

Tin Whisker Reliability Assessment by Monte Carlo Simulation

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Abstract

Tin whiskers can grow between adjacent terminals of an electronic device causing electrical shorts. Concerns about the impact of this phenomenon have been widespread, but have not been quantified for reliability risk. We have created a Monte Carlo simulation to examine the failure rate of tin plated products due to whisker growth. The simulation uses statistical distributions of actual whisker lengths measured on plated products exposed to the iNEMI and JEDEC tin whisker test methods. These distributions were used to generate simulations of millions of whiskers, whose likelihood for creating an electrical short is simulated. We have found that the reliability risk is strongly related to the use of a nickel barrier material, post plating mechanical damage and the plating process used to create the tin plating. Projected failure rates, in terms of percent defect rates, are provided for various terminal finishes and terminal spacings.

I. INTRODUCTION

In the last few years, researchers have struggled to identify root causes for tin whisker growth, whisker mitigation practices and alternatives to tin/lead plating. It is well understood that tin whiskers pose a reliability risk for electronic circuits. It is also intuitive that this risk is greater when the spacing between conductors is decreased. However, we are not aware of any work in the literature aimed at quantifying the levels of risk that exist for failure due to tin whiskering.

Whisker growth rates are difficult to predict and measure. Traditionally reported tin whisker growth rates are in the range of 0.1 angstroms/S for pure tin systems and Chen *et al* recently reported much faster rates, 2-6 angstroms/second on tin-manganese films.¹ Predictions on the maximum whisker length obtained from a tin film are even more varied. Most reports on whisker length are empirical evidence of the longest whiskers for a given test condition.

These data are difficult to use to predict reliability. Tin whisker growth events seem to be frequent, when we examine whiskers growing on a finished component. However, if we examine the likelihood for tin whisker growth from a metallurgical perspective, it is a much more rare occurrence. For example, consider a tin plated sample with a nominal grain size of 2 μm , and a plated area of 1mm². This sample contains about 320,000 grains. If we measure a whisker density of 50 whiskers/mm² then this sample would grow 50 whisker grains out of 320,000 possible tin grains; this is 156 grains per million grains plated may be susceptible to whiskering. How many of these whiskers pose a risk of creating an electrical short with neighboring conductors?

II. TEST METHODS

Our approach to solving this problem is to use a statistical representation of actual whisker lengths to help predict the likelihood for failure. The test method has two independent portions: 1) growing and measuring tin whiskers and 2) simulating whisker failure rates numerically.

A. Growing tin whiskers

In order to understand the distribution of tin whisker lengths that may occur on tin platings, we needed to create tin plated samples that grew tin whiskers. Two samples were created. The first was one that was known to be likely to form tin whiskers, while the second has some levels of tin whisker mitigation applied to the plating process.

To make a sample that would have significant tin whisker growth, a sheet of C26000 (CuZn30) brass was electroplated with a matte tin that has been proven to whisker in previous testing.² The tin plating was nominally 3 μm thick and was plated directly onto the brass substrate.

The sample of whisker mitigated tin plating was a low stress, low carbon content (0.05% C) matte tin deposit that was plated over 1.27 μm of semi-bright nickel from a nickel sulphamate plating bath. The nickel was plated directly onto C51100 (CuSn4) phosphor bronze electrical contacts. The contacts were cut from the plating carrier strip then assembled into electrical connectors.

Both of the samples were then exposed to environmental aging conditions known to promote tin whisker growth. Three sets of samples were divided then exposed to room temperature aging, heat/humidity (60 C, 93% relative humidity) and thermal cycling (-40 to 85 C, air to air, 3 cycles per hour) as per the iNEMI recommended practices.³ In previous testing, we have found that heat and humidity conditions grew whiskers the fastest on copper base metal samples. Inspection of the samples after 6 months of aging (or 2500 cycles) showed some whisker growth on all of the samples, but once again, heat and humidity exposures were the most favorable for growing tin whiskers.

B. Measurement of tin whiskers

While each of the samples showed some degree of whisker growth, the lengths for room temperature exposure and thermal cycling were much smaller than the lengths for heat and humidity conditioned parts. Thus,

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we focused our measurements on the worst case conditions, the heat/humidity samples.

Each part was inspected by SEM for whisker length. The SEM measurement method is reasonably accurate due to the large depth of field, however there are some significant limitations. First, the tin platings used for this study are matte tin deposits. The surface is inherently rough due to the surface morphology of the growing tin grains and substrates. This limits the ability to measure very small tin whiskers (nodules) since they are difficult to discern from typical surface irregularities. The smallest tin whiskers measured in this study were 2.5 μm . Due to the nature of tin whisker growth and incubation of tin whiskers, the greatest percentage of tin whiskers measured was expected to be these very short tin whiskers.

For the highly whiskered part, a representative portion of the sample was selected for inspection, then every whisker in that region was measured. In this case, 267 whiskers were measured with a length range of 2 μm to 663 μm . The area over which these whiskers were observed was measured and the whisker density was computed to be 2381 whiskers/ mm^2 . An example of the observed whisker density is provided in Figure 1.

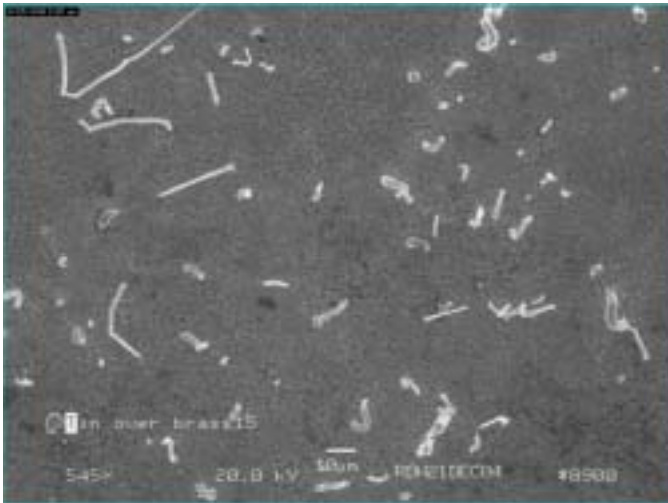


Figure 1. Tin whisker growth on a known whisker prone matte tin over brass.

For the whisker mitigated part, dozens of leads were inspected. Whisker growth was nil in most areas of the plated terminal. A series of whisker measurements were made in traditional areas of inspection and the maximum whisker length was 5 μm . This short length will not cause an electrical failure in any typical electronic component. Whisker growth is promoted by stress on tin deposits and as such, we were able to find longer whiskers growing at the end of the solder tail, where the plating carrier strip had been sheared from the terminal body. Thus, we used only the end of the solder tail as the area of inspection, which is the worst case scenario. We

measured every whisker on multiple leads, up to 250 μm from the end of the terminal. In this case, 103 whiskers were measured with a length range of 2 μm to 109 μm . The area over which these whiskers were observed was measured and the whisker density was computed to be 45.6 whiskers/ mm^2 .

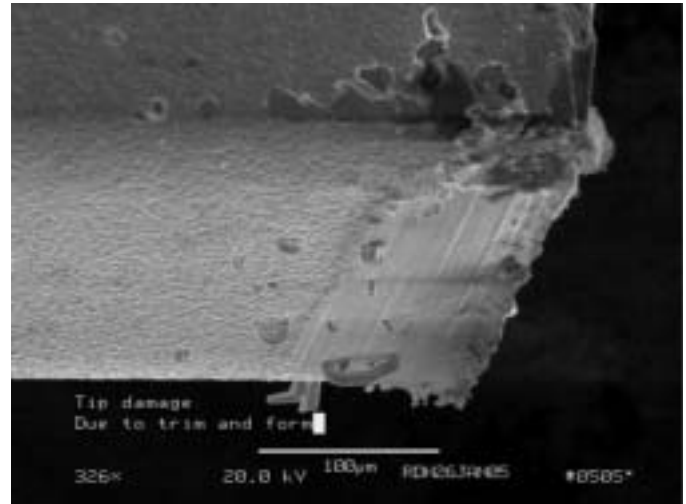


Figure 2. Tin whisker growth that occurs preferentially on the surface of the matte tin over nickel where the tin has been damaged during the carrier strip trimming operation. The left hand portion of the tin plating, which has not been disturbed, shows no evidence of tin whisker growth.

C. Simulating Tin Whisker Shorting

The intent of this work is to help predict the likelihood for electrical shorting between adjacent leads of a typical component. To form a framework for the analysis, we used a typical fine pitch component to establish suitable spacings between contacts and terminal areas that could potentially lead to shorting.

The Monte Carlo approach is useful since we can use the orientation variability to more realistically predict the likelihood for failure. Generating a 100 μm long whisker will not necessarily lead to a short in a conductor with 100 μm spacing. Any angle, other than normal to the terminal surface, will reduce the effective shorting length of the whisker and reduce the likelihood for shorting.

A few key assumptions were made in this analysis:

- 1) Whiskers do not grow to short to each other. Whiskers will only grow to touch another terminal. Based on our history of observation and presuming a low whisker density (true for mitigated tin whisker platings), the likelihood for two tin whiskers touching each other is very low.
- 2) For this analysis, the whiskers were presumed to grow as a filament and in a straight line. While this does not always happen, it is the worst case scenario since this produces the longest whiskers.
- 3) Whisker growth angles and orientations (described in greater detail below) were assumed to be random. The rotational angle is truly random. However, the angle of inclination between the plated surface and the whisker growth is restricted. In our analysis we assume 0 to 89 degree freedom in this angle. SEM observations suggest that this angle is more commonly between 0 and 80 degrees, but whiskers have been infrequently observed to grow nearly parallel to the plated surface.

These three key assumptions are reasonable based on our history of whisker observation and our desire to examine those scenarios at greater risk for tin whisker growth.

A Mathcad® program was written to simulate whisker formation. Referring to Figure 3, an original rectangular area, A1, and opposing parallel area, A2, are defined based on the dimensions of a particular connector. The thickness is the copper strip thickness of the contact solder tail and the Length is the length of the tail at the minimum separation distance, Separation D. The areas A1 and A2 therefore represent the closest spacing separation areas between two opposing contacts. The number of whisker locations in A1 is calculated using a measured whisker density, described above. The location (x1,y1) of each whisker is randomly generated using random number functions available in Mathcad®. Additionally, the random functions were used to identify a whisker rotation angle θ , from 0 to 360 degrees and an inclination angle Φ , from 0 to 89 degrees, for each whisker. A critical whisker length, *critl*, is defined as the length necessary for each individual whisker to touch an infinite parallel plane at the appropriate separation distance. The distances x2 and y2 are calculated from the critical length, rotation and elevation angles. These distances are added to the original location to give the location for touching the parallel plane in x1,y1 coordinates. These “touching locations” are truncated to include only those that are located within the thickness of the original area. Values outside the length of the original area were not excluded since it was reasoned that the contact does extend in the length direction but at a greater separation distance. This assumption was adopted as a conservative approach.

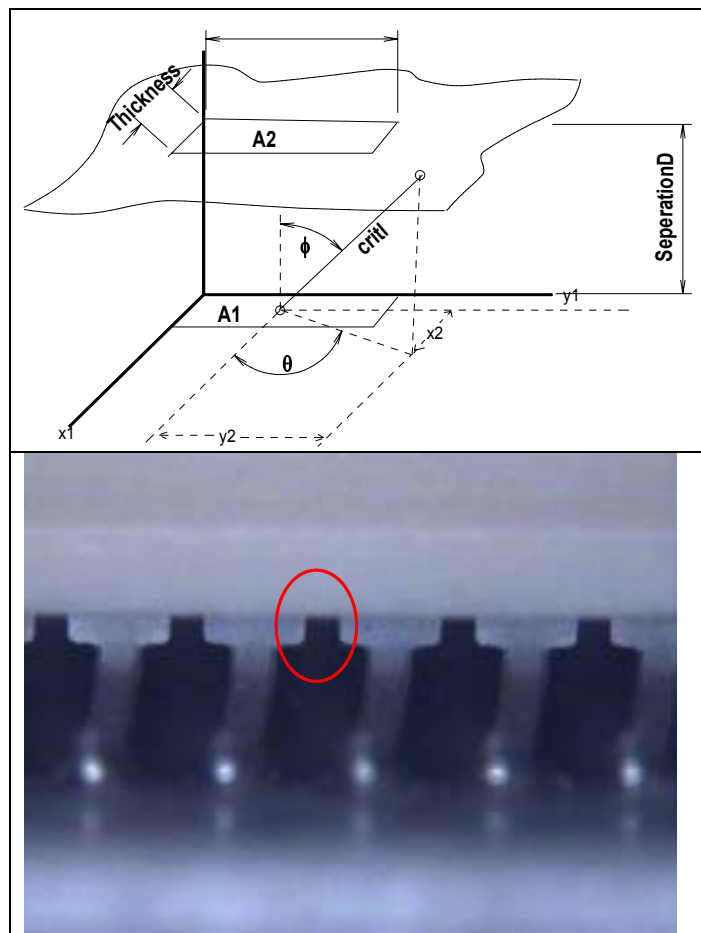


Figure 3. (Top) Schematic of the spacing between adjacent conductors and the geometry of tin whisker growth used for the simulation. (Bottom) Picture of a SMT component with fine pitch between leads and the areas used for this study.

D. Statistical Distributions of Whiskers

Actual whisker lengths were simulated by mathematically generating a distribution based on a best possible fit to experimentally observed whisker length data. Tin whisker growth data is not normally distributed. This is due to the nature of tin whisker growth and the experimental difficulties involved in measuring very small whisker lengths (for which there are many). The two whisker distributions were mathematically fit to a variety of statistical distributions in an attempt to find a distribution that generally fits the data but also represents the extremes of the data well. Fundamentally, we are not very concerned about modeling whiskers that are very short, or even medium in length. The longest whiskers are those that are most likely to cause failures. Further, it is likely that whiskers longer than those observed in our experimentation will grow on some samples (on a statistically large enough sample); thus predicting the longest whiskers that could grow with this type of distribution was important. This approach has been used previously to study etch pit depths in nuclear waste containers.⁴

The statistical package MINITAB[®] was applied to the sample populations of whisker lengths to test for normality and to fit the distributions. While a log normal distribution was originally considered, it had poor fit, especially at the extremes. For these experiments, both the low density and high density whisker distributions best fit Johnson Transforms.⁵ That is the transformed whisker length data was assumed to be normally distributed and as such the random normal probability function within MathCad[®] could be used to produce a simulated population of whisker lengths after applying an inverse Johnson Transform.⁶ The formulas we used for the Johnson Transformation were S_B and S_U and are as follows.

$$S_B = \gamma + \eta \cdot \ln\left(\frac{X - \varepsilon}{\lambda + \varepsilon - X}\right)$$

$$S_U = \gamma + \eta \sinh^{-1}\left(\frac{X - \varepsilon}{\lambda}\right)$$

For the mitigated low density distribution consisting of 103 data points, the S_B transformation was applied, leading to a P-value of 0.656 with $\gamma=4.42865$, $\eta=0.920594$, $\varepsilon=1.08831$ and $\lambda=569.8497$. For the high density non whisker mitigated tin distribution consisting of 267 data points, the S_U transformation was a better fit and produced a P-value of 0.29105 with $\gamma=-3.15904$, $\eta=0.665433$, $\varepsilon=1.79036$ and $\lambda=0.199948$. A P-value for an Anderson-Darling test ≥ 0.1 is generally considered a reasonable fit. This is a 90% Confidence that a Type II error (incorrectly assuming that the transformed distribution is Normal) does not occur. Both of these distributions meet that criteria and can be considered a good fit to the data.

Figure 4 shows a comparison plot of ordered original whisker length data (ranked from smallest to largest on the x-axis and shown as data points) and of simulated data (shown as a dashed line drawn through the data) for the mitigated low whisker density plating. The simulation data is a good fit of the experimental data. In this image, we have simulated thousands of whiskers, so we can see that the dashed line extends beyond the observed whisker distribution.

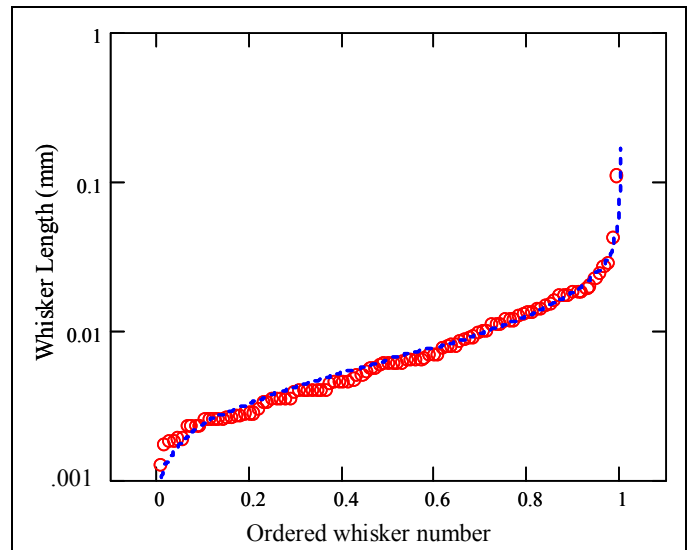


Figure 4 Comparison plot of ordered original whisker length data (circles) and S_B simulated data (dashed line) for the whisker mitigated, low whisker density plating.

Figure 5 shows a similar whisker distribution for the unmitigated tin whisker distribution. Again the correlation between the simulation and the experimental data is good.

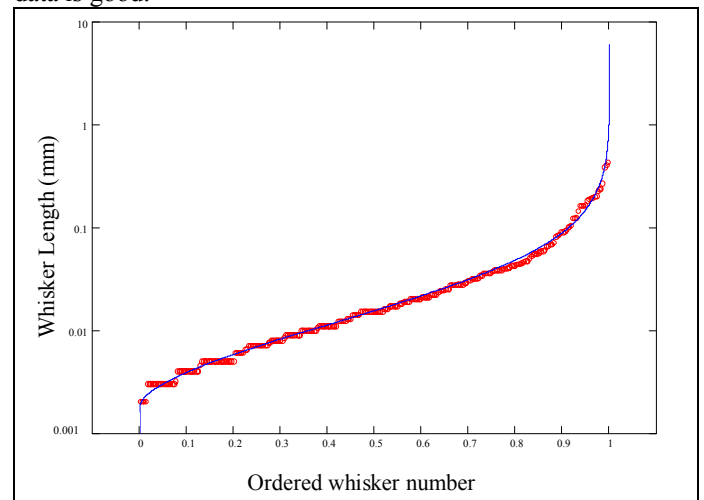


Figure 5 Comparison plot of ordered original whisker length data (squares) and S_U simulated data (dashed line) for the non-whisker mitigated, high whisker density plating.

E. Predicting Electrical Shorts

Mathcad[®] was used to simulate tens of millions of tin whiskers growing at random locations on terminals of varying spacing and with the two whisker distributions. The simulated actual whisker lengths were compared to the lengths required to “touch” the adjacent terminal. A whisker length equal to or larger than the corresponding touching length was identified as a failure (a potential electrical short). One whisker failure defines failure for the entire area and also for the entire component.

This process was repeated to match the number of areas with the corresponding available areas (terminals) in a component. One area failure defines a component failure. Conversely, a passed component has no failures for any of the areas of the terminals in the device. Components with various numbers of terminals were tested to understand the impact of I/O count to failure risk.

Finally, this process is repeated many times to simulate the statistics for possible component failure. Appendix 1 shows a flow chart describing the logic of the Mathcad® simulation program.

III. RESULTS

The whisker mitigated tin plating, used for part of this study, did not form any whiskers in *unstressed* areas of the terminal finish. As a result, modeling the failure rate for this case is a trivial solution and was not pursued. Terminal spacings would need to be in the range of 10 μm in order to create any significant failure rates. As such, we focused on the failure rates for non-tin whisker mitigated tin and whisker mitigated tin, which had been *stressed* by post plating trimming of the base metal.

Figure 6 shows the simulated failure rate in percent of a 232 area component using non-tin whisker mitigated tin plating over brass. From this chart, it is clear that this is not a recommended practice for fine pitch products. In order to achieve failure rates of less than 1%, the spacing between conductors needs to be greater than 6mm. As can be seen from this chart, the distribution has the expected 'S' shape where the slope increases dramatically as you approach 0 percent failure rates.

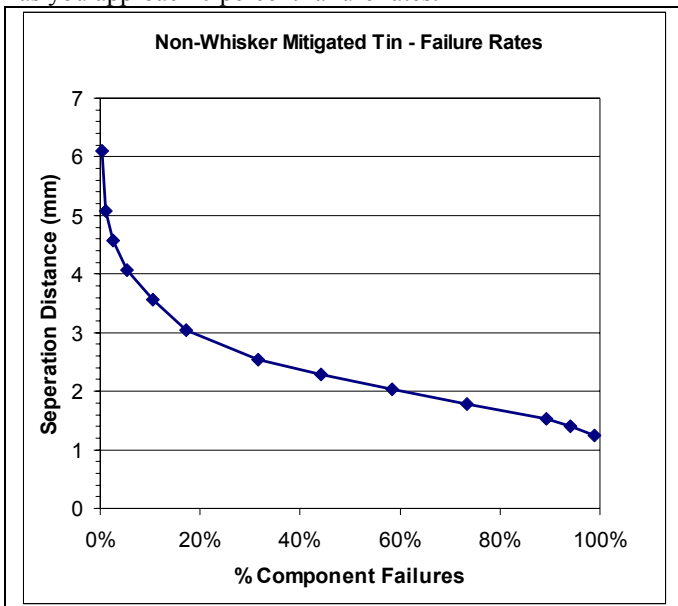


Figure 6. Simulated component failure rate as a function of terminal separation distance for a non-whisker mitigated tin plated component.

Normal electronic components are targeting ppm defect levels. However, these simulated failure rates are much

higher (i.e., they are presented in terms of percents in stead of ppm). This chart simply quantifies the phenomena with which many researchers are already familiar: tin whiskers can lead to electrical shorts in fine spaced electrical components.

By comparison, we can chart the failure rate of whisker mitigated tin plating, as shown in Figure 7. Using the same axes, we have added the whisker mitigated rates as a pink line. For equivalent spacing between conductors, the failure rates are much lower for the whisker mitigated tin. This work was completed by simulating 500 components with 232 areas per component. While this simulation produced millions of whiskers, and hence opportunities for shorting, most of the whiskers were very short and thus the simulation did not have sufficient resolution to demonstrate ppm level failure rates. Figure 8 shows the simulated failure rates for whisker mitigated tin plating with greater resolution of the y-axis (separation distance between conductors), but the rates are still provided in terms of percents.

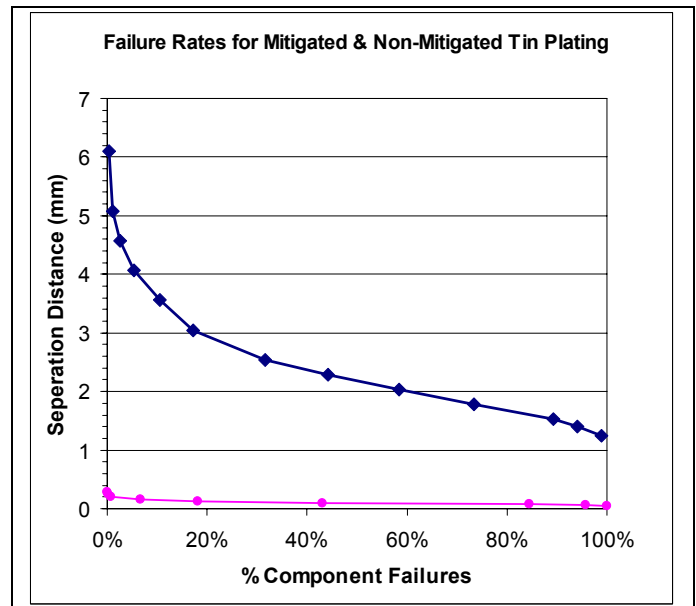


Figure 7. Simulated component failure rate as a function of terminal separation distance for a non-whisker mitigated tin plated component (blue line) versus whisker mitigated tin (pink line).

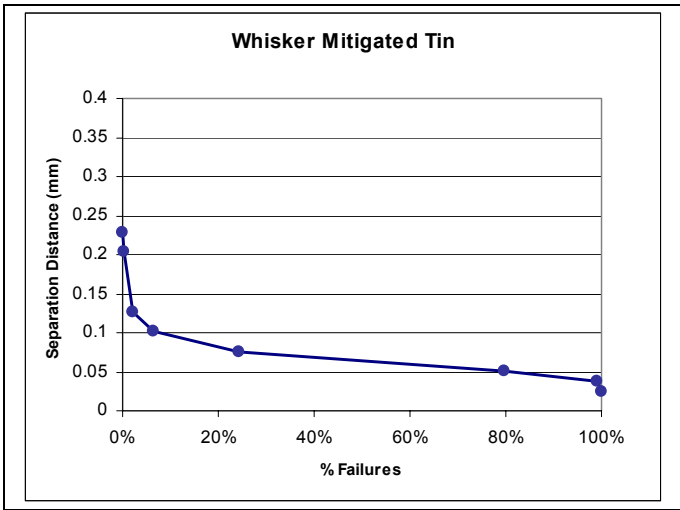


Figure 8. Simulated failure rate chart of whisker mitigated tin plating with greater resolution in Y-axis. Chart was created simulating 500 connectors with 232 areas per connector.

In order to improve the resolution of curve at low and desirable ppm levels of failure rates, the simulation was expanded. In order to get to 100ppm levels of failure rates, we needed to simulate 10,000 components per lead spacing with 232 areas per component. Due to the large number of whiskers that would have to be simulated for the non-whisker mitigated tin, this portion of the simulation could not be accomplished using the available simulation tools. Thus, we only simulated the whisker mitigated tin.

Figure 9 shows the higher resolution simulated failure rates for whisker mitigated tin. The line depicting the failure rate is somewhat jagged, which demonstrates the low number of failures used to create these results. 100ppm failure rate is equivalent to one component failure in the 10,000 components simulated at that lead spacing. This chart shows that for regions where the tin is whisker mitigated but has been stressed, a spacing of about 380 μm is required to get to 0ppm failure rates in this particular component.

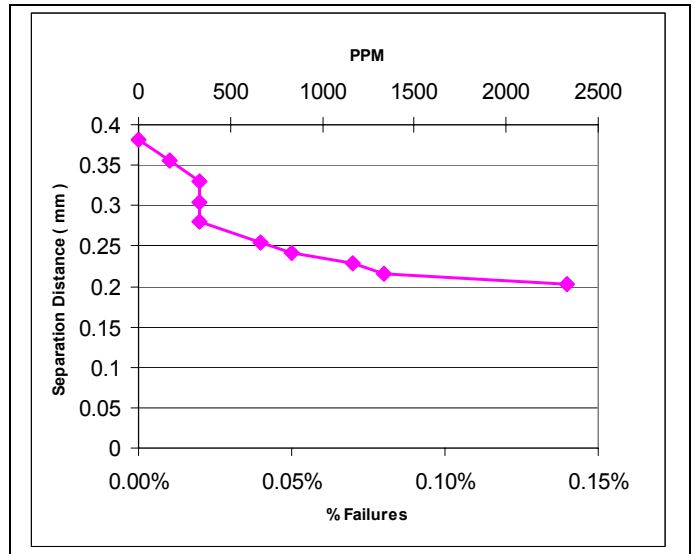


Figure 9. Simulated failure rate chart for whisker mitigated tin showing greater resolution at low defect levels. A separation distance of about 380 μm is required to get to 0ppm failure rates.

The component of interest in this study had 232 areas that were susceptible to tin whisker shorting. To get a rudimentary understand of the impact of I/O count, the simulation was also performed as if the component had just 2 areas of I/O. Figure 10 shows the failure rates for the previously described 232 area component as well as a 2 area component (in pink). For equivalent terminal spacings, the likelihood for failure is much lower in the low I/O component than for the high I/O component. There have been reports that some 2 position devices, such as capacitors, are less likely to whisker and many of these devices converted to pure tin plating a decade ago. The results from this work might suggest that the whisker growth may be equivalent, but the likelihood for failure (based on the number of I/Os and the relative spacing of the conductors) is relatively small.

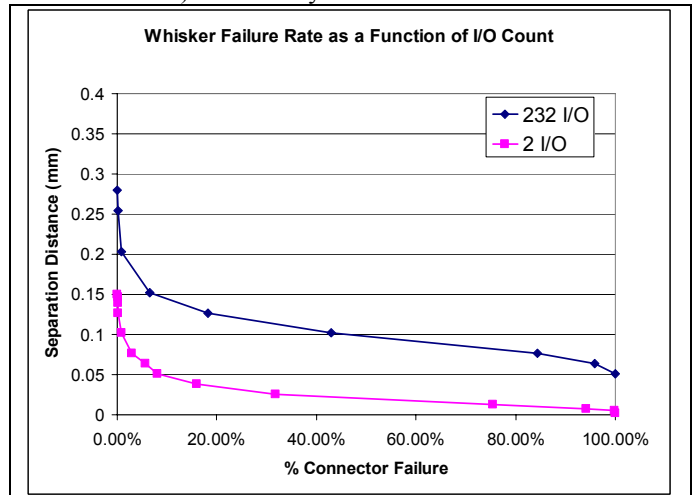


Figure 10. Simulated whisker failures rates for whisker mitigated tin for two different I/O count components. Failure rate is non-linearly related to I/O count.

IV. CONCLUSIONS

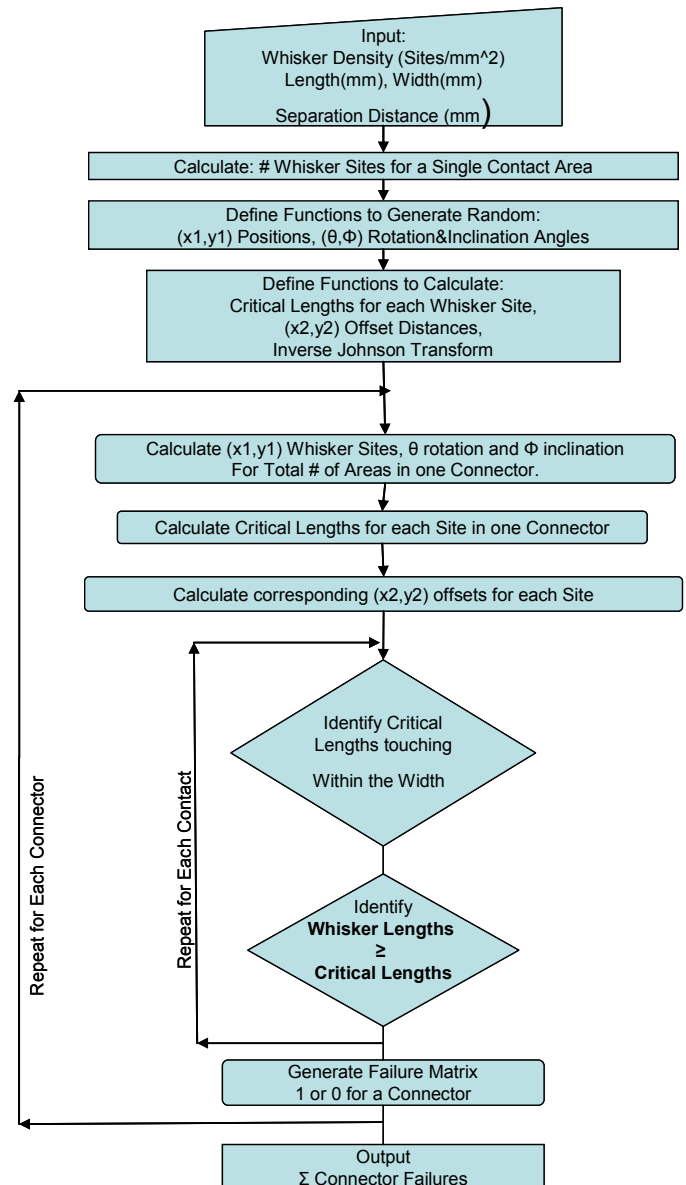
Monte Carlo simulation techniques have been used to predict failure rates for electrical components due to tin whisker growth in tin platings. The following conclusions can be drawn from this work:

1. Tin whiskers are a reliability risk for many electronic devices.
2. Tin platings that do not incorporate whisker mitigation strategies are particularly prone to grow long whiskers that can lead to electrical shorts.
3. Tin whisker mitigation techniques, such as those used here, reduce the likelihood for failure, especially in fine spaced electronic components.
4. Simulated failure rates were lower for components with smaller I/O counts and the relationship between I/O count and failure rate is non-linear.
5. Simulated failure rates in the ppm range are achievable in tin plated electronic components of typical fine pitch spacing.
6. Using measured tin whisker distributions helps to statistically describe the propensity of a tin finish to grow tin whiskers.

ACKNOWLEDGMENT

The authors wish to thank Karen Benjamin of Tyco Electronics for her assistance with statistical interpretation and Rick Perko for his continuing support of tin whisker research at Tyco Electronics.

APPENDIX 1



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⁵ This is not that surprising since the Johnson Transformation is one of the methodologies employed in extreme value statistics. For additional information, see for example, Wadsworth, H. M., "Handbook of Statistical Methods for Engineers and Scientists", McGraw Hill, 1990, pg. 6.29

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