Application Report
SPRABY2–March 2015

Board Level Reliability Primer for Embedded Processors

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ABSTRACT

This application report discusses the fundamentals of board level reliability (BLR) (sometimes referred to in literature as “second-level reliability”) testing and modeling as applied by the Texas Instruments Embedded Processing Group.

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1 Introduction

BLR is a broad-based topic generally encompassing the thermo-mechanical degradation behavior in time (application field use) of surface-mounted IC components on printed circuit boards (PCBs). Reliability characterization activities are normally focused on ball grid array (BGA) or QFN packages, as leaded QFP technologies, generally being more mature, have been well-characterized in the past and are established as relatively low BLR risk, except perhaps for the most demanding applications. Unlike component-level reliability testing with BLR, the distinctive requirement is that the component is surface mounted to the test board/interposer, ideally emulating thermo-mechanical stresses that the component would be exposed in the application. (The test board design, construction and materials are selected with this goal.)

BLR thermo-mechanical characterization can include environments such as temperature cycling, thermal shock, mechanical shock, vibration and mechanical bending. The overriding purpose is to characterize the “intrinsic” thermo-mechanical fatigue behavior of the region between the package and the PCB commonly referred to as the “second-level” interface (as opposed to die bumps between the package substrate and die, which is referred to as “first-level” interface). For example, on a BGA package this would imply failure in the solder ball or the interface of the solder ball with the package substrate or PCB land pad. The term “intrinsic” in this context is intended to imply end-of-life behavior (material wear-out), not including early failures due arising from manufacturing defects either with the component package or the PCB, or, alternatively, from the surface mount process of the component to the PCB.

2 Test Environments

At Texas Instruments Embedded Processing, the BLR evaluation tests chosen for the particular component or package are determined by the package technology itself as well as the target end-use equipment. Temperature cycle testing is included in almost all cases where BLR testing is performed. Mechanical tests, on the other hand, are more selectively performed depending on the targeted equipment and customer base. Broadly speaking, special test vehicles called “daisy chains” are constructed for the purpose of BLR testing and other targeted mechanical evaluations of the package. The “daisy chain” package usually does not contain the functional die, rather a specially constructed die and substrate with metal routes and nets that extend from the package substrate through the second-level interface (BGA or QFN terminals) to the PCB. Depending on the design, the routing of the nets may also extend into the daisy chain die, which would imply through the “first-level” interface on a bumped device, and the die may contain various vertical levels of metallization. The “daisy chain” design (including the ball and terminal footprint) and materials at a minimum should closely match the final production component in terms of stress and strain profile at the first level interface (solder balls). Specialized BLR test boards are designed to interface with the test oven electronics and manufactured, again, with the goal of being representative of the end-use application board.

3 Test Method

Unless indicated otherwise, TI follows the IPC-9701 specification for Temperature Cycle testing [2]. Changes in resistance are monitored in-situ, for example, virtually real time with monitoring equipment. This approach is in contrast to non-in-situ, whereby, boards are removed from stress and “readout” of resistance changes is performed with meters external to the temperature cycle chamber. One of the key advantages of in-situ is that precise cycles to failure for a given test DUT can be determined, thus, improving the accuracy of the subsequent reliability modeling. Usual IPC-9701 temp cycle conditions used by TI are 0°C-100°C or -40°C-125°C (sometimes both), with the selections determined according targeted application areas for the products under qualification. Ramp and dwell time targets and tolerances are specified within the IPC-9701 document. The ramp and dwell profile is particularly important in context of the key failure mechanism of intended focus – solder joint creep.

3.1 Factors Affecting Reliability Performance

A myriad of factors can influence the ultimate reliability performance of the system (component surface mounted to PCB). Among the prominent factors are:

- PCB material (FR4), thickness, layering and design (via under pad)
- PCB land pad design (SMD, non-SMD), paste material and solder stencil thickness
- Use of under-fill and choice of under-fill materials between PCB and component
- Solder ball (BGA) material (eutectic Sn/Pb, SAC387, SAC305)
- Package substrate to BGA interface and attach materials (electrolytic Ni/Au, thin Ni, SOP, Cu-OSP, ENIG)
- BGA size and diameter, pitch, grid array layout (populated or de-populated grid locations)
- Die dimensions and location of edges with respect to solder ball locations
- Package lid or mold compound materials

The choice of solder ball material is particularly salient in optimization of the package for targeted failure mechanisms such as impact or shock resistance. No single alloy is ideal for all environments and uses although usually choices are made based on optimization for a key, primary factor (temperature, vibration, shock, and so forth) and good or at least acceptable performance for secondary factors. As a general case, TI’s material selection is optimized for temperature cycle fatigue, SAC305 on current designs and SAC387 on some legacy designs, but in the case of some products targeted hand-held mobile or other specialized, targeted applications other alloys have been used (with drop, impact and shock resistance, for example, in mind as the primary concerns).

4 Modeling Approach

With materials and design selected, the daisy chain test vehicles manufactured, and BLR test data, the focus then turns to reliability modeling. Typically, the 2-P (two-parameter) Weibull distribution is used for lifetime modeling of the BLR test data. The Weibull distribution is often associated with characterizing the “weakest links” in a “system”. This is notionally the case for solder joint fatigue failures. Mechanical Finite Element modeling is often undertaken to identify relative strain energy density across the array of solder ball. The solder balls with the highest strain energy densities are those that (statistically) are expected to fail first, in other words, the “weakest links”. Normally, about 30-50 component samples are tested and the testing continues until at least about 2/3 of the units fail (a fail being defined as a pre-requisite percentage increase in resistance). Early failures are typically due to board manufacturing issues, such as non-wet solder joints. Failure analysis is regularly performed to confirm these cases. Units failing due to manufacturing (defect) issues are excluded (censored) from the Weibull model (see Figure 1), the purpose of which is to characterize the intrinsic fatigue lifetime of the solder joints (usually the BGA to package, or second-level interface). In cross-sectional terms, this is the location of the highest strain energy density (particularly at the corners). The fatigue crack propagates across the neck of the solder ball until sufficient resistance change triggers a failure condition on the monitoring equipment. Note that while the examples of modeling shown in this document are based on Temperature Cycle testing, mechanical shock and drop or bend data are plotted by the same tools and techniques.

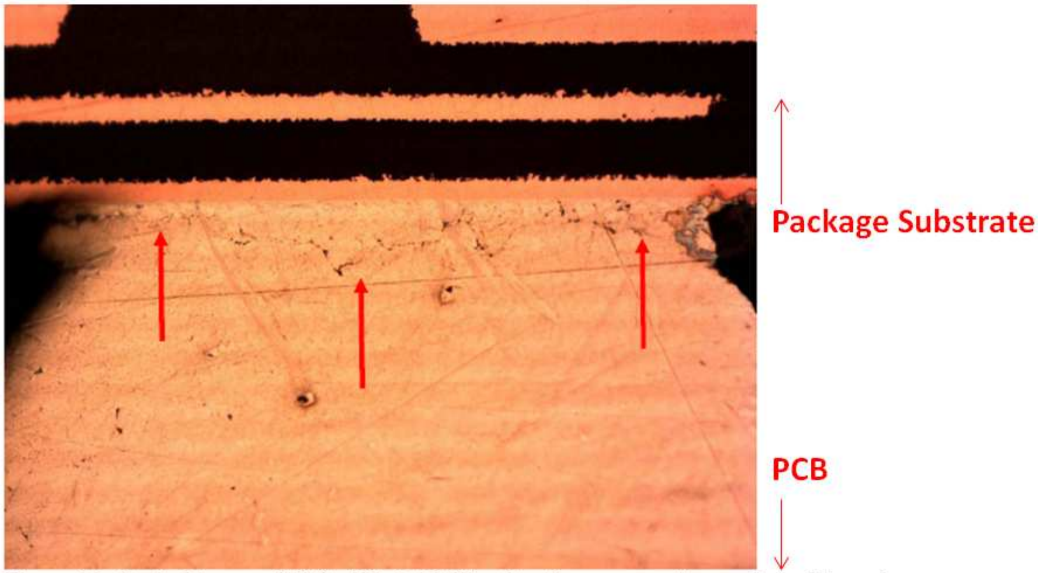

Figure 28: Optical image of Y10 of Unit A8-U1, after the cross section analysis. The red arrows point to a crack at the device ball interface that tied to the reported failing daisy chain loops.

Failure Location: Fatigue crack at BGA interface to package substrate

Figure 1. Representative Optical Micrograph Image of Intrinsic Solder Joint Fatigue Failure

The 2-P Weibull model consists of a Slope parameter and a Scale parameter. Unfortunately, authors use different terms to represent these parameters in various publications, so the symbols used in a particular text to identify Slope and Scale must be identified case by case. In Equation 1, F is the Fail Fraction (Cumulative Distribution Function - CDF, or unreliability), R is the Reliability function (fraction surviving), Eta is the Scale Parameter (also known as characteristic life), Beta is the shape parameter, and AF is the acceleration factor (accelerated test to use conditions). Note that “t” (time) is transposable in the BLR context with “number of cycles” (there is a time equivalent for cycles and vice versa).

4.1 Weibull 2-P Fail Fraction (CDF) With Acceleration Factor

$$F(t) = 1 - R = 1 - e^{-\left(\frac{t}{AF \cdot \eta}\right)^{\beta}} \tag{1}$$

There are two primary methods for plotting the Failure Fraction vs. Time distribution (a process known as “point estimation”): Maximum Likelihood Estimation (MLE) and Rank Regression. For typical BLR data, where the majority of the sample has known precise times (cycles) to failure and the majority of the units (~2/3 or more of the sample), the MLE method is generally recommended. The details are beyond the scope of this application report. For more information, see Tobias and Trindade, “*Applied Reliability*” (3rd Edition), CRC Press, 2012 [4].

Note that while there are available methods to plot reliability graphs “by hand” (without aid of computer software), it is generally preferable to use computer programs dedicated to the task. Many choices are available, including dedicated reliability engineering packages (Reliasoft *Weibull*++ or *ALTA*) as well as more general statistical analysis packages with modules targeted to reliability analysis (SAS JMP). These programs typically offer advanced features such as confidence bound estimates and multiple methods of point estimation. The acceleration factor for solder joint fatigue, the focal failure mechanism of BLR temperature cycle test, is described by the Modified Coffin-Manson, also known as Norris-Landzberg, equation.Section 4.2 is the general AF relationship. “Acc” and “Field” refer to accelerated test and Field (application) conditions, respectively. T is in degrees °C (or K), with ΔT referring to the difference of maximum and minimum temperatures for the cycle. *v* is the cyclical frequency of the temperature cycle (cycles/time). Ea is the temperature activation energy and “k” is Boltzmann’s Constant. For eutectic Sn/Pb solder, the parameter values are well established as m=1/3, n=1.9 and Ea/k = 1414 (for example, Vaduseven and Fan, “*An Accelerated Model for Lead-Free (SAC) Solder Joint Reliability under Thermal Cycling*”, IEEE ETC, 2008). The reported parametric values on Pb-free solder can vary substantially according to the alloy. For SAC (SnAgCu) alloys in particular, N. Pan et al. have reported m=0.136, n=2.65 and Ea/k = 2185 (“*An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability under Various Thermal Cycle Conditions*”, Proc. SMTA, 2005, pp. 876-883) [3]

4.2 Norris-Landzberg Acceleration Factor Equation

$$AF = \left(\frac{\Delta T_{Acc}}{\Delta T_{Field}}\right)^{n} \left(\frac{\nu_{Field}}{\nu_{Acc}}\right)^{-m} e^{\left[\frac{E_a}{k}\left(\frac{1}{T_{Max-Field}} - \frac{1}{T_{Max-Acc}}\right)\right]} \tag{2}$$

Note that a useful source for N-L parameters for non-hermetic packages for representative end-equipment classes is JEDEC document JESD47 (see Annex A for the most current revision I as of July 2014) [1]. For more information, see the JEDEC web site.

Equation 2 is a representative Weibull 2-P plot of 0/100C BLR Temp Cycle data a Pb-free BGA package generated using specialized reliability software (Reliasoft *Weibull*++).

NOTE: The N-L / Modified Coffin Manson acceleration factor has not been applied to the data in Figure 2.

The Maximum likelihood method is used for point estimation. The blue line is the maximum likelihood fit for the data. The red lines represent 90% confidence bounds on reliability versus cycles (in the MLE case, the confidence bounds are calculated using the likelihood ratio method). It is also possible to generate confidence bounds for time (or cycles) instead of or in addition to reliability. At approximately the mean of the data, there is typically little difference between the two approaches. The further in time from the mean of the data in either direction, however, the more difference is observed, and in either case the confidence bounds widen in relative terms. The choice of the method depends on context and preference. As in the in-situ BLR T/C case, the precise number of cycles to failure is known for a given unit, the reliability bounds were chosen.

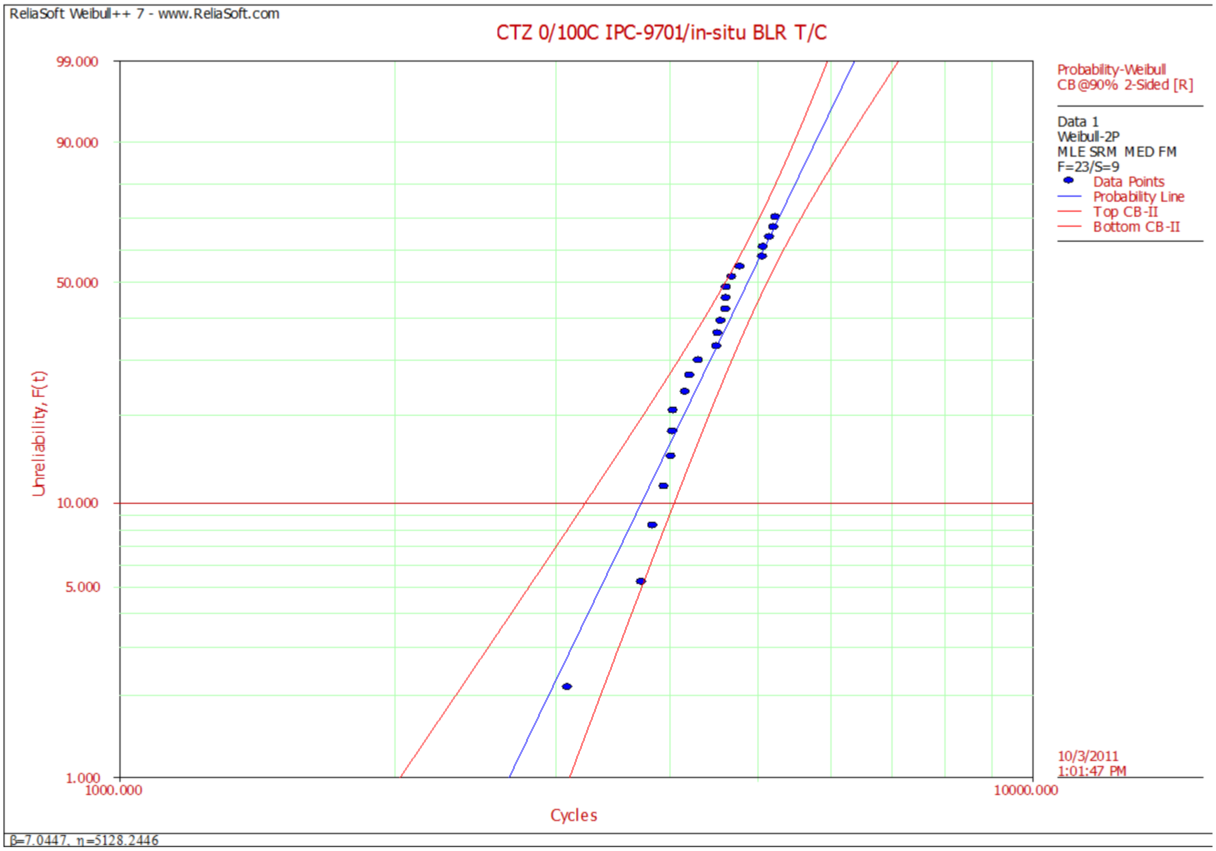

Figure 2. Typical Weibull 2-P Plot for Board Level Reliability Temp Cycle Data

Modeling software can also be used to compare parameters across datasets and differences in the joint ranges of parameters according to confidence bound limits. Figure 3 is known as a “Contour Plot”. The two “ellipses” on the left of the plot represent data generated for two different vendors of package substrates, and the two ovals on plots for a third vendor. The red and blue lines (on the right) represent different levels on confidence bounds for the same dataset. The interpretation of the contour plot is that the line represents the boundary of equal probability for the combination of the two parameters (in this case scale/Eta and shape/Beta). For instance, for a 90% confidence level contour, if the process of data collection were repeated an infinite number of times, 90% of the contours generated for the datasets should contain the true values of the parameters within the areas of the contour. The higher the percentage of the confidence bound for a given dataset, the greater the perimeter of the line as well as the area contained within the perimeter of the line. Likewise, a smaller confidence bound contour will be contained (as a subset) within a larger confidence bound contour.

Finally, some of the most advanced reliability modeling software is capable of simultaneously solving for maximum likelihood reliability model parameters and acceleration model parameters for multiple datasets (assuming linear acceleration). For example, suppose the reliability of a new solder alloy or package technology was undergoing reliability characterization. Multiple datasets would be generated at different temperature cycle conditions. A kinetic (acceleration) model would then be assumed, for instance Modified Coffin-Manson in the case of solder joint fatigue. As long as the data generated all are represented by the same failure mechanism, the best joint fit for the reliability and kinetic parameters would be generated along with confidence bounds for the reliability estimates for any given application (use) condition. The caveat on extrapolating to a use condition is that the physics of failure at the use condition and accelerated test conditions are all the same.

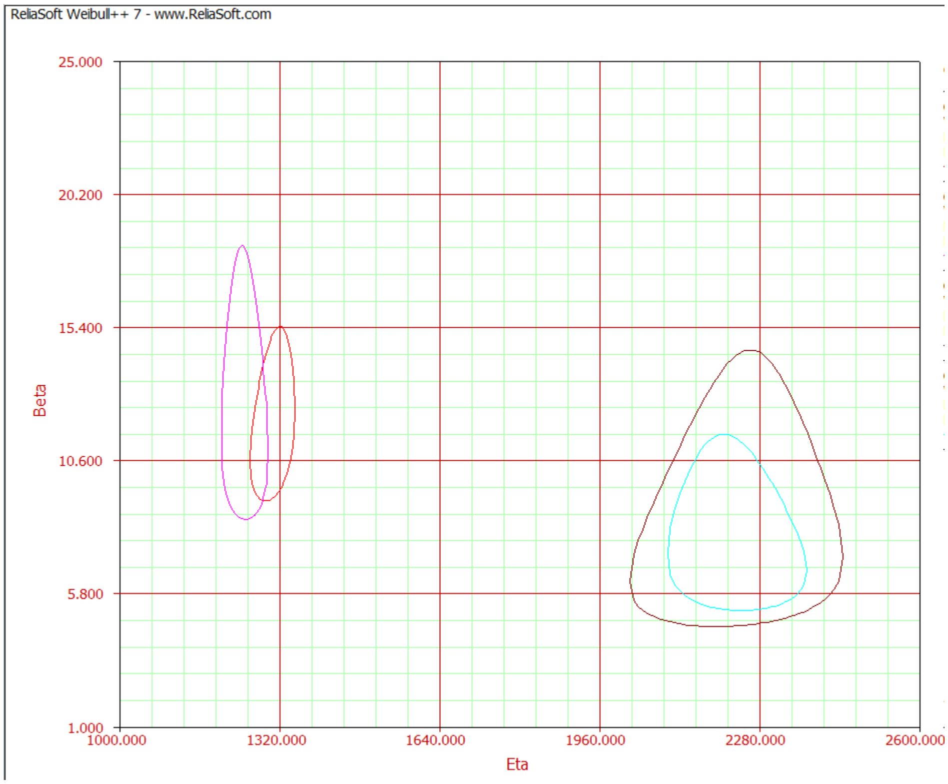

Figure 3. Weibull 2-P Contour Plots for Shape (Beta) and Scale (Eta) Parameters

5 References

1. JEDEC JESD47: *Stress-Test-Driven Qualification of Integrated Circuits*: www.jedec.org
2. IPC-9701: *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*: www.ipc.org
3. Pan et al., “*An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability Under Various Thermal Cycle Conditions*”, Proc. SMTA, 2005, pp. 876-883.
4. Tobias and Trindade, “*Applied Reliability*” (3rd Edition), CRC Press, 2012, pp 248-255.

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