# Monte Carlo Simulation of BGA Failure Distributions for Virtual Qualification

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## ABSTRACT

Any approach to qualification of advanced technologies during product development must include an assessment of variation expected in product life over the life cycle. However, testing product design options in development, to approach an optimal design, is costly and time consuming. Hence, simulation of product life distributions for virtual qualification, can be a valuable tool to evaluate and qualify design options. This paper presents a physics of failure based approach to virtual qualification of advanced area array assemblies, against solder fatigue failure. The approach applies Monte Carlo Simulation to evaluate solder joint fatigue life distributions, given material property variations and manufacturing capabilities. Preliminary results using the simple Engelmaier Model as the basis of simulations are presented. Simulation results are compared to data accumulated from two test environments and two BGA product types. The results reveal some of the limitations of the Engelmaier Model as a basis for simulation. They also show the potential of this approach to virtual qualification for design and manufacturing capability assessment in development.

## INTRODUCTION

Product qualification is intended to assure that a new design will meet the lifetime required for the application with minimal risk of failure. In addition, qualification is used to assure manufacturing processes produce minimal risk of early failure due to defects or inadequate process capability. We are forced to recognize in applying qualification, that materials properties and various geometric variables subject to manufacturing processes are random variables. These variations give rise to uncertainty in product life, as shown in Figure 1.

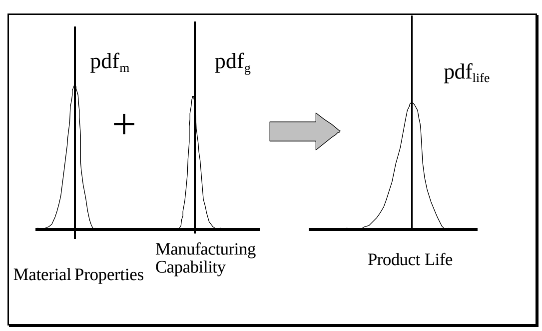


Figure 1  Materials property variation

Qualification must assure the design and manufacturing capability produce adequate product life. The method of qualification must also recognize variations in materials properties and manufacturing capability produce uncertainty in product life.

In conventional qualification, we therefore select a sample size and test the sample products under stress to failure or until some specified time period. We then examine the confidence we have in our design and manufacturing processes.

Yet, many options in architecture may be selected to create a hierarchy of packaging for an electronic product. There are many materials options and potential manufacturing processes. In addition, new developments provide expanding options. Virtual qualification is therefore desirable as an alternative to testing all potential options. Virtual qualification implies that we evaluate a model of the product under stress. We can therefore evaluate and qualify many options in architecture for a product in rapid time, at lower cost. However, we must still fulfill the requirement of understanding the impact of variation as illustrated above, in Figure 1. Hence, Monte Carlo simulation becomes a valuable approach to developing a virtual qualification scheme.

The following sections present an approach to simulation of life based upon input variation of materials properties and manufacturing capability. To illustrate this approach to virtual qualification, we apply the process to Ball Grid Array architectures and compare the results to qualification test data on actual product. Two test conditions and architectures are evaluated. As summarized in Table 1.

**Table 1. Qualification Conditions**

| ***Test Facility*** | ***BGA Package Style*** | ***Actual Test Sample Size*** | ***Cyclic Conditions*** |
|---|---|---|---|
| Jet Propulsion Laboratory | 313 PBGA<br>35 mm X 35mm<br>1.27 mm pitch<br>Full Array<br>15x15mm die | n=13 | -30 to +100$^o$C<br>$t_D$ @100$^o$C = 20min<br>$t_D$ @-30 $^o$C = 10 min<br>Ramp time = 20 min |
| Motorola Semiconductor Products | 119 PBGA<br>14 mm X 22 mm<br>1.27 mm pitch<br>Full Array<br>9 x 16 mm die | n = 27 | 0 to +100$^o$C<br>$t_D$ = 5 min<br>Ramp time = 10 min |

## VIRTUAL QUALIFICATION BY SIMULATION

A method of virtual qualification is summarized in Figure 2. In this case, time to failure models representing the dominant failure mechanisms are embedded in a Monte Carlo simulation. Input variations representing manufacturing capability and material properties are modeled as triangular distributions. These estimates must be extracted from materials testing and manufacturing history.

The process is exercised as follows:

- The test or application conditions are determined.
- A failure model is selected.
- The input distributions are then sampled using a random number generator.
- The life is calculated from the failure model.
- The result is stored.
- The input distributions are sampled again and calculation is repeated for a preset number of samples.
- The results of the stored are analyzed by fitting the data to a distribution, which represents the life distribution of the failure mechanism.

In the case of the BGA application, we initially have selected the well-known Engelmaier model to represent the failure mechanism of solder fatigue for these initial studies.

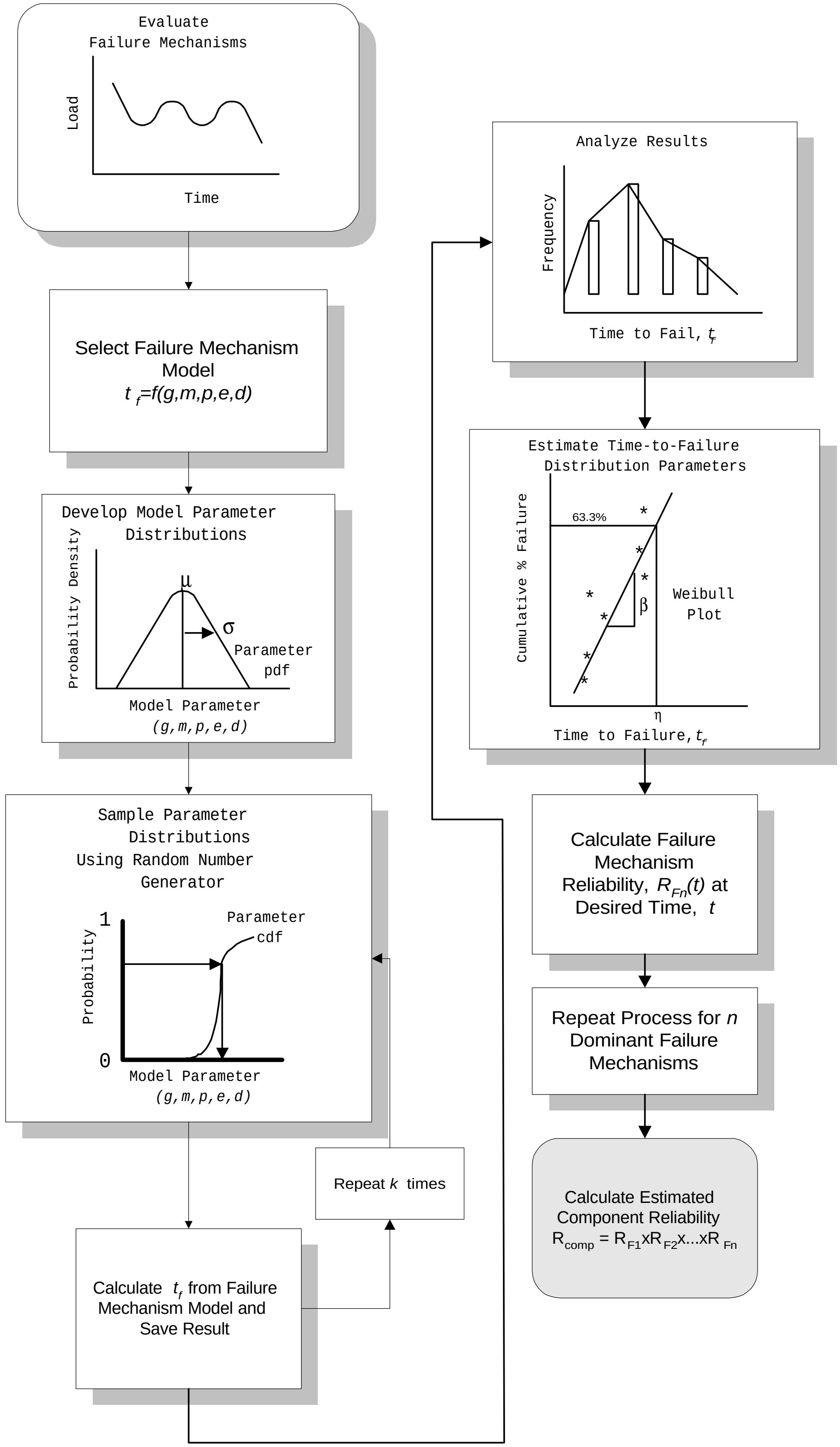


Fig. 2. Virtual Qualification Process by Monte Carlo Simulation (Evans and Evans 1999).

## BGA LIFE SIMULATION

For Ball Grid Array products, a primary failure mechanism is solder fatigue. Solder fatigue is induced as a result of coefficient of thermal expansion mismatches between the BGA carrier substrate and the PWB used for interconnection. Changes in temperature by power cycling or thermal cycling induce cyclic strains. Cyclic strain causes an accumulation of damage that results in the development of cracks and eventually fracture. Creep and stress relaxation maximizes the damage induced in the solder.

There are several approaches to modeling this complex process, which may serve as a basis for virtual qualification of a BGA assembly. Each approach has some limitations. Among the simplest model is the Engelmaier model. This model assumes that the shear strain developed is proportional to the maximum strain in the solder, when the solder fully deforms in accordance with the differences in the coefficients of thermal expansion between the BGA component and the PWB used to mount and interconnect the components. The maximum strain is then related to the number of cycles to failure by the Manson -Coffin relationship.

The relationship is well known and is easily derived (Engelmaier 1983, 1989, 1990). The following equations express the Engelmaier model:

$$\Delta g = x\,\frac{L_D\left(a_{PWB} - a_{BGA}\right)\Delta T}{2h} \qquad (1)$$

where the shear strain range, $\Delta\gamma$ is a function of the critical distance from the neutral point of the part. However, $L_D$, the diagonal distance from corner joint to corner joint in the failing row of solder balls, is easily measured. Equation 1 also includes the height of the solder joint , *h,* the differences in the coefficients of thermal expansion (CTEs), *a* , and the temperature differential *DT*.

$\xi$ is the strain correction factor, which depends upon the package style. Engelmaier reports that $0.7<\xi<1.5$. Values less than 1 imply the a reduction in the predicted maximum possible shear strain, due to constraining factors, whereas values greater than 1 imply added strains due to significant warping, large strain concentrations or localized thermal mismatches. Warping increases with increasing *DT* and will also lead to development of significant tensile strains. Overall, solder joint strains are more accurately predicted by finite element methods than with correction factors. However, the simplicity of equation 1 is attractive and it provides a rapid closed form solution.

In the case of BGA style packages, Amagi (1998) reported that the strains in the critical BGA joints are a function of the total number of balls on the BGA. The net strain is inversely proportional to the number of balls, *S.* Hence, increasing the number of balls constrains the net expansion. Therefore, $\xi \propto 1/S$ and $\xi<1$. A simple comparison of test results and calculated values for the median value of the number of cycles to failure shows that $\xi = 0.54$ for the Motorola Qualification, which is the value used for the 119 pin BGA. $\xi = 0.46$ for the JPL Qualification, which is the value applied for the 313 pin BGA. In these cases, $\xi$ in only valid for the stated package, under conditions in which warping is not significant.

The number of cycles to failure is then a function of the shear strain in accordance with the well-known Manson-Coffin equation:

$$\Delta g = 2e_f'(2N)^c \qquad (2)$$

where $e_f'$ is the fatigue ductility coefficient and *N* is the cycles to failure. Engelmaier fit the fatigue ductility exponent, *c*, to test data for many different conditions, accumulated by Wild (1975). This empirical relationship accounts for added creep damage and stress relaxation that varies with time.

$$c = -0.442 - 6x10^{-4}\,xT_s + 1.74x10^{-2}\ln\left[1+\frac{360}{t_D}\right] \qquad (3$$

where Ts is the average temperature of the solder and $t_D$ is the cyclic hold time. In testing, $\Delta T$, *Ts* and $t_D$ are variables known with precision. This is not the case with field conditions.

The Engelmaier model uses several obvious simplifying assumptions, which are debated in the literature. The model is applied most appropriately to a temperature range of 0 - 100°C and to a cycle with a symmetrical hold time allowing for significant stress relaxation. In addition, as discussed, warping effects and complex strains are not modeled. Beyond the model envelope of 0 - 100$^{o}$C range, more complex methods should be applied. The strain energy must be estimated from finite element calculations, the damage mechanisms must be partitioned and their contribution to the total strain energy separated. Miners rule is then applied (Dasgupta 1992). A closed form approximation to life can be extracted from this procedure using a statistically designed experiment. (Evans, Evans and Ryu 1997)

In spite of its limitations, the Engelmaier model does contain the primary variables describing the life of a BGA solder joint for shear strain dominated fatigue damage, with appreciable creep. This particularly applies for full array style packages, in which the die influences the coefficient of expansion, at the critical failing row of joints. Evans et. al. (1997) suggested that a few primary variables are likely to dominate fatigue reliability. Hence, the Engelmaier model's simplicity is attractive for a Monte Carlo simulation.

The set of variables comprising the Engelmaier model consists of materials properties and geometric variables. These variables are random variables that contain significant uncertainty. The accuracy in applying the Engelmaier model or any other damage modeling is dependent upon proper treatment of these uncertainties.

The geometric variables have variations, which are defined by the BGA manufacturing process, PWB fabrication and PWB assembly processes. For example, $L_D$ has variation arising from pad placement accuracy on the BGA substrate and PWB; $h$ varies according to the screening process variations and solder paste parameters. $a_{BGA}$ is influenced by the materials and geometry that define the BGA structure. It is a function of the coefficients of thermal expansion of the materials, the thicknesses and moduli of elasticity. The material properties may vary considerably for all polymers in the structure and the thickness will vary according to the BGA fabrication processes, such as die bonding and encapsulation.. $a_{PWB}$ will vary according to the printed wiring board fabrication processes and the variations in the reinforcements and resins that comprise the board. Finally, $e_f^{'}$ is an alloy ductility property of the solder, which will have considerable uncertainty associated with it, according to solder ductility and microstructure variations.

In summary equations (1)-(3), contain a set of random variables. They must be treated as such, in order to exercise a qualification of a product. In order to implement our process of virtual qualification, materials testing and manufacturing characterization must quantify the levels of uncertainty. The inputs to the equations were modeled as simple triangular distributions. The triangular distribution parameters included the minimum value, maximum value and most likely value of the random variable. These parameters were measured from actual samples of the two BGA packages subjected to qualification.

Height variations were determined from cross sections of mounted packages at the critical failing row of joints at the die perimeter. The diagonal distance $L_D$ was determined by x-ray of unmounted packages to accurately identify the position of the die and failing row of joints. CTE measurements were taken also at the critical row by removing the package material around the die perimeter and measuring the remaining trimmed package by TMA. The number of measurements varied for each parameter and ranged from 6 - 20 depending upon package sample availability. The triangular distribution parameters were estimated from the data. The results are summarized in Table 2.

The fatigue ductility coefficient was also estimated as a random variable. The most likely value was taken as 0.325, which is frequently reported in the literature. The range of this variable was taken as 0..28-0.37. This range is consistent with the range of true strain at fracture for Sn63Pb37, as measured from tensile testing (Hagge 1982). True strain at fracture is closely related to the ductility coefficient, $e_f^{'}$ (Fuchs and Stevens 1980).

The PWB in either case was FR-4. The coefficient of expansion of FR-4 was measured by TMA in the X and Y (warp and fill) directions, keeping in mind that PWB laminates are orthotropic. The Motorola test substrates were measured from 6 samples and the variation was determined according to observed values; the X direction ranged from 13.1 to 18.1 $ppm/^oC$ and the Y direction measured 16.1 to 19.3 $ppm/^oC$. Previously published data were used for the JPL simulation. TMA values reported by Ghaffarian (1997) showed the average values for FR4 were 14.5 $ppm/^oC$ in X and 16.8 $ppm/^oC$ in Y . The same variation was used as measured from Motorola samples.

**Table 2. BGA Package Parameter Variations Used as Inputs to Engelmaier Model**

| | ***Motorola 119 PBGA*** | | | ***JPL 313 PBGA*** | | |
|---|---|---|---|---|---|---|
| | Min | Most | Max | Min | Most | Max |
| ***h* *(mm)*** | 0.5503 | 0.5669 | 0.5815 | 0.514 | 0.562 | 0.631 |
| ***$L_D$* *(mm)*** | 16.203 | 16.259 | 16.362 | 17.178 | 17.203 | 17.230 |
| $\alpha_{BGA-X}$ ***ppm/$^o$C*** | 7.407 | 7.462 | 7.54 | 5.225 | 6.10 | 7.02 |
| $\alpha_{BGA-Y}$ ***ppm/$^o$C*** | 7.735 | 7.81 | 8.01 | 5.46 | 6.22 | 6.91 |

## INITIAL SIMULATION RESULTS

Initial simulation data are shown in Table 3. The data were compiled at 1000 simulation runs.

**Table 3. Simulation Results for Two Qualification Conditions**
**n=1000 Simulations**

| | ***Motorola Qualification*** | ***JPL Qualification*** |
|---|---|---|
| **2P_Weibull** | | |
| Beta | | |
| Eta | 7.1768 | 6.9534 |
| Mean | 13044.16 | 9189.18 |
| Variance | 12217.8 | 8259.9 |
| 0.01 Percentile | 4023241.5 | 2110502.75 |
| 0.05 Percentile | 6871.4 | 4742.0 |
| Percentile | 8623.4 | 5994.7 |
| | 9533.2 | 6648.5 |
| **3P_Weibull** | . | |
| Beta | | |
| Eta | 3.1298 | 3.1036 |
| Mu | 5809.88 | 4166.68 |
| Mean | 7059.71 | 4894.96 |
| Variance | 12257.8 | 8621.44 |
| 0.01 Percentile | 3308168.0 | 1725965.3 |
| 0.05 Percentile | 8395.8 | 5841.4 |
| 0.1 Percentile | 9308.8 | 6495.1 |
| | 9890.5 | 6912.8 |

| | | |
|---|---|---|
| **Lognormal** | | |
| Mu | 9.4027 | 9.0509 |
| Sigma | 0.1516 | 0.1526 |
| Mean | 12261.5 | 8625.74 |
| Variance | 3496341.9 | 1753815.95 |
| 0.01 Percentile | 8518.5 | 5977.6 |
| 0.05 Percentile | 9445.8 | 6632.9 |
| 0.1 Percentile | 9980.8 | 7011.1 |

Examination of the plotted simulation data shows that the data tend to curve concave downward. This is also often observed in test data (Mawer and Luquette 1997). An example of this is shown below in the plotted simulation data shown in Figure 3. The data curve downward in a pronounced fashion and deviate from the fit distribution. This effect is also apparent in test data (Mawer and Luquette 1997). However, it is not as pronounced, as the sample sizes for actual tests are much smaller and data does not accumulate for small probabilities of failure.

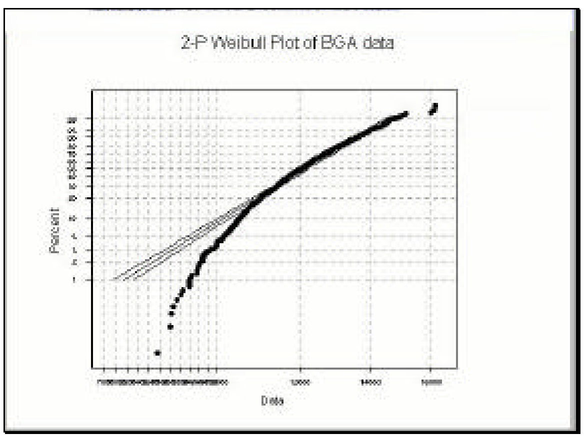


Fig. 3. A 2-P Weibull plot showing pronounced curvature. This indicates a 3-P Weibull may be more appropriate to the data.

The pronounced curvature generally indicates that there is a failure free period before wear out takes effect and implies that the three parameter (3-P) Weibull Distribution should be fit to the data. Hence, the simulation data were also fit to the 3-P Weibull using the method of O'Connor (1991). The data were also fit to the logNormal distribution, which is recommended by Blish (1997). A $\chi^2$ goodness of fit test was performed on all three distributions as shown in Table 4.

Without detailing the descriptions of statistical inference that can be found in good references (O'Connor 1991, Evans and Evans 1999), Table 4 can be simply interpreted. A distribution can be said to fit the data if the cut-off value of the $\chi^2$ statistic extracted from tabulated values is greater than the calculated test value statistic. The confidence level of the fit is 1-$\alpha$, where $\alpha$ is the probability of error. As an example, at a confidence level of 99%, $\chi^2_{\alpha} > \chi^2_{Test}$ for the Motorola Qualification Conditions. Inspection of Table 4, quickly shows that the simulation data best fit the 3-P Weibull distribution for both test conditions. The data fit this distribution at all three tested confidence levels, for the Motorola qualification conditions, and fit the JPL qualification conditions at 90 and 95%. The data do not fit the 2-P Weibull at the tested confidence levels of 90, 95 or 99%. The data fit the logNormal only at a confidence level of 90%, but not at higher confidence levels of 95 or 99%.

## ANALYSIS OF ACTUAL QUALIFICATION TEST DATA

As previously explained, data were obtained on actual assembled products at Motorola and JPL facilities under two different qualification testing condition. The conditions were different for the two data sets, as were the sample sizes, *n*. Each data set was fit to the same three wear out distributions as the simulated data. The results of the analysis are summarized in Table 5.

In addition, a $\chi^2$ goodness of fit test was also performed on the data. The results are summarized in Table 6.

**Table 4. $\chi^2$ Goodness of Fit Test Results on Simulation Data for Three Wear Out Distributions**

| | *Motorola Qualification* | | | *JPLQualification* | | |
|---|---|---|---|---|---|---|
| | *2P_Weibull* | *3P_Weibull* | *lognormal* | *2P_Weibull* | *3P_Weibull* | *lognormal* |
| ***Test statistics*** | *173.82* | *17.82* | *28.08* | *95.91* | *25.85* | *39.36* |
| ***Cut off for a=*** | | | | | | |
| 0.01 | 33.41 | 33.41 | 33.41 | 33.41 | 33.41 | 33.41 |
| 0.05 | 27.58 | 27.58 | 27.58 | 27.58 | 27.58 | 27.58 |
| 0.1 | 24.77 | 24.77 | 24.77 | 24.77 | 24.77 | 24.77 |

**Table 5. Results of Fitting Distributions on Actual Data for Two Qualification Conditions**

| | *Motorola Qualification n=27* | *JPL Qualification n=13* |
|---|---|---|
| **2P_Weibull** | | |
| Beta | 6.88 | 21.405 |
| Eta | 12215.52 | 4103.56 |
| Mean | 11416.6 | 4001.4 |
| Variance | 3799486.75 | 53897.6 |
| 0.01 Percentile | 6259.4 | 3309.9 |
| 0.05 Percentile | 7932.7 | 3571.9 |
| 0.1 Percentile | 8807.7 | 3694.1 |
| **3P_Weibull** | | |
| Beta | 2.8733 | 21.1721 |
| Eta | 5442.72 | 4059.875 |
| Mu | 6575.83 | 43.64 |
| Mean | 11427.2 | 4001.4 |
| Variance | 3358903.5 | 53881.88 |
| 0.01 Percentile | 7673.6 | 3310.7 |
| 0.05 Percentile | 8511.7 | 3572.1 |
| 0.1 Percentile | 9062.8 | 3694.1 |

| | | |
|---|---|---|
| **Lognormal** | | |
| Mu | 9.3294 | 8.2919 |
| Sigma | 0.1696 | 0.062 |
| MeanVariance | 11427.4 | 3998.91 |
| 0.01 Percentile | 3810258.0 | 61493.43 |
| 0.05 Percentile | 7592.1 | 3455.6 |
| 0.1 Percentile | 8522.3 | 3604.6 |
| | 9063.9 | 3686.6 |

**Table 6. $\chi^2$ Goodness of Fit Test Results on Actual Qualification Test Data for Three Wear Out Distributions**

| | *Motorola Qualification n=27* | | | *JPLQualification n=13* | | |
|---|---|---|---|---|---|---|
| | ***2P_Weibull*** | ***3P_Weibull*** | ***lognormal*** | ***2P_Weibull*** | ***3P_Weibull*** | ***lognormal*** |
| ***Test statistics*** | *2.3030* | *0.6264* | *0.5719* | *0.2905* | *0.2919* | *1.1635* |
| ***Cut off for a=*** | | | | | | |
| ***0.01*** | 11.3449 | 11.3449 | 11.3449 | 11.3449 | 11.3449 | 11.3449 |
| ***0.05*** | 7.815 | 7.815 | 7.815 | 7.815 | 7.815 | 7.815 |
| ***0.1*** | 6.2511 | 6.2511 | 6.2511 | 6.2511 | 6.2511 | 6.2511 |

Actual test data will fit any of the three of the wear out distributions. An inspection of Table 6 shows that the parameters and distributions in Table 5, can all be used to represent the results of the qualification test. This can be explained in part by the sample size. The sample sizes do not allow for accumulation of data below a probability of failure of 0.02 for the Motorola data and below 0.05 for the JPL data. Recall that BGA fatigue data will tend to deviate from the 2-P Weibull at lower probabilities of failure. A probability plot shows the characteristic behavior of curvature in the Motorola data even though the data apparently may be fitted to a 2-P Weibull. This suggests the 3-P Weibull is a better model. If we accept the 2-P Weibull, we will predict lower reliability than either the logNormal or 3-P Weibull. While this is conservative, it may have economic implications, particularly for producers. LogNormal is the least conservative.

## COMPARISON OF SIMULATIONS AND ACTUAL TEST DATA

A comparison of Tables 3 and 5 show that the simulation data are very representative of the actual test data for the Motorola qualification test conditions. The 2-P and 3-P Weibull probability plots comparing the data sets are shown in Figures 4 and 5. The 2-P Weibull plots clearly show the curvature in the actual and simulated test data. As discussed, this suggests the
3-P Weibull should be used for the data. In comparing the 3-P Weibull plots, we see the data for the simulation and the actual test data are closely matched, for $\xi$ =0.54. The fitted 3-P parameters result in less than 7% difference in the life prediction at a probability of failure of 0.01. The fitted data also plotted well within the 95% confidence bands of the actual data. This relatively close match is

encouraging for Monte Carlo simulation as a virtual qualification tool.

However, the fitted 3-P Weibull plots also show that the simulation was somewhat non-conservative. This may indicate that one or more of the sources of variation, input to the model, is not accurately representing the true variation in the parameter. However, it would be very interesting to make a comparison of the simulation to actual test data, for a larger sample size.

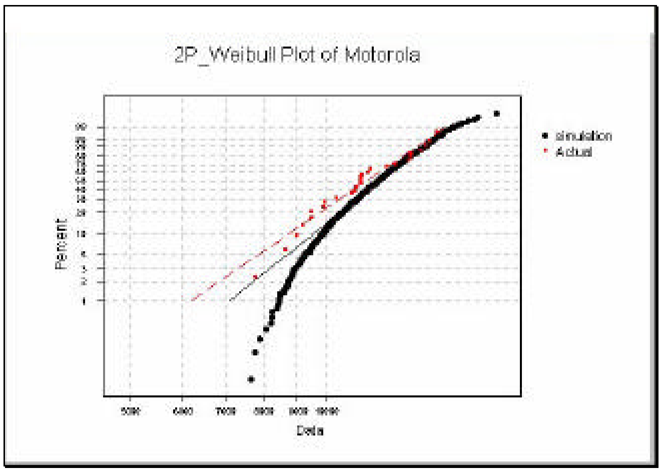


Figure 4. 2-P Weibull plot of simulation and actual test data for the Motorola qualification test conditions. Both data sets show curvature.

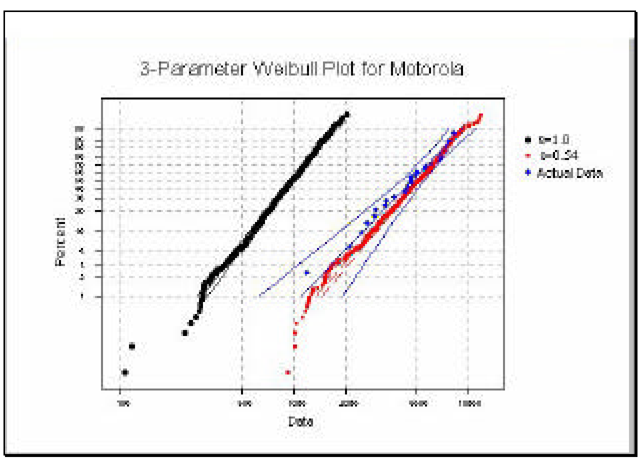


Fig. 5. 3-P Weibull plots of simulation and actual test data for the Motorola test conditions. The plot compares the simulation data generated for $\xi$ =1.0 and $\xi$ =0.54.

A comparison of the JPL data simulations and actual data do not compare well. The 3-P Weibull shape parameter for the simulation and actual data are dramatically different. This is not surprising and can be explained by the fact that the Engelmaier model does not represent the process of failure in the JPL Qualification. The JPL Qualification temperature range exceeds the envelope of the model application. In addition, the JPL Qualification does not use a symmetrical test cycle. In order to represent the JPL test conditions, we must apply a more complex process of strain energy prediction and strain partitioning to represent the damage occurring in the solder. However, the process of simulation has provided much more information to assess the differences than in comparing two single point predictions. Simply comparing the estimated mean life allows us only to say that the Engelmaier model is in error.

**CONCLUSIONS**

While this research is preliminary, several conclusions can be drawn. This effort advances our understanding of physics of failure and shows the value of proper treatment of uncertainty and variation in reliability modeling. In addition, we can see that Monte Carlo simulation, as presented in Figure 2, is a valuable tool for implementation into a virtual qualification test scheme for electronic devices and assemblies. It is compatible with proper physics of failure assessment, while providing advantages of properly treating uncertainty. In addition, we that see much more information is available about the process of failure, from a Monte Carlo simulation.

This work also underscores other facts about qualification. Sample size is an extremely important issue in qualification testing. The accuracy of any prediction from test data is dependent upon initial sample size, by effecting the proper selection of a failure distribution and confidence in the data. However, we are often severely limited by cost in prototype development. Hence, simulation can be a valuable supplemental, low cost analysis process. In addition, we see that careful consideration must be given to selection of a failure distribution to model the uncertainty in product life. The distribution cannot be arbitrarily selected. Probability plotting and goodness fit tests can be valuable, provided we have a sample size to differentiate candidate distributions.

Specifically for BGA solder fatigue, we can draw some additional conclusions. The 3 parameter Weibull Distribution should be carefully considered for the analysis of qualification data, as seen from both actual and simulated data. This is consistent with findings of other investigators (Lau 1995). The 3 parameter Weibull may best represent fatigue failures in BGA solder joints, in comparison to the two parameter Weibull or log Normal. In addition, the Engelmaier Model has been shown not to represent the process of fatigue damage outside its intended envelope of 0-100$^{o}$C. In order to model test data outside this range, a more complex strain partitioning approach should be employed. In addition, simulating other package styles would require careful consideration of the simulation basis.

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