747	6748	7101	2266	2266	2349	2622
1.00	SnPb	SAC305	215	5672	5672	6409	6409	2502	2502	2808	2808
1.00	SnPb	SAC305	215	6033	6037	6624	6742	2857	2857	3074	3074
1.00	SnPb	SAC305	215	8232	8232	8233	8709	1368	1368	1410	1423
1.00	SnPb	SAC305	215	7770	7771	9085	9166	1932	1934	2021	2021
1.00	SnPb	SAC305	215	6635	6636	7307	7895	2122	2122	2174	2174
1.00	SnPb	SAC305	215	6673	6675	6780	8991	2435	2435	2442	2447
1.00	SnPb	SAC305	215	6793	6793	7853	8488	2181	2181	2270	2270
1.00	SnPb	SAC305	215	4495	4495	4518	6045	1606	1606	1628	1628
1.00	SnPb	SAC305	215	5754	5754	5798	5886	2480	2480	2521	2524
1.00	SnPb	SAC305	215	5539	5540	6533	6533	2583	2587	2657	2657
1.00	SnPb	SAC305	215	4872	4872	5581	5581	2202	2202	2447	2447
1.00	SnPb	SAC305	215	4545	4545	5108	5147	2252	2252	2316	2316
1.00	SnPb	SAC305	215	4543	4543	4888	4888	2186	2186	2213	2213
1.00	SnPb	SAC305	215	5920	5920	6323	7773	2598	2598	2623	2917
1.00	SnPb	SAC305	215	2706	2708	3368	3368	2466	2467	2814	2814
1.00	SnPb	SAC305	215	5649	5649	6492	6553	2348	2348	2455	2455
1.00	SnPb	SAC305	215	7853	7853	8124	8874	2779	2779	2849	2858
1.00	SnPb	SAC305	215	7165	7165	7836	8293	2293	2293	2497	2506
1.00	SnPb	SAC305	215	5927	5927	6446	6446	2196	2196	2359	2359
1.00	SnPb	SAC105	215	5375	5375	5456	5504	1710	1710	1714	2056
1.00	SnPb	SAC105	215	4849	4849	5147	5147	1825	1825	1897	1898
1.00	SnPb	SAC105	215	4088	4089	4648	4648	1511	1511	1518	1857
1.00	SnPb	SAC105	215	5573	5573	5626	6113	1896	1896	1901	2043
1.00	SnPb	SAC105	215	3394	3396	3784	4041	1638	1644	1711	1854
1.00	SnPb	SAC105	215	3885	3885	4407	4423	1506	1506	1509	1521
1.00	SnPb	SAC105	215	5839	5839	5993	6415	1809	1811	1854	1964
1.00	SnPb	SAC105	215	5179	5180	5471	6087	1625	1625	1682	2218
1.00	SnPb	SAC105	215	4489	4489	4705	4705	1614	1614	1619	1620
1.00	SnPb	SAC105	215	3883	3883	3891	4059	2137	2138	2150	2185
1.00	SnPb	SAC105	215	4279	4283	4553	4913	2180	2180	2195	2195
1.00	SnPb	SAC105	215	4870	4870	4940	4940	1881	1881	1922	1971

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.00	SnPb	SAC105	215	4231	4231	4605	4605	1017	1017	1261	1409
1.00	SnPb	SAC105	215	3266	3266	3494	3494	1783	1783	1783	1783
1.00	SnPb	SAC105	215	5574	5574	5606	6122	1504	1504	1514	1789
1.00	SnPb	SAC105	215	5243	5243	5692	5692	1608	1608	1620	1620
1.00	SnPb	SAC105	215	4778	4778	4997	4997	1783	1783	1870	1996
1.00	SnPb	SAC105	215	4356	4356	4389	4893	1986	1986	1989	2041
1.00	SnPb	SAC105	215	3741	3744	4702	4719	1997	1997	2084	2143
1.00	SnPb	SAC105	215	3895	3895	4431	4431	1684	1688	1769	1810
1.00	SnPb	SACX	215	3310	3310	3353	3379	1877	1886	1947	1949
1.00	SnPb	SACX	215	2635	2635	2781	2787	2323	2323	2344	2344
1.00	SnPb	SACX	215	3847	3847	3855	3855	1878	1878	1918	1975
1.00	SnPb	SACX	215	3903	3903	3912	4785	1757	1757	1784	1968
1.00	SnPb	SACX	215	4494	4495	4800	4831	2067	2067	2096	2129
1.00	SnPb	SACX	215	4208	4209	4938	5067	1858	1858	1871	1904
1.00	SnPb	SACX	215	3880	3881	3883	3928	1719	1719	1720	1911
1.00	SnPb	SACX	215	3470	3470	4083	4083	2040	2043	2187	2223
1.00	SnPb	SACX	215	3390	3391	3842	3842	1985	1985	2050	2094
1.00	SnPb	SACX	215	2387	2387	2586	3043	1735	1735	1744	1766
1.00	SnPb	SACX	215	2635	2640	2993	3028	1723	1724	1856	1891
1.00	SnPb	SACX	215	16	16	16	16	1373	1374	1394	1394
1.00	SnPb	SACX	215	4361	4361	4529	4577	1459	1460	1609	1609
1.00	SnPb	SACX	215	3604	3605	3675	3675	1642	1643	1707	1707
1.00	SnPb	SACX	215	3684	3694	3838	4030	1633	1633	1644	1685
1.00	SnPb	SACX	215	3850	3850	4090	4351	1379	1379	1474	1474
1.00	SnPb	SACX	215	3726	3726	3733	4006	1588	1588	1619	1619
1.00	SnPb	SACX	215	3796	3796	3834	4059	1430	1430	1440	1485
1.00	SnPb	SACX	215	3659	3659	4587	4587	2019	2020	2071	2071
1.00	SnPb	SACX	215	3219	3219	4167	4227	1349	1349	1431	1431
1.00	SnPb	LF35	215	3476	3480	4193	4193	1402	1402	1815	2067
1.00	SnPb	LF35	215	3430	3434	4768	4873	2026	2045	2167	2301
1.00	SnPb	SAC105	220	4827	4827	5023	5023	2425	2431	2634	2640
1.00	SnPb	SAC105	220	5429	5442	5704	5985	2209	2209	2221	2352
1.00	SnPb	SAC105	220	4290	4293	5180	5180	1891	1891	1891	1891
1.00	SnPb	SAC105	220	5652	5658	6452	6452	2059	2059	2167	2167
1.00	SnPb	SAC105	220	5347	5348	6229	6229	1686	1686	2274	2278
1.00	SnPb	SAC105	220	4648	4648	5334	5432	1732	1733	1745	1757

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.00	SnPb	SAC105	220	3013	3023	3191	3191	1979	1979	2006	2164
1.00	SnPb	SAC105	220	4942	4942	5875	5875	1987	1987	2075	2075
1.00	SnPb	SAC105	220	4119	4122	4857	4857	2513	2513	2514	2802
1.00	SnPb	SAC105	220	3298	3300	4237	4237	1904	1904	1958	1965
1.00	SnPb	SAC105	220	4085	4086	5223	5223	1869	1869	1881	1961
1.00	SnPb	SAC105	220	3982	3986	4620	4620	1529	1530	1538	1567
1.00	SnPb	SAC105	220	4482	4482	5448	5452	1844	1844	1873	1873
1.00	SnPb	SAC105	220	4054	4054	4704	4704	1793	1793	1829	1829
1.00	SnPb	SAC105	220	3827	3827	4287	4599	2094	2094	2115	2115
1.00	SnPb	SAC105	220	4395	4398	5499	5502	2197	2197	2233	2233
1.00	SnPb	SAC105	220	3328	3329	4473	4473	1655	1656	2027	2027
1.00	SnPb	SAC105	220	4471	4471	4264	5428	1909	1910	1991	2034
1.27	SnPb	SnPb	215	5396	5396	5558	5558	1722	1722	1825	1825
1.27	SnPb	SnPb	215	2136	2138	3463	2463	1379	1380	1388	1388
1.27	SnPb	SnPb	215	3173	3175	3175	3530	1168	1168	1190	1229
1.27	SnPb	SnPb	215	3127	3131	4312	4312	2790	2790	2792	2811
1.27	SnPb	SnPb	215	2801	2801	2824	2855	2021	2021	2021	2022
1.27	SnPb	SnPb	215	2757	2758	2952	3455	1944	1944	1949	1954
1.27	SnPb	SnPb	215	2217	2217	2725	2725	2500	2499	2500	2565
1.27	SnPb	SnPb	215	2504	2504	2616	2616	1809	1809	1820	1823
1.27	SnPb	SnPb	215	5612	5628	5802	6310	1807	1807	1812	1837
1.27	SnPb	SnPb	215	3953	3953	3962	3964	3374	3374	3394	3394
1.27	SnPb	SnPb	215	2337	2337	2371	2538	1405	1405	1407	1462
1.27	SnPb	SnPb	215	4544	4567	4571	5035	1398	1397	1403	1405
1.27	SnPb	SnPb	215	2949	2949	3007	3007	1672	1672	1696	1696
1.27	SnPb	SnPb	215	4612	4612	4722	4904	1488	1488	1511	1511
1.27	SnPb	SnPb	215	4872	4879	5138	5138	1734	1734	1782	1785
1.27	SnPb	SnPb	215	2600	2599	2607	2649	1752	1752	1754	1826
1.27	SnPb	SnPb	215	2879	2879	2882	2980	1315	1315	1317	1317
1.27	SnPb	SnPb	215	3135	3136	3521	3521	2036	2036	2177	2195
1.27	SnPb	SnPb	215	2403	2403	2974	2974	1568	1568	1577	1612
1.27	SnPb	SnPb	215	3163	3184	3272	3326	2345	2346	2353	2370
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	3388	3389	3409	3522
1.27	SnPb	SAC305	215	9879	9879	9881	n.f.	2906	2906	2914	2925
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
1.27	SnPb	SAC305	215	9748	9748	9767	n.f.	n.f.	n.f.	n.f.	n.f.

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.27	SnPb	SAC305	215	7589	7589	8577	9146	2184	2184	2186	3235
1.27	SnPb	SAC305	215	6367	6367	6486	6754	2682	2682	2699	2712
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	3170	3170	3271	3327
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	2170	2170	2312	2682
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	2263	2263	2273	2478
1.27	SnPb	SAC305	215	10054	10059	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
1.27	SnPb	SAC305	215	7233	7235	7278	n.f.	3115	3110	3152	3485
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	3430	3430	3445	3445
1.27	SnPb	SAC305	215	5782	5784	5801	6133	2613	2613	2618	2841
1.27	SnPb	SAC305	215	9040	9042	9062	9778	3275	3275	3312	3519
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
1.27	SnPb	SAC305	215	6737	6737	7267	9320	3010	3010	3010	3015
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	2699	2698	2810	2875
1.27	SnPb	SAC305	215	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.
1.27	SnPb	SAC305	215	7353	7358	8515	n.f.	2945	2950	3050	3469
1.27	SnPb	SAC305	215	7801	7802	7896	9170	n.f.	n.f.	n.f.	n.f.
1.27	SnPb	SAC105	215	7088	7088	7325	9409	3538	3542	3548	3548
1.27	SnPb	SAC105	215	6385	6385	6385	7392	2456	2456	2459	2807
1.27	SnPb	SAC105	215	9620	9620	9620	n.f.	1459	1459	1528	1940
1.27	SnPb	SAC105	215	5939	5939	5942	n.f.	2318	2318	2321	2723
1.27	SnPb	SAC105	215	5996	5999	6004	n.f.	2115	2115	2117	2131
1.27	SnPb	SAC105	215	5441	5441	5491	5646	1404	1404	1407	1444
1.27	SnPb	SAC105	215	5538	5610	5807	n.f.	2426	2426	2426	2433
1.27	SnPb	SAC105	215	3796	3797	3822	4091	1810	1810	1837	1843
1.27	SnPb	SAC105	215	8552	8556	8587	n.f.	2502	2502	2634	3336
1.27	SnPb	SAC105	215	6649	6649	6649	8955	2096	2097	2097	3530
1.27	SnPb	SAC105	215	4853	4853	4859	5951	1834	1834	1836	1836
1.27	SnPb	SAC105	215	6651	6652	6662	8231	n.f.	n.f.	n.f.	n.f.
1.27	SnPb	SAC105	215	7233	7233	7242	n.f.	2644	2644	2651	3311
1.27	SnPb	SAC105	215	3265	3366	3508	4433	2577	2577	2579	2672
1.27	SnPb	SAC105	215	7002	7002	7002	n.f.	2352	2352	2357	2366
1.27	SnPb	SAC105	215	5881	5881	5882	9288	2360	2360	2366	2366
1.27	SnPb	SAC105	215	8488	8488	8488	9456	2108	2108	2156	2739
1.27	SnPb	SAC105	215	9007	9007	9007	9338	3131	3131	3132	3501
1.27	SnPb	SAC105	215	4863	4863	4867	4998	2953	2953	2956	2969
1.27	SnPb	SAC105	215	7966	7966	7966	n.f.	2703	2703	2710	3082

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.27	SnPb	SACX	215	n.f.	n.f.	n.f.	n.f.	1663	1663	1663	1665
1.27	SnPb	SACX	215	4494	4494	4476	4897	2274	2273	2281	2316
1.27	SnPb	SACX	215	2470	2470	2545	2561	1444	1444	1513	1522
1.27	SnPb	SACX	215	8991	8991	9010	n.f.	2366	2366	2367	3520
1.27	SnPb	SACX	215	6240	6240	6240	9057	2541	2541	2552	2967
1.27	SnPb	SACX	215	6136	6147	6223	7533	2763	2763	2763	2794
1.27	SnPb	SACX	215	6346	6346	6371	6999	2468	2469	2507	2558
1.27	SnPb	SACX	215	5730	5731	5731	6019	2062	2063	2203	2326
1.27	SnPb	SACX	215	4863	4866	4895	7604	2118	2120	2121	2266
1.27	SnPb	SACX	215	3707	3707	3714	3866	2355	2350	2474	3124
1.27	SnPb	SACX	215	8510	8512	8521	10083	2600	2601	2601	2604
1.27	SnPb	SACX	215	9319	9495	10021	n.f.	2118	2143	2190	2449
1.27	SnPb	SACX	215	n.f.	n.f.	n.f.	n.f.	1939	1940	1948	2058
1.27	SnPb	SACX	215	3938	3938	5401	7201	2286	2287	2325	2325
1.27	SnPb	SACX	215	n.f.	n.f.	n.f.	n.f.	3484	3484	3492	3497
1.27	SnPb	SACX	215	3327	3326	3414	3414	1861	1864	1894	1894
1.27	SnPb	SACX	215	2128	2128	2571	2668	2208	2208	2262	2754
1.27	SnPb	SACX	215	n.f.	n.f.	n.f.	n.f.	3215	3215	3216	3523
1.27	SnPb	SACX	215	5302	5302	5302	6365	2492	2492	2493	2722
1.27	SnPb	SACX	215	4270	4270	4422	5292	2499	2499	2499	2601
1.27	SnPb	LF35	215	2620	2620	2880	2885	1125	1137	1246	1407
1.27	SnPb	LF35	215	3934	3936	4384	4410	1121	1130	1790	1793
1.27	SnPb	SAC105	220	6732	6732	6741	7924	2448	2448	2452	2799
1.27	SnPb	SAC105	220	5483	5483	5490	7419	1585	1585	1614	1616
1.27	SnPb	SAC105	220	8195	8195	8230	n.f.	1727	1727	1759	1895
1.27	SnPb	SAC105	220	n.f.	n.f.	n.f.	n.f.	2490	2489	2490	3020
1.27	SnPb	SAC105	220	4733	4734	4757	5835	1914	1914	1920	1942
1.27	SnPb	SAC105	220	8939	8939	8947	9232	2356	2356	2369	2369
1.27	SnPb	SAC105	220	5467	5471	5515	n.f.	1567	1567	1585	1587
1.27	SnPb	SAC105	220	6087	6087	6087	6258	2545	2543	2554	2637
1.27	SnPb	SAC105	220	4378	4378	4783	6796	1766	1766	1784	2060
1.27	SnPb	SAC105	220	7232	7236	7262	8368	1778	1775	1786	1818
1.27	SnPb	SAC105	220	5536	5536	5578	6322	1356	1356	1399	1441
1.27	SnPb	SAC105	220	n.f.	n.f.	n.f.	n.f.	1390	1390	1402	1537
1.27	SnPb	SAC105	220	9437	9437	9442	9443	1333	1333	1346	1346
1.27	SnPb	SAC105	220	6930	6930	6962	7667	1448	1448	1464	1500

Treatment				0 °C to 100 °C TCR				-40 °C to 125 °C TCR			
Pkg Desc (mm)	Paste Alloy	Ball Alloy	PRT (°C)	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.	$\bar{X}$ and R	IPC-9701A	500 Ω	Inf. Resist.
1.27	SnPb	SAC105	220	4180	4180	4218	4331	2903	2903	2911	3068
1.27	SnPb	SAC105	220	5018	5018	5023	5448	2719	2719	2719	2797
1.27	SnPb	SAC105	220	7894	7894	7895	8023	1817	1819	2028	2031
1.27	SnPb	SAC105	220	7670	7676	7676	n.f.	1983	1983	1986	1986

Appendix B

AIC Values for Weibull and Lognormal Distributions

Weibull AIC	Lognormal AIC	Paste Alloy	Ball Alloy	Pitch (mm)
246.67	244.49	SbPb	SbPb	0.80
262.44	262.30	SbPb	SbPb	0.50
298.39	295.75	SbPb	SbPb	1.00
340.24	335.71	SbPb	SbPb	1.27
193.73	192.87	SbPb	SAC305	1.27
282.22	279.71	SbPb	SAC305	0.50
307.11	310.75	SbPb	SAC305	0.80
349.73	353.78	SbPb	SAC305	1.00
290.86	291.10	SbPb	SAC105	0.80
294.49	291.94	SbPb	SAC105	0.50
325.43	325.06	SbPb	SAC105	1.00
328.92	329.93	SbPb	SAC105	1.27
299.42	302.36	SbPb	SACX	1.00
306.72	304.60	SbPb	SACX	1.27
310.94	309.49	SbPb	SACX	0.50
313.52	312.34	SbPb	SACX	0.80
236.75	239.28	SnPb	LF35	0.50
288.14	285.45	SnPb	SAC105	1.27
293.79	294.90	SnPb	SAC105	1.00
207.54	206.79	LF	SAC305	1.27
306.03	307.56	LF	SAC305	0.50
314.03	314.04	LF	SAC305	0.80
326.91	329.65	LF	SAC305	1.00
245.15	240.99	LF	SAC105	1.27
292.77	291.41	LF	SAC105	0.80
298.17	299.07	LF	SAC105	0.50
311.08	310.50	LF	SAC105	1.00
284.37	280.33	LF	SACX	0.80
302.07	300.66	LF	SACX	0.50
309.45	306.71	LF	SACX	1.00
321.49	318.98	LF	SACX	1.27
295.64	291.06	LF	SAC205	1.27
300.05	298.15	LF	SAC205	1.00
300.61	298.65	LF	SAC205	0.80
301.93	301.60	LF	SAC205	0.50

Weibull AIC	Lognormal AIC	Paste Alloy	Ball Alloy	Pitch (mm)
293.12	293.20	LF	LF35	0.50
294.07	297.05	SbPb	SbPb	0.50
305.16	300.19	SbPb	SbPb	1.00
306.35	306.53	SbPb	SbPb	1.27
317.67	315.35	SbPb	SbPb	0.80
303.81	302.24	SbPb	SAC305	0.50
306.94	306.51	SbPb	SAC306	0.80
311.83	307.12	SbPb	SAC307	1.00
325.32	324.44	SbPb	SAC308	1.27
310.14	310.73	SbPb	SAC107	1.00
311.82	310.77	SbPb	SAC108	1.27
312.49	315.46	SbPb	SAC105	0.50
315.39	318.24	SbPb	SAC106	0.80
301.43	302.67	SbPb	SACX	1.27
308.11	308.37	SbPb	SACX	0.80
309.89	315.38	SbPb	SACX	0.50
310.51	315.43	SbPb	SACX	1.00
218.22	216.23	SnPb	LF35	0.50
279.01	278.01	SnPb	SAC105	1.00
293.57	292.36	SnPb	SAC105	1.27
294.34	294.09	LF	SAC305	0.80
296.23	299.58	LF	SAC305	0.50
297.70	301.07	LF	SAC305	1.00
314.49	315.69	LF	SAC305	1.27
299.91	300.45	LF	SAC105	1.27
309.25	309.74	LF	SAC105	0.80
310.47	312.50	LF	SAC105	0.50
314.75	313.15	LF	SAC105	1.00
280.88	278.20	LF	SACx	0.50
286.30	286.87	LF	SACx	0.80
311.41	317.63	LF	SACx	1.00
325.47	327.82	LF	SACx	1.27
302.51	301.92	LF	SAC205	1.27
305.62	305.88	LF	SAC205	1.00
313.80	313.23	LF	SAC205	0.80
315.93	317.72	LF	SAC205	0.50
315.87	320.52	LF	LF35	0.50