SERDP TIN WHISKER TESTING AND MODELING: SIMPLIFIED WHISKER RISK MODEL DEVELOPMENT

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ABSTRACT

Most commercial electronics manufacturers began a large-scale movement toward tin rich finishes and solders in 2006 due to European Union Reduction of Hazardous Substances (RoHS) legislation banning lead. Unfortunately, this can create an increased risk of tin whisker induced electrical failures, particularly for defense and aerospace equipment using commercial off the shelf (COTS) items. This paper presents a statistical tin whisker short circuit risk modeling framework for surface mount assemblies having various combinations of tin-lead and lead-free materials. While industry and academia have not developed a robust model correlating whisker length to environmental exposure, the framework does include the results of the multi-year SERDP testing program that is assessing tin whisker growth on lead-free manufactured assemblies in various environments. Since tin whisker length data is expected to mature over the next decade as more measurements are made in the field, a novel technique is employed to facilitate rapid recalculation of short circuit risk as new whisker growth characteristics become available. This is achieved by first determining the geometric lead-to-lead spacing characteristics for various parts. The geometric modeling includes manufacturing variation not readily apparent from the drawings such as printed wiring board conductor spacing reductions due to etching and bulbous solder that decreased conductor-to-conductor spacing. The spacing distributions are then compared to the whisker growth length distribution to determine the probability of a bridging occurrence. Then, the short circuit probability is determined for a given circuit voltage by using NASA data. The computational framework is also used to evaluate the effectiveness of tin-lead hot solder dip and partial conformal coating whisker mitigations.

Key words: Tin Whiskers, Lead Free, Assembly, Testing, Short Circuit Risk Modeling, Statistics

BACKGROUND ON PRIOR WORK

The tin whisker short circuit condition requires that a whisker grow from one lead to an adjacent lead and then conduct sufficient electrical current to cause a fault [1]. A schematic illustration of whisker between leads is shown in Figure 1. The first part of the analysis was to create a probabilistic spacing model for various packages that is independent of time (e.g. only dependent upon the lead geometry). The spacing distribution was then cross-correlated the whisker length distribution to establish the bridging probability

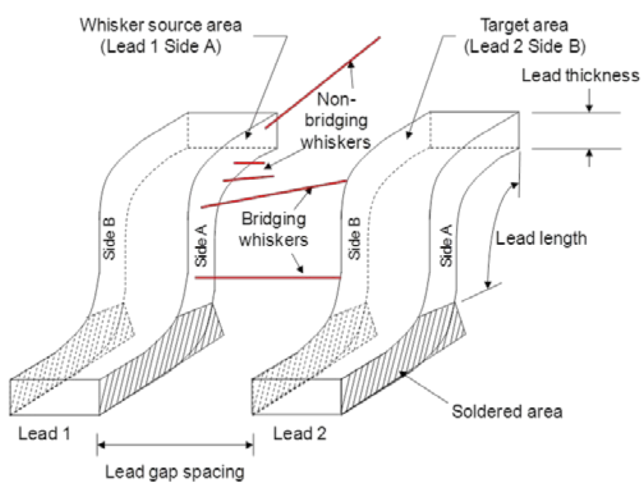


Figure 1: Tin whisker bridging [1].

Whisker risk was assessed by developing a Monte Carlo model of the relevant lead geometries in a method similar to that used others for parallel plates [2][3][4]. The current approach used a simplified actual lead geometry and leveraged the efficiencies of Crystal Ball ™ software specifically developed for Monte Carlo analysis. The model inputs and outputs along with the general calculation flow are summarized in Figure 2.

The simplified whisker model is currently limited to gull-wing type leads on flat packs or quad flat packs (QFPs) (see Figure 3). The gull wing leads represent one of the higher risk circuit card features because of the closes spacing and large parallel tin surfaces. The geometric modeling can easily be extended to other geometries.

A key benefit of separating the whisker "length independent" geometric modeling is that a reduced number of Monte Carlo simulations are needed. In a conventional Monte Carlo whisker bridging calculation, a whisker having a selected length and growth angles would be "grown" from selected point on the source and one would determine if it "hit" the target. Thus each combination of lead geometry and whisker length requires a Monte Carlo simulation. However in the present work, the Monte Carlo analysis is used to determine the specific "distribution of spaces" that a hypothetical whisker could bridge across (see Figure 4) for each lead configuration assuming a uniform whisker angle distribution (see *Whisker view factor section* for further discussion on this assumption). Then the resulting spacing distribution is compared with the whisker length distribution to determine the whisker bridging probability. The overall model was also extended to include the whisker short circuit dependence on voltage.

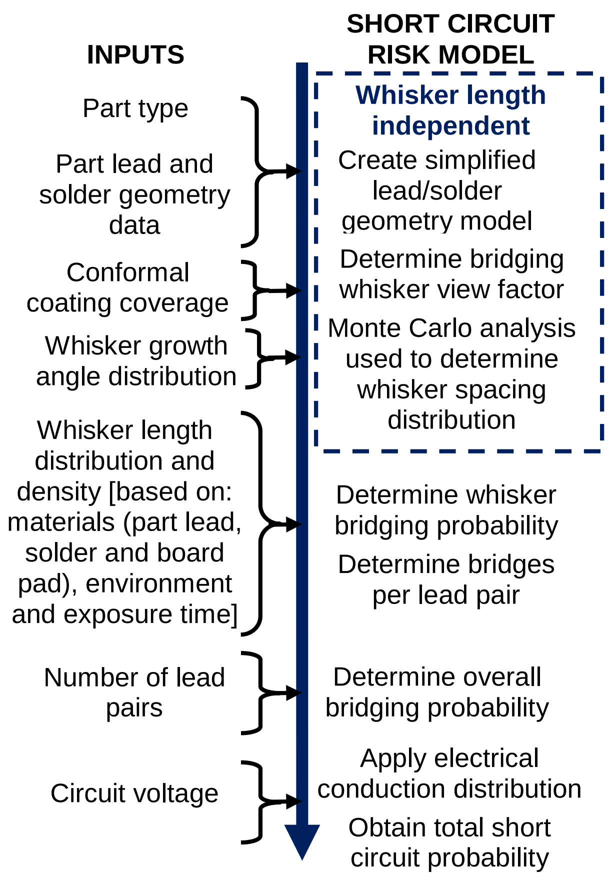


Figure 2: Short circuit risk model in**p**uts and modeling analysis step details for a given part.

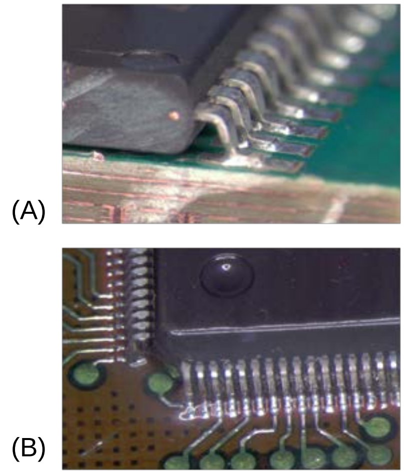


Figure 3: Part types used for the bridging risk simulation; (A) photograph of a flat pack with one end ground away to reveal the metal regions behind the lead, and (B) photograph of a QFP part corner with conformal coating.

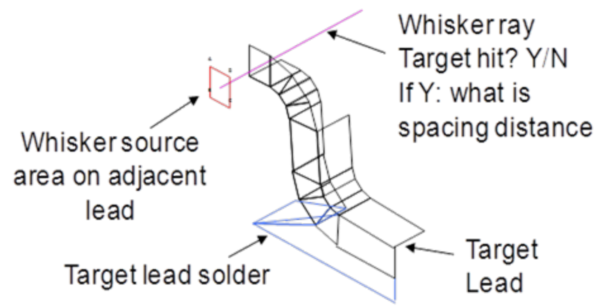


Figure 4: Spacing distance for a bridging whisker.

Lead geometry modeling

The geometric modeling uses a simplified lead geometry simulating the general lead form, but with sharp corners as shown in Figure 5. Datasheet dimensions for the gull-wing parts were reduced to the following part dimensions:

- Lead span length (L_L)
- First bend distance (A)
- First bend height (H)
- Lead foot length (f)
- Lead thickness (t)
- Lead width (W_L)

MODIFICATIONS TO EXISTING WHISKER RISK MODEL

The whisker risk Monte Carlo model described in the prior SERDP work [1] was modified based on recent lead-free assembly tin whisker testing at 85 °C and 85 percent relative humidity (85C/85RH) [5] that generated over 75,000 whiskers after 4,000 hours of testing (see Figure 6). The following items were incorporated:

- Whisker generation from the side of the printed wiring board pad (PWB) pad
- Addition of a bulged area of the solder beyond side of PWB pad
- Use of a single lead/solder/pad configuration to for source and target whiskers in conjunction with a “whisker mirror”
- Several whisker length distributions for different parts of the solder joint can be used, depending upon lead material and environment [5][6]
- Added capability for Cauchy, log-Cauchy, Weibull, and numerical whisker length distributions, and added a third parameter to some distributions as applicable
- Added the short circuit probability calculation for a particular circuit voltage [7] and bridging probability

The updates to model geometry (see Figure 5) will be discussed next, which will be followed by a discussion of the distributions and the short circuit probability calculation.

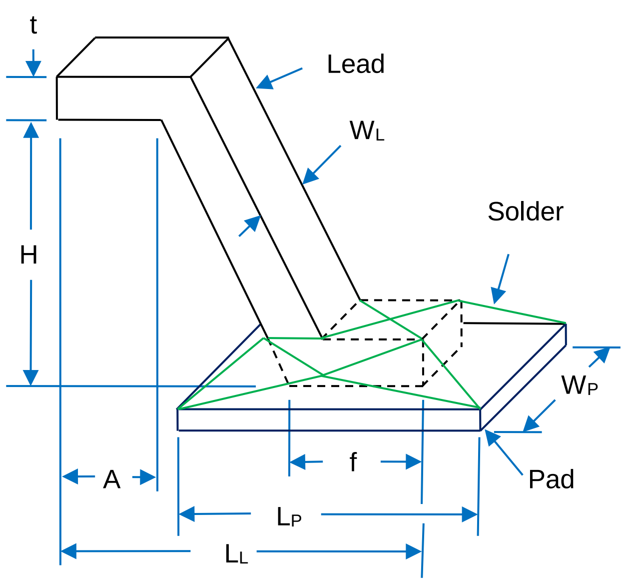


Figure 5: Simplified geometry

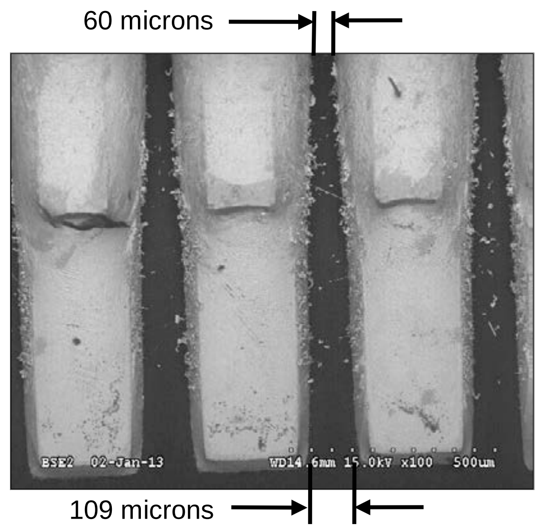


Figure 6: Whisker growth from board pad edge and reduced spacing due to solder bulge.

PWB pad

Because testing identified significant whisker growth originating from the side of the PWB pad, the side of the PWB pad was added to the whisker risk model. In the present work, the printed wire board pad thickness is modeled to be 0.063 mm, typical of complex assemblies with multiple via and surface plating operations, and is centered about the lead foot. This involved adding four triangles at the side and inside edges of the PWB pad. Because whiskers originating from the outside edge of the PWB have no capability to generate a bridge, these areas were not included.

Solder bulge

The solder in the original model and the revised model goes from the top of the board pad to the top of the lead foot and on top of the lead foot. This represents a minimum heel fillet for a J-STD-001 Class 3 joint [5], which is conservative. However, the model is non-conservative because side and toe solder fillets are included in the model even though they are not required by J-STD-001. Observation and measurement of some typical SAC305 lead-free soldered assemblies indicated bulging of solder adjacent to the soldered lead with a corresponding reduction in spacing (see Figure 6) [5]. This involved adding four triangles to represent the solder bulge. The maximum bulge location is modeled to be half way up the solder (see Figure 5).

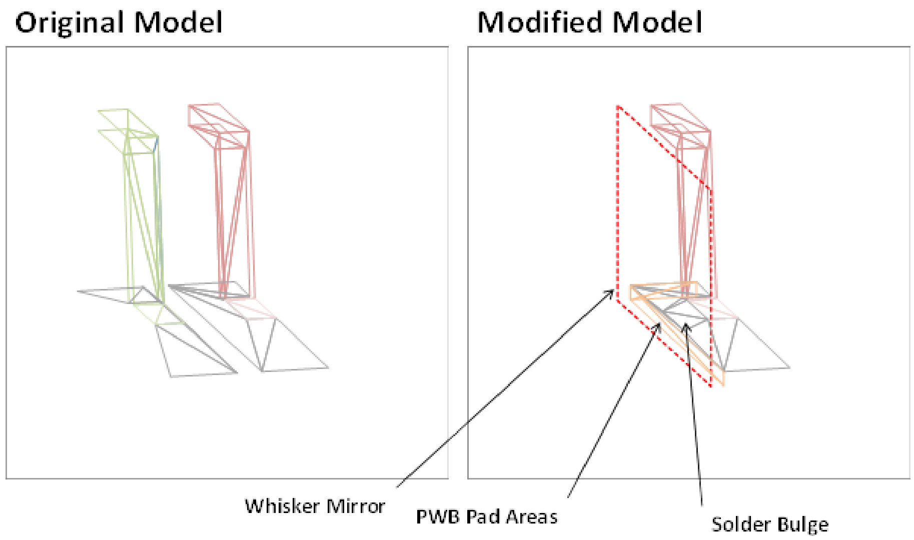


Figure 7: Modifications to whisker risk model

Whisker mirror

The original model generated the geometry for two separate leads based on the lead pitch. To simplify the addition of the areas described above, a whisker mirror (see Figure 7) is used in between the lead locations to allow an identical lead to be represented without actually generating the geometries. The specific whisker vector is reflected by reversing the vector component perpendicular to the whisker mirror. Because an Excel lookup table is used to detect the contact between the reflected whisker and the lead/solder/pad, the Extreme Speed option was no longer functional with the Oracle Crystal Ball™ Monte Carlo software so the computation speed was somewhat slower. The performance of the whisker mirror was compared with the original model to verify the accuracy of the whisker mirror concept.

Whisker length distributions

The original model used different lognormal distributions for whiskers originating at the lead and solder. To support the pad whiskers (see *PWB pad* section) a separate distribution for pad whisker length was added.

Three-parameter lognormal distribution

The probability density function for the lognormal distribution is given by the following equation:

x_0 = Minimum

μ = Location parameter

σ = Scale parameter

$$f(x) = \frac{1}{(x - x_0)\cdot\sigma\cdot\sqrt{2\cdot\pi}} \cdot e^{\left[-\frac{\left(\ln(x - x_0) - \mu\right)^2}{2\cdot\sigma^2}\right]}$$

Three-parameter log-Cauchy

The probability density function for the log-Cauchy distribution is given by the following equation:

x_0 = Minimum

μ = Location parameter

σ = Scale parameter

$$f(x) = \frac{1}{(x - x_0)\cdot\pi} \cdot \left[\frac{\sigma}{\left(\ln(x - x_0) - \mu\right)^2 + \sigma^2}\right]$$

Cauchy distribution

The probability density function for the Cauchy distribution is given by the following equation:

x_0 = Location parameter

γ = Scale parameter

$$f(x) = \frac{1}{\pi\cdot\gamma\cdot\left[1 + \left(\frac{x - x_0}{\gamma}\right)^2\right]}$$

Weibull distribution

The probability density function for the Weibull distribution is given by the following equation:

x_0 = Minimum

α = Characteristic Life

β = Shape parameter

$$f(x) = \frac{\beta}{\alpha}\cdot\left(\frac{x - x_0}{\alpha}\right)^{\beta - 1} \cdot e^{\left[-\left(\frac{x - x_0}{\alpha}\right)^{\beta}\right]}$$

Numerical distribution
Because some measurements indicated a small but significant fraction of very long whiskers beyond those represented by some calculated distributions [5][6], the capability for a numerical distribution of whisker length was added. The numerical distribution is entered by providing a cumulative percentage and corresponding length. The cumulative numerical distribution is numerically differentiated to obtain a probability density function (PDF) with intermediate values linearly interpolated. The interpolated PDF is used in place of the calculated PDF in the whisker bridging probability calculation.

Location (third) parameter
The location parameter is a finite minimum length such that no whiskers are shorter than that length. Although there is some controversy over the use of a third location parameter in logarithmically based distributions and the third parameter is difficult to fit, a third parameter was added to provide additional flexibility to consider a minimum length whisker. The location parameter was added to the lognormal, log-Cauchy, and Weibull distributions.

Whisker short circuit probability
As demonstrated by Courey [7], not all whisker bridges resulted in shorts. The tip of the whisker can have varying thicknesses of oxide, which decreases the probability of electrical shorting. In the present work, the bridges calculated are multiplied by the shorting probability based on applied voltage from Figure 8. For example, the shorting probability is 41.4% for a five volt bias.

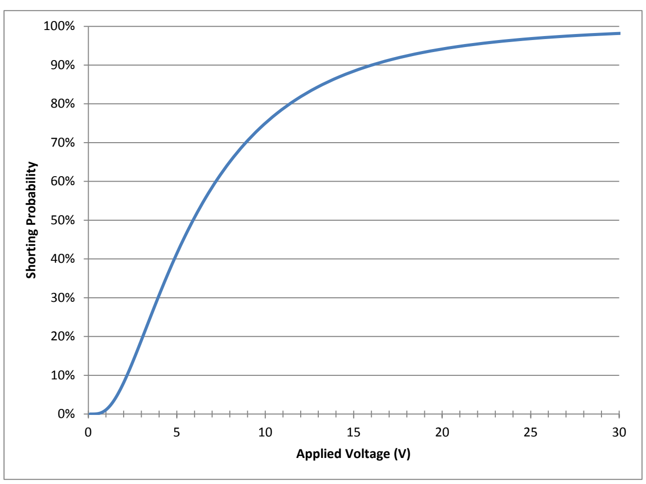


Figure 8: Probability of a bridge shorting (from Courey [7]).

WHISKER RISK DATA SUBSET
The general approach for developing the simplified whisker risk model was to develop generic relationships based on view factors and spacing distributions developed from a subset of lead geometries.

Specific lead geometries used were:
- SOIC (1.27-mm pitch)
- 0.65-mm pitch
- 0.5-mm pitch
- 0.4-mm pitch

For the 0.5-mm pitch geometry, thick and thin packages were considered with additional consideration given to long and nominal leads for thick packages. Typical dimensional tolerances (max., min., nominal) as provided in part drawings were also included. The specific list of packages and dimensions used is provided in Table 1.

Monte Carlo modeling was conducted for the listed parts/geometries for uncoated and partially coated leads. Partial coating is defined as follows:
- 90% effective on outside of lead
- 50% effective on sides of lead
- 0% effective on back/inside of lead

Separate calculations were performed for whiskers sourcing at the PWB pad, lead, and solder. A solder bulge based on a pad spacing reduction of 49 microns (see Figure 6) was considered to act at 50 percent of the lead thickness.

SIMPLIFIED MODEL DEVELOPMENT
Development of the simplified model was based on developing whisker view factor and spacing distribution based on lead and pad dimensions. All calculations were based on the use of dimensionless parameters to avoid complications in the simplified model due to selection of units.

Whisker view factor
The whisker view factor represents the probability that an infinite whisker will bridge between adjacent leads. All of the calculations were implemented in Microsoft Excel™ which is also the platform for the Crystal Ball™ software. Five probability distributions were used with random variables to generate the simulated whiskers as follows:
- Source area lookup – determines which source triangle is used to generate the whisker (scaled by area of triangle) – uniform distribution
- Triangle base fraction – determines position along the base of the source triangle – Uniform distribution
- Triangle side fraction – determines position from the triangle vertex (opposite the base) to point along the base – Triangular distribution
- Whisker angle from normal – Uniform distribution (see text)
- Whisker azimuth – Uniform distribution

An additional uniform random variable is used in conjunction with the conformal coating effectiveness on the applicable target surface to determine if a bridge occurred. A uniform distribution was selected for the whisker angle from the normal based on discussions among the investigators over the apparently conflicting results obtained by Susan [10] and Fang [11]. Each Monte Carlo calculation used one million simulated whisker trials with the results filtered for infinite whiskers resulting in a potential bridge. As shown in Figure 9, the ratio of potential bridges to the overall trials determined the whisker view factor for one lead to the other and a cumulative spacing distribution was developed for those whiskers indicating a bridge.

A trial and error method in conjunction with the Excel solver was used to develop a metric that has best correlation to whisker view factor based on dimensional calculations derived from part/pad data.

Table 1: Parts and dimensions considered (dimensions in mm).

Part - variant	Package Height	Pkg. Seating Plane	PWB Pad Length (L_P)	PWB Pad Width (W_P)	Lead Span Length (L_L)	Lead Foot Length (f)	Lead Thick. (t)	Lead Width (W_L)	Lead Pitch
SOIC-nominal	2.34	0.205	2.16	0.7	1.385	0.815	0.275	0.415	1.27
SOIC-max	2.35	0.29	2.16	0.7	1.495	1.02	0.32	0.48	1.27
SOIC-min	2.29	0.12	2.16	0.7	1.285	0.61	0.23	0.35	1.27
0.65mm-nominal	1.05	0.1	1.587	0.49	1	0.625	0.15	0.245	0.65
0.65mm-max	1.05	0.15	1.587	0.49	1.15	0.75	0.15	0.3	0.65
0.65mm-min	1.05	0.12	1.587	0.49	0.85	0.5	0.15	0.19	0.65
0.5mm-Long/Thick-nominal	3.4	0.375	1.762	0.37	1.3	0.6	0.145	0.22	0.5
0.5mm-Long/Thick-max	3.6	0.5	1.762	0.37	1.3	0.75	0.2	0.27	0.5
0.5mm-Long/Thick-min	3.2	0.25	1.762	0.37	1.3	0.5	0.09	0.17	0.5
0.5mm-Thick-nominal	1.4	0.1	1.64	0.37	1	0.6	0.145	0.22	0.5
0.5mm-Thick-max	1.45	0.15	1.64	0.37	1	0.75	0.2	0.27	0.5
0.5mm-Thick-min	1.35	0.05	1.64	0.37	1	0.45	0.09	0.17	0.5
0.5mm-Thin-nominal	0.8635	0.1015	1.589	0.37	0.95225	0.5465	0.145	0.235	0.5
0.5mm-Thin-max	0.965	0.152	1.589	0.37	1.13	0.699	0.2	0.27	0.5
0.5mm-Thin-min	0.888	0.051	1.589	0.37	0.7745	0.394	0.09	0.177	0.5
0.4mm-nominal	1.4	0.1	1.64	0.291	1	0.6	0.145	0.18	0.4
0.4mm-max	1.45	0.15	1.64	0.291	1	0.75	0.2	0.23	0.4
0.4mm-min	1.35	0.05	1.64	0.291	1	0.45	0.09	0.13	0.4

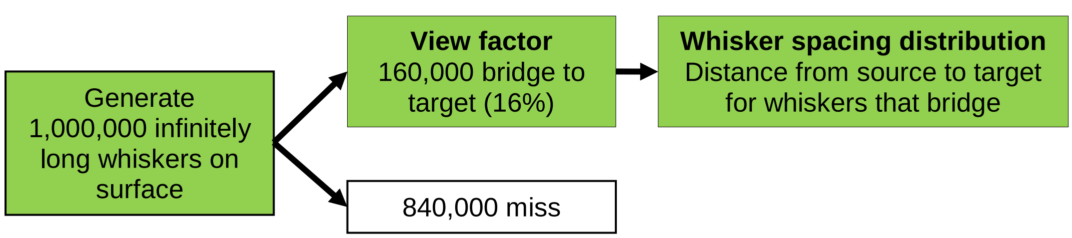


Figure 9: Example of a QFP lead view factor and whisker spacing distribution calculation flow.

Lead whisker uncoated view factor

The view factor for whiskers originating at the lead surface is based on the following metric (M_L):

s = Lead spacing

t = Lead thickness

A_W = Whiskerable area

A_S = Single sided area

$$M_L = \left(\frac{A_S}{A_W + s^2}\right)^{1.421215} \cdot \left(\frac{t}{s}\right)^{1.153123}$$

A plot providing the modeled view factor as a function of the above metric and the derived equation is provided in Figure 10.

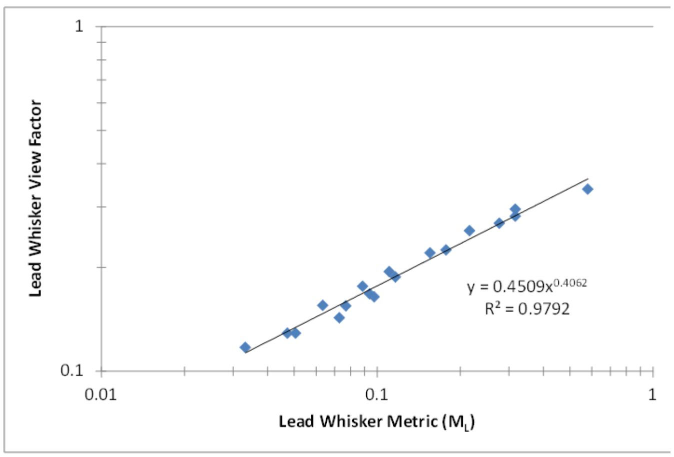


Figure 10: Lead whisker view factor correlation

Solder whisker uncoated view factor

The view factor for whiskers originating at the pad surface is based on the following metric (M_S):

s = Lead spacing

t = Lead thickness

A_W = Whiskerable area

$$M_S = \left(\frac{A_W}{s^2}\right)^{-0.50606} \cdot \left(\frac{t}{s}\right)^{1.97517}$$

A plot providing the modeled view factor as a function of the above metric and the derived equation is provided in Figure 11.

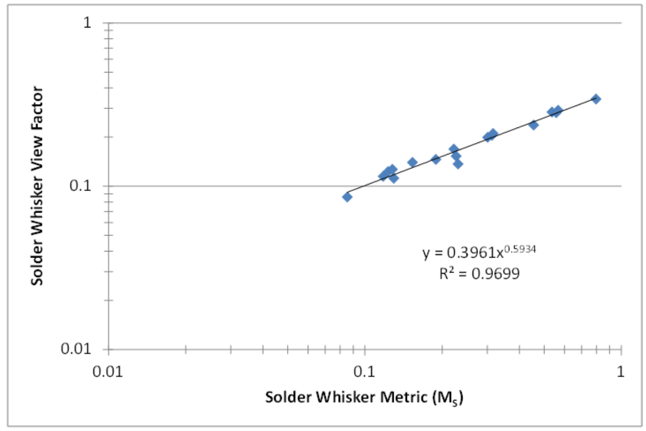


Figure 11: Solder whisker view factor correlation

Pad whisker uncoated view factor

The view factor for whiskers originating at the pad surface is based on the following metric (M_P):

s = Lead spacing

t = Lead thickness

$$M_P = \left(\frac{t}{s}\right)^{1.686625}$$

A plot providing the modeled view factor as a function of the above metric and the derived equation is provided in Figure 12.

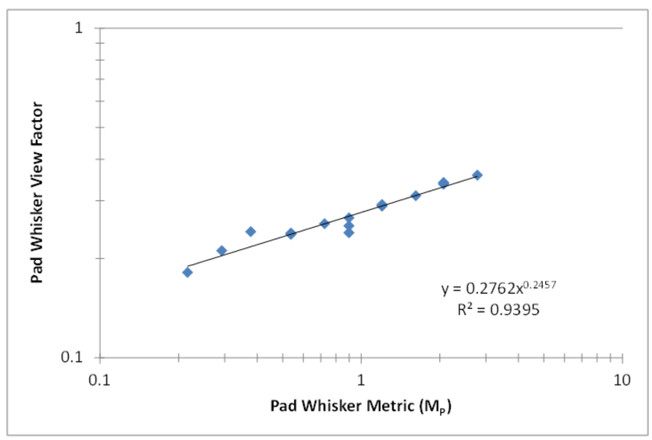
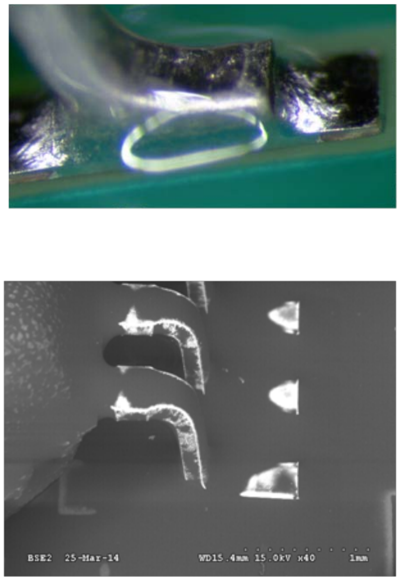


Figure 12: Pad whisker view factor correlation

Partially-coated whisker view factor

Although adjustment for uniformly conformally coated configurations can be globally applied to the appropriate overall uncoated view factor, partially coated configurations are more complex. Considering coating effectiveness of 90 percent on outside, 50 percent effective on sides, and 0 percent effective on back/inside (see Figure 13) the view factor is plotted relative to the uncoated view factor (see Figure 14) where it can be seen that the modeled view factor for the partially-coated configuration is 60 percent of the uncoated configuration (40 percent coating effectiveness).



(B)

Figure 13: Conformal coating coverage assessment of low VOC 100 percent solids spray coatings. (A) Optical image, and (B) isometric SEM. The white color in the SEM images indicates that the coating thickness is less than three microns.

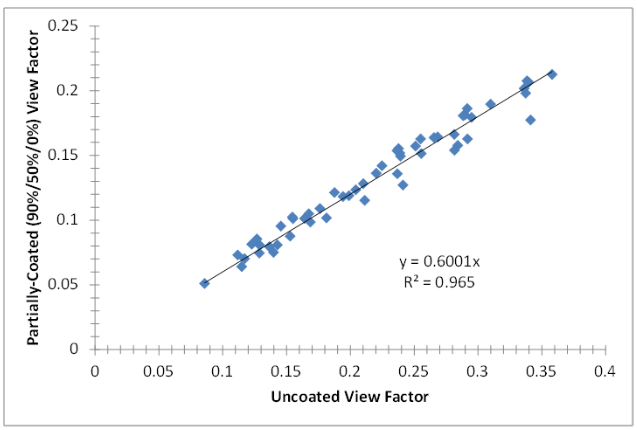


Figure 14: Partially-coated versus uncoated view factors

Spacing distribution

The spacing distribution provides a cumulative fraction versus length between the minimum and maximum spacing starting at leads, solder, or pads and ending at any other feature. Development of an appropriate distribution requires calculation of the minimum and maximum spacing and the appropriate intermediate fractions.

Minimum spacing

The minimum lead spacing is determined as a linear combination of PWB pad width, lead width, lead pitch, and spacing. The Excel solver is used to optimize the coefficients based on the minimum sum-squared error (SSE) between the predicted minimum spacing and that obtained from the model. Values of the coefficients to calculate the minimum spacing are provided in Table 2.

Table 2: Coefficients to calculate minimum spacing

	PWB Pad Width	Lead Width	Lead Pitch	Spacing
Coeffs for Lead Spacing:	-0.59941	-0.39821	1.014216	0
Coeffs for Solder Spacing:	0.002369	-0.00227	0	1.00259
Coeffs for Pad Spacing:	-1.06902	0.054753	1.012726	0

Maximum spacing

The maximum lead spacing is determined as the diagonal of a rectangular prism with height defined in relationship to the first bend height. The width of the prism is defined as a linear combination of the lead width, lead pitch, and PWB pad width. The length of the prism is defined as a linear combination of the PWB pad length, lead span length, and first bend distance. The Excel solver is used to minimize the SSE between the predicted maximum spacing and that obtained from the model. Values of coefficients to calculate the maximum spacing are provided in Table 3.

Distribution development

The distributions are developed based on a non-dimensional distribution dividing the length values at each distribution point by the appropriate nominal spacing and then scaling the results linearly such that the maximum spacing produces a value of 10 while maintaining nominal spacing at one. Plotting the results as a function of cumulative spacing fraction produces reasonably consistent results as shown in Figure 15 through Figure 17.

Table 3: Coefficients to calculate maximum lead spacing

	Length Direction				Width Direction		
	PWB Pad Length	Lead Span Length	First Bend Dist.	First Bend Height	Lead Width	Lead Pitch	PWB Pad Width
Coeffs for Lead Spacing:	0.569988	0.357226	0.395243	1.086483	0	1.151966	0.205718
Coeffs for Solder Spacing:	0.514016	0.478274	0.407232	1.040679	0	1.30039	0
Coeffs for Pad Spacing:	0.662121	0.166851	0.433574	1.105011	0.792507	0.476286	0.514922

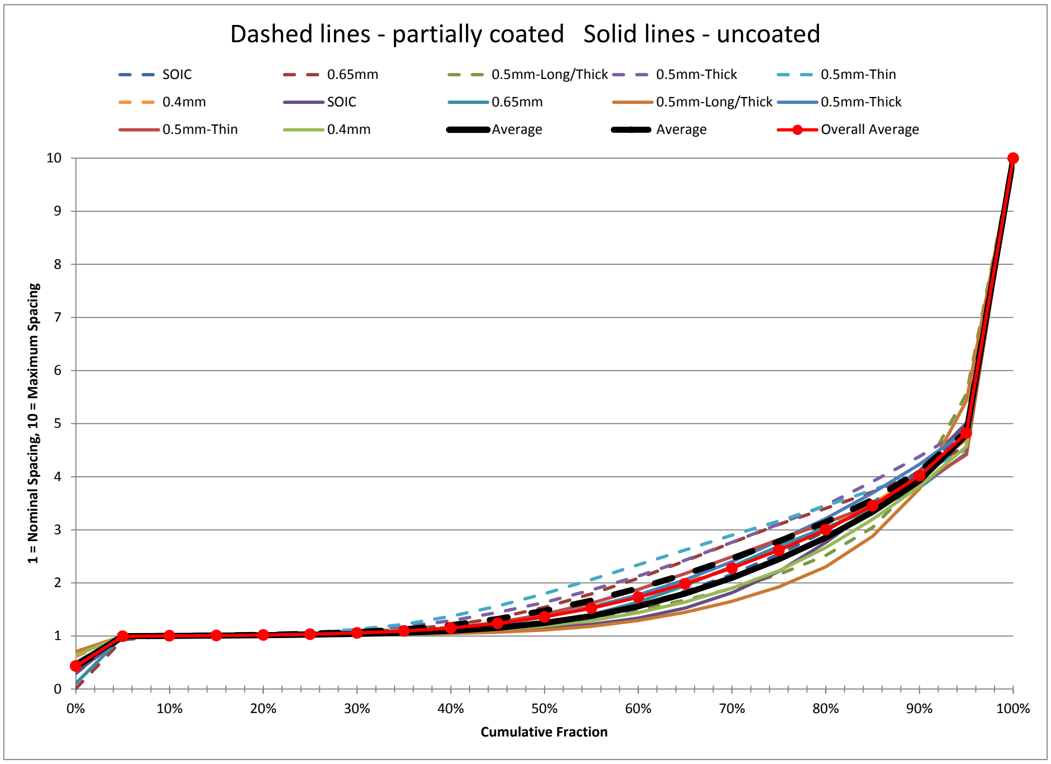


Figure 15: Non-dimensional spacing distribution for lead whiskers

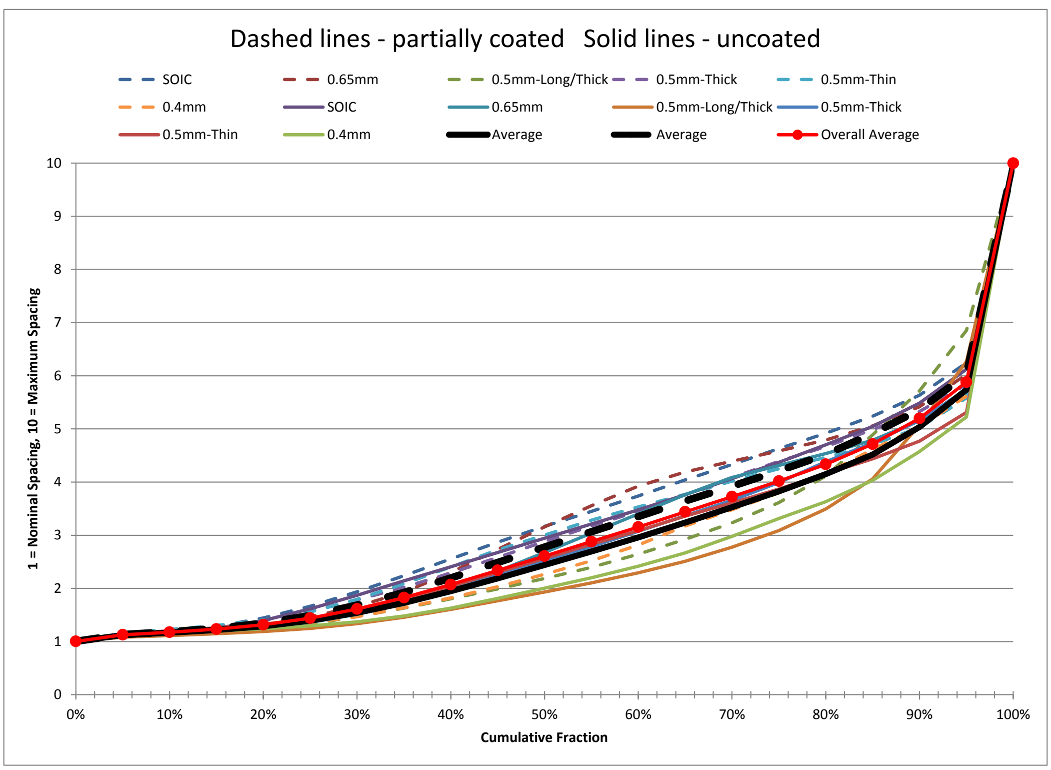


Figure 16: Non-dimensional spacing distribution for solder whiskers

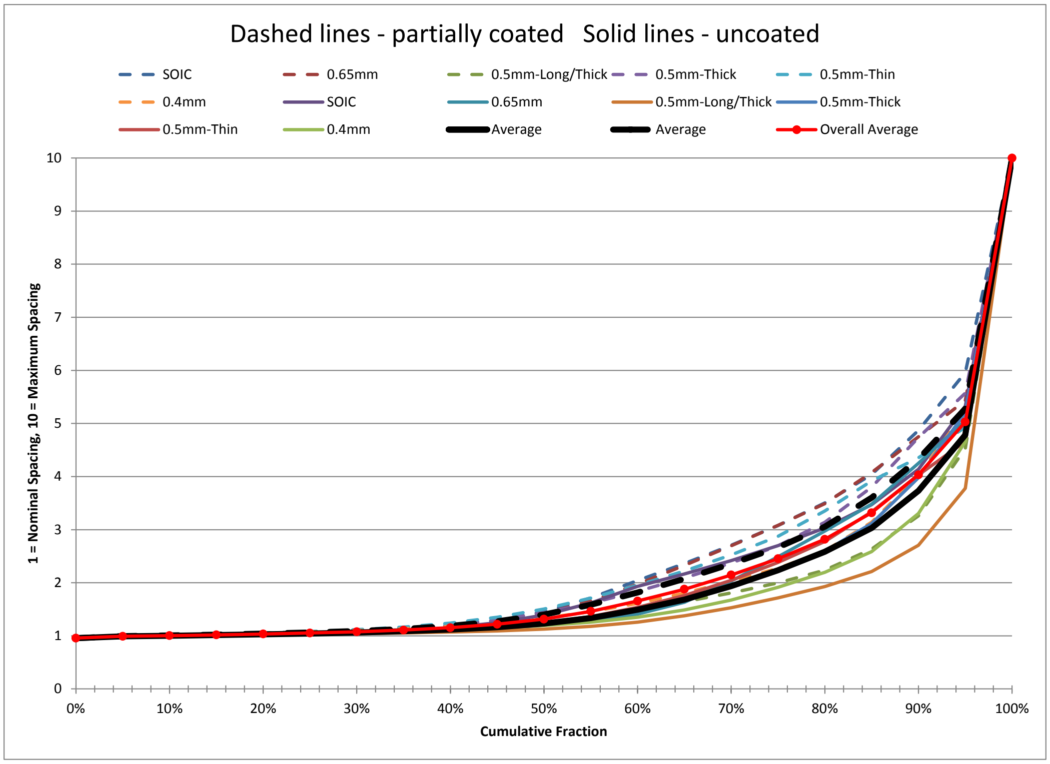


Figure 17: Non-dimensional spacing distribution for pad whiskers

Specific non-dimensional distribution values for each type of whisker are summarized in Table 4. These values are used in conjunction with the appropriate nominal and maximum spacing to extract the length values for fractions greater than or equal to 5 percent. For whiskers originating at the solder or pad, the zero percent value is the minimum of the value extracted from the non-dimensional distribution and the minimum spacing value calculated in the *Minimum spacing* section. Because of the large variation in spacing with the non-dimensional distribution for the lead whisker at zero percent (see Figure 15), the extracted lead whisker spacing distribution always uses the minimum calculated value (from *Minimum spacing* section).

Table 4: Non-dimensional whisker distribution (1 = nominal spacing, 10 = maximum spacing)

	Whisker Type		
Cumulative	**Lead**	**Solder**	**Pad**
0%	see text	1.0044	0.9578
5%	0.9942	1.1273	0.9913
10%	1.0030	1.1763	1.0043
15%	1.0087	1.2343	1.0179
20%	1.0183	1.3171	1.0341
25%	1.0331	1.4415	1.0534
30%	1.0564	1.6133	1.0768
35%	1.0935	1.8256	1.1080
40%	1.1513	2.0714	1.1527
45%	1.2376	2.3390	1.2185
50%	1.3597	2.6078	1.3157
55%	1.5228	2.8800	1.4609
60%	1.7293	3.1547	1.6554
65%	1.9823	3.4407	1.8783
70%	2.2778	3.7257	2.1462
75%	2.6158	4.0182	2.4525
80%	2.9996	4.3348	2.8195
85%	3.4536	4.7155	3.3169
90%	4.0182	5.1980	4.0333
95%	4.8218	5.8805	5.0295
100%	10.0000	10.0000	10.0000

CALCULATION OF BRIDGES, SHORTS, AND ROLL-UP

Bridge calculation [1]

Whisker bridging probability

Where $f_S(s)$ and $f_W(w)$ are whisker spacing and length distributions respectively, the whisker bridging probability is given by:

$$P_B = \int_0^{\infty} \int_{-\infty}^{\infty} f_S(s) \cdot f_W(b+s)\, ds\, db$$

The above double integral is implemented numerically in Microsoft Excel™ based on the aforementioned whisker spacing distribution from the Monte Carlo analysis and the appropriate whisker length distribution. This value represents the probability that a whisker is of sufficient length to bridge between adjacent leads. The results of a hypothetical example calculation are given in Figure 18. The spacing distribution can quickly be compared to the whisker length distribution. The positive values of the bridge interference distribution are where the whisker is longer than the conductor-to-conductor space (note: the negative values, not plotted, occur when the whisker is shorter than the space).

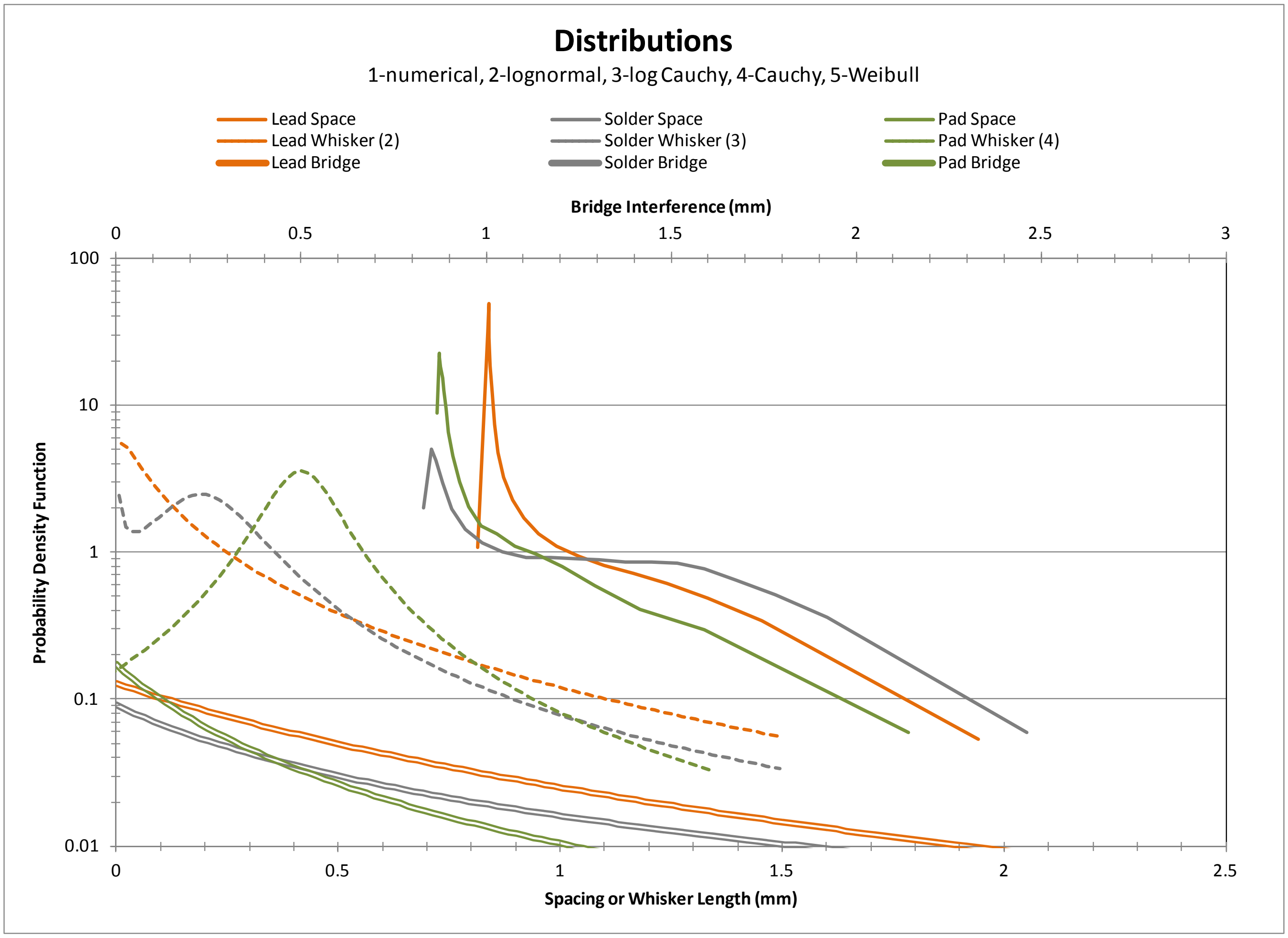


Figure 18: Hypothetical example of lead, solder and pad spacing/whisker length distribution and bridge interference plots.

Bridges per lead pair

Calculation of the overall number of bridges is determined on a part basis by multiplying the whiskerable area by the whisker density to determine the whiskers generated per lead. The whiskers-per-lead value is then multiplied by the whisker view factor and the whisker bridging probability to determine the bridges per lead pair.

Shorts per lead pair

As demonstrated by Courey [7] not all whisker bridges result in shorts, so the bridges calculated are multiplied by the shorting probability based on applied voltage from Figure 19. Based on 5 Volts applied, the shorting probability is 41.4 percent. So if 10 bridges are present, four would cause an electrical short circuit.

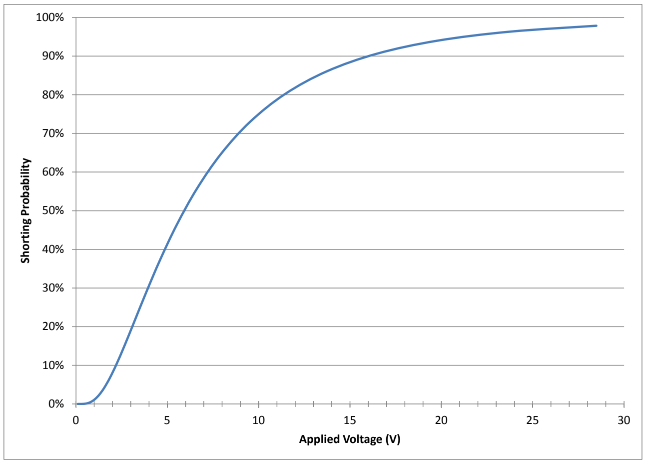


Figure 19: Probability of shorting

Overall roll up

The shorts per part are determined by multiplying the shorts per lead pair by the number of spaces. The shorts per part is multiplied by the number of parts with the same lead configuration and number of leads and then summed for all of the parts in the assembly.

COMPARISON OF ORIGINAL AND SIMPLIFIED MODELS

The simplified model was verified with the original calculation using 76 of the parts originally analyzed (see *Appendix: Parts used to verify simplified model* section). Total bridges per part were calculated based on a whisker density of 400 whiskers/mm^2, with a lognormal length of 0.01 mm at 1.696 percent and of 0.733 mm at 99.8 percent. Good agreement was achieved between the original and simplified model as shown in Figure 20.

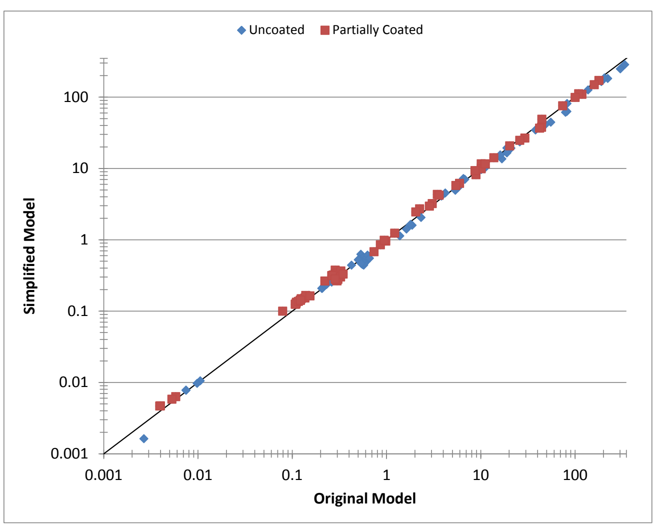


Figure 20: Comparison of bridges per part for original and simplified models

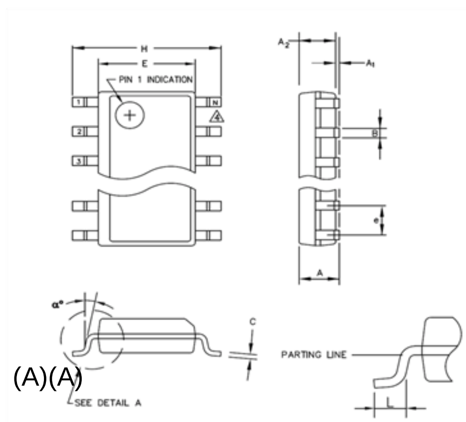
WHISKER RISK SPREADSHEET

A Microsoft Excel™ spreadsheet has been developed that incorporates the aforementioned calculations, and will be made available at no charge to interested researchers on an as-is basis. This spreadsheet provides for user definition of the following:

- Multiple lead geometries for roll-up calculation (optional)
- Lead geometry
- Lead, solder, and pad whisker length distributions
- Lead, solder, and pad whisker density (whisker/mm^2)
- Shorting probability distribution

Calculation example

A sample calculation is performed for a 128 pin 0.4 mm pitch plastic thin quad flat pack (Practical components A-LQFP128-14mm-.4mm-2.0-Sn see [8]). The part geometry entered into the spreadsheet is shown in Figure 21. The resulting simplified lead geometry (ref. Figure 5) computed using the default parameters in Table 5 is given in Table 6. The computed simplified geometry values are shown in parentheses and can be adjusted by the user in the adjacent spread sheet cells. A board pad thickness of 0.063 mm is used in the present calculation to account for the initial surface copper with the additional plated copper from the plated-through-hole plating process.



Part Drawing Dimensions (mm):

Package Height (A_2) =	1.4
Package Seating Plane (A_1) =	0.1
Lead Span (H) =	16
Body Width (E) =	14
Lead Foot Length (L) =	0.6
Lead Thickness (c) =	0.145
Lead Width (B) =	0.18
Lead Pitch (e) =	0.4
Lead Angle From Vertical (α deg) =	0
Number of Leads =	128
(B) Number of Sides with Leads =	4

Figure 21: (A) Geometry nomenclature used for inputting part geometry into the model and (B) TQFP128 dimensions.

Table 5: Model default parameters used to determine the simplified lead geometry

Default Parameters
(* - only used with part drawing dimensions):

PWB Pad Length over Lead Foot Length (mm) =	1.04
PWB Pad Width over Lead Width (mm) =	0.111
PWB Pad Thickness =	0.063
Fraction for Minimum Whisker Length Plot (Note 1)=	5.00%
Fraction for Maximum Whisker Length Plot (Note 1) =	90.00%
Use Geometric Mean for Midpoints (Note 2)=	TRUE
Lead Exit Fraction (*) (of package height) (Note 3) =	50%
Minimum First Bend Distance (*) (mm) =	0.1
Pad Spacing Reduction from Solder Bulge (mm) (Note 4) =	0.049
Relative Height of Bulge (Note 4) =	50%
Rounding Digits for Prompt Display =	4

Notes:
(1) Only used for plotting calculated distributions
(2) Geometric mean: (TRUE - geometric-recommended, FALSE - arithmetic, applies to distribution calculations)
(3) Lead exit fraction is used as part of the computation of "h" when part drawing dimension are used. A 50 percent value represents a lead that exits the middle of the package body.
(4) Solder bulge modification factors: Solder joints where the lead and board pad widths are approximately the same can exhibit a bulge in the solder joint at the lead. A 50 percent "relative height of bulge" value represents a bulge that is located half way up the solder joint.

Table 6: Computed TQFP128 simplified lead geometry

Manual Lead Dimensions (mm) (default value in parentheses if applicable, no need to enter):	
Lead Span Length (d, **1**) =	
First Bend Distance (a, **0.4**) =	
First Bend Height (h, **0.8**) =	
Lead Foot Length (f, **0.6**) =	
Lead Thickness (t, **0.145**) =	
Lead Width (**0.18**) =	
Lead Pitch (**0.4**) =	
Total Lead Spaces (**124**) =	
PWB Pad Length (**1.64**) =	
PWB Pad Width (**0.291**) =	
PWB Pad Thickness (**0.063**) =	
Overall Coating Effectiveness =	**0%**

The calculated lead, solder and pad parameters are given in Table 7 and Table 8. The whisker view factor and the spacing limits before bridging occurs are shown in Table 9 and Table 10.

Table 7: Calculated joint parameters

Lead Spacing (mm) =	0.22
Solder Spacing (mm) =	0.06
Pad Spacing (mm) =	0.109
Lead Thickness/Spacing (non-dim) =	0.659091
Lead Thickness/Solder Spacing (non-dim) =	2.416667
Lead Thickness/Pad Spacing (non-dim) =	1.330275
Lead View Factor Metric (non-dim) =	0.25971
Solder View Factor Metric (non-dim) =	0.456533
Pad View Factor Metric (non-dim) =	1.61824

Table 8: Calculated areas (mm^2)

Whiskerable Lead Area (mm^2) =	0.613983
Whiskerable Solder Area (mm^2) =	0.531264
Whiskerable Pad Area (mm^2) =	0.121653
Single Side Area (mm^2) =	0.359775

Table 9: Whisker view factors (infinite whisker hits/lead pair, non-dim)

From Lead =	0.260763
From Solder =	0.248734
From Pad =	0.310875

Table 10: Whisker Spacing Limits

Minimum from Lead (mm) =	0.15958
Maximum from Lead (mm) =	1.769001
Minimum from Solder (mm) =	0.060436
Maximum from Solder (mm) =	1.779439
Minimum from Pad (mm) =	0.10386
Maximum from Pad (mm) =	1.746053

The whisker density and length distribution parameters for the lead, solder and board pad are needed to determine the whisker bridging risk. The TQFP64 with a similar lead form to the TQFP128 exhibits side of lead wetting like the SOT5 used in the high temperature/high humidity experiments (see the *Appendix: TQFP128 lead form* and *Whisker density* sections).

Whisker density varies greatly depending upon the location on the lead and the environmental exposure. In the present example, a whisker density of 69 whiskers/mm^2 is selected for the lead and a whisker density of 936 whiskers/mm^2 is used for the solder and the board pad based on 1,000 hours at 85°C/85%RH observations. The current modeled solder joint represents "thin solder regions," which would tend to grow whiskers. If the solder were to be modeled higher up on the lead, another distribution would be needed to differentiate between the thick region of solder less prone to whisker growth and the thin regions of solder more prone to whisker growth.

Regarding whisker length, there are multiple distribution forms available (see Table 21 in the *Appendix: Whisker length distribution* section for some examples). Distribution selections in the spread-sheet are: 1-numerical, 2-lognormal, 3-log Cauchy, 4-Cauchy, 5-Weibull. For present example, the lognormal parameters for the whisker growth from SAC305 solder on the copper board pads after 1,000 hours at 85°C/85%RH with (1) cleaned parts and boards (lognormal μ = -4.978 ln(mm) and σ = 0.710) and (2) with contaminated parts and assemblies (lognormal μ = -4.795 ln(mm) and σ = 0.6962) are used. The whisker distribution inputs into the spread-sheet are given in Table 11, Table 12 and Table 13 (Note the location parameter, "Whisker Minimum" is set to zero for 2-parameter distributions).

Table 11: Lead whisker distribution

Lead Whisker Distribution (fill in green highlighted cells as appropriate):	
Distribution =	2
Whisker Density (whiskers/mm^2) =	**69**
Whiskerable Area =	0.61398318
Total Whiskers Generated =	42.3648392
Whisker Bridging Fraction =	0.00%
Whisker View Factor =	0.26076271
Coating Effectiveness =	0%
Total Whiskers Bridging =	**6.6475E-06**
3-Parameter Lognormal Distribution:	
Whisker Minimum (0) =	
Whisker µ (location, ln(mm)) =	-4.795
Whisker σ (scale,nondim) =	0.6962

Table 12: Solder whisker distribution

Solder Whisker Distribution (fill in green highlighted cells as appropriate):	
Distribution =	2
Whisker Density =	**936**
Whiskerable Area =	0.5312642
Total Whiskers Generated =	497.263292
Whisker Bridging Fraction =	0.01%
Whisker View Factor =	0.24873426
Coating Effectiveness =	0%
Total Whiskers Bridging =	**0.01112485**
3-Parameter Lognormal Distribution:	
Whisker Minimum (0) =	
Whisker µ (location,ln(mm)) =	-4.795
Whisker σ (scale,nondim) =	0.6962

Table 13: Pad whisker distribution

Pad Whisker Distribution (fill in green highlighted cells as appropriate):	
Distribution =	2
Whisker Density =	**936**
Whiskerable Area =	0.121653
Total Whiskers Generated =	113.867208
Whisker Bridging Fraction =	0.00%
Whisker View Factor =	0.31087479
Coating Effectiveness =	0%
Total Whiskers Bridging =	**0.00126625**
3-Parameter Lognormal Distribution:	
Whisker Minimum (0) =	
Whisker µ (location,ln(mm)) =	-4.795
Whisker σ (scale,nondim) =	0.6962

Over the lifetime of a product in harsh service, some amount of ionic contamination is expected. The whisker short circuit calculation results for the case of the SAC305 soldered TQFP128 with no conformal coating and a 5V circuit voltage and a contaminated part and board combination after 1,000 hours at 85°C/85%RH are shown in Table 14. The associated spacing, whisker length and bridging interference plots are shown in Figure 22. The computed TQFP128 short circuit probability is 0.6358. Thus if there are two of these devices on the board, the total shorting probability becomes 2 x 0.6358 = 1.2716. Thus with two TQFP128 parts present a short circuit failure is expected.

Short circuit risk can be changed by improving cleanliness, adding conformal coating, or replacing SAC305 solder with tin-lead solder. With clean parts and boards, the whisker short circuit risk is reduced roughly by a factor of two to 0.315 (see Table 15) under the same environmental conditions. The addition of conformal coating reduced the short circuit risk by a factor of 1.7 for the case where there is 90 percent coating coverage on the front, 50 percent on the side and no coating on the back are found by setting the overall coating coverage to 40 percent (see Table 16). (Note that this calculation at the present time assumes that the coating did not change the whisker growth density or length characteristics, even though it is generally agreed that most electronic grade coatings would reduce both of these attributes. Once data becomes available, the density and length distributions can be updated.) The largest reduction in short circuit probability is obtained by changing the solder from SAC305 to tin-lead. In this case, the whisker risk is reduced by a factor of over 4,000 to 0.00015 because the solder and the board pad whisker density would become zero (see Table 17).

Table 14: Whisker shorting results for a SAC305 soldered TQFP128 with no conformal coating and an applied voltage of 5 volts (1,000 hour 85C/85%RH exposure with mildly contaminated parts and boards; lognormal μ = -4.795 ln(mm) and σ = 0.6962).

Total lead spaces =	124		
Applied Voltage =	**5**	**V**	
Shorting Probability =	41.4%		
Whisker Type:	**Lead**	**Solder**	**Pad**
Bridges per lead:	6.65E-06	0.011125	0.001266
Bridges per part:	0.000824	1.379482	0.157015
Shorts per part:	0.000341	0.570522	0.064938
TOTAL SHORTS =	**0.6358**		

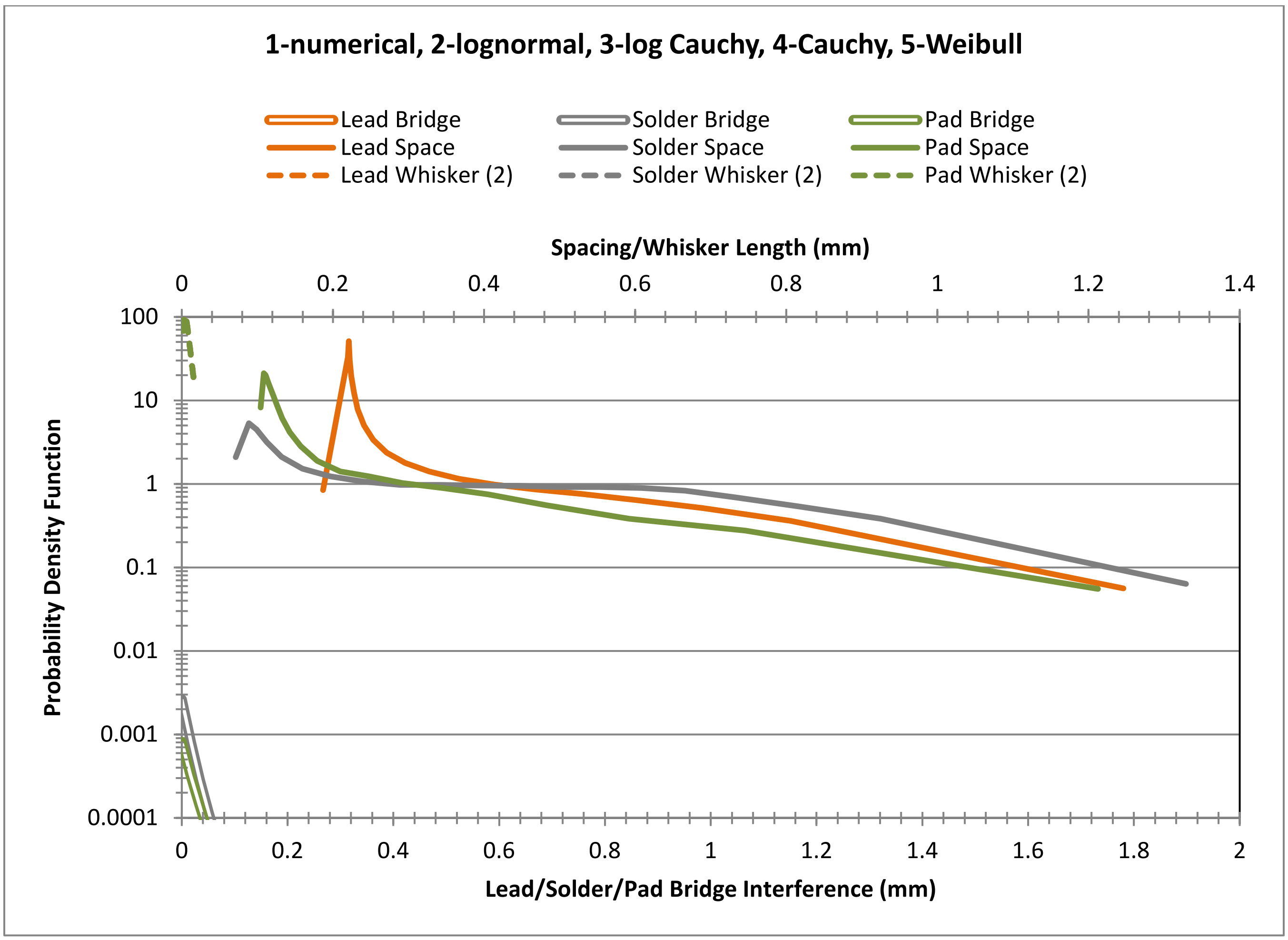


Figure 22: TQFP128 spacing, whisker length and bridging interference plots for a SAC305 soldered assembly with no conformal coating and an applied voltage of 5 volts (1,000 hour 85C/85%RH exposure with mildly contaminated parts and boards; lognormal μ = -4.795 ln(mm) and σ = 0.6962).

Table 15: Whisker shorting results for a SAC305 soldered TQFP128 with no conformal coating and an applied voltage of five volts (1,000 hour 85C/85%RH exposure with clean parts and boards; lognormal μ = -4.978 ln(mm) and σ = 0.710).

Total lead spaces =	124		
Applied Voltage =	**5**	**V**	
Shorting Probability =	41.4%		
Whisker Type:	**Lead**	**Solder**	**Pad**
Bridges per lead:	2.910E-06	0.005542	0.000596
Bridges per part:	0.000361	0.68722	0.073926
Shorts per part:	0.000149	0.28422	0.030574
TOTAL SHORTS =	**0.315**		

Table 16: Whisker shorting results for a SAC305 soldered TQFP128 with 40 percent conformal coating coverage and an applied voltage of five volts (1,000 hour 85C/85%RH exposure with mildly contaminated parts and boards; lognormal μ = -4.795 ln(mm) and σ = 0.6962).

Total lead spaces =	124		
Applied Voltage =	**5**	**V**	
Shorting Probability =	41.4%		
Whisker Type:	**Lead**	**Solder**	**Pad**
Bridges per lead:	3.989E-06	0.00668	0.000760
Bridges per part:	0.000495	0.82769	0.094209
Shorts per part:	0.000205	0.34231	0.038963
TOTAL SHORTS =	**0.381**		

Table 17: Whisker shorting results for a tin-lead soldered TQFP128 with no conformal coating and an applied voltage of five volts (1,000 hour 85C/85%RH exposure with clean parts and boards; lognormal μ = -4.978 ln(mm) and σ = 0.710).

Total lead spaces =	124		
Applied Voltage =	**5**	**V**	
Shorting Probability =	41.4%		
Whisker Type:	**Lead**	**Solder**	**Pad**
Bridges per lead:	2.91045E-06	0	0
Bridges per part:	0.000361	0	0
Shorts per part:	0.000149	0	0
TOTAL SHORTS =	**0.00015**		

CONCLUSION

The whisker short circuit risk modeling provides a means of comparing various mitigations and component geometry types. The partitioning of the calculation between the geometry and the whisker distribution allows rapid recalculation of short circuit risk as new whisker distributions become available.

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APPENDIX

Parts used to verify simplified model

No. of Parts	Type	Leads
1	MSOP	8
1	MSOP	16
1	PQFP	80
1	QFP	72
12	SOIC	8
13	SOIC	14
13	SOIC	16
2	SOIC	20
2	SOIC	28
5	SOT	4
1	SOT	6
1	SOT	8
1	SSOP	16
5	SSOP	20
1	SSOP	24
1	SSOP	28
4	SSOP	48
3	TQFP	100
1	TQFP	128
2	TQFP	144
2	TSSOP	10
2	TSSOP	16
1	TSSOP	24

TQFP128 lead form

The TQFP64 part shown in Figure 23 is has a similar lead form to a 0.4 mm pitch TQFP128. The lead material of the TQFP64 is copper alloy C7025 composed of Cu2.2-4.2Ni0.25-1.2Si0.05-0.3Mg, which has been tested but not yet been analyzed for whisker growth after environmental exposure. The closest part for which there is data available is the SAC305 assembly with the SOT5 (small outline transistor with five leads) part [5].

Whisker density

Estimates of the whisker density were made from the 85°C/85 percent relative humidity testing of SAC305 soldered assemblies [5]. The longest whisker growth and the highest density is on the SOT5 copper 194 alloy leads with a composition of Cu2.1-2.6Fe-0.015-0.15P-0.05-0.2Zn.

(A)

(B)

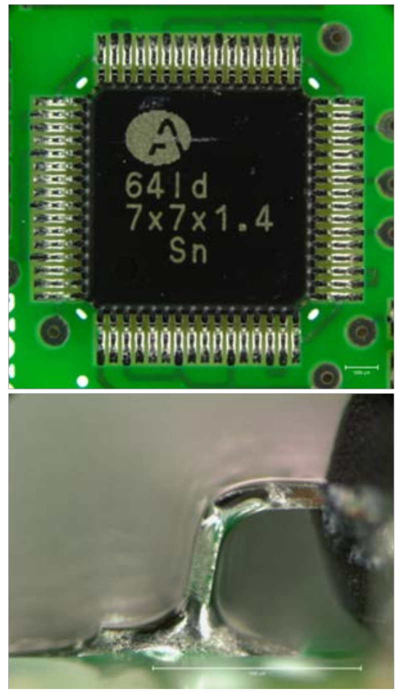

Figure 23: TQFP64 overall top view and side view. Practical components A-LQFP64-.7mm-.4mm-2.0-DC-Sn (0.4 mm pitch)

The board pads are copper in this experiment. The whisker growth reference locations are given in Figure 24. The whisker count for the non-contaminated assemblies is given in Table 18. Examining the local solder whisker density at the board pad edge more closely, the whisker density is an order of magnitude larger than was observed on bright tin [11]. The pad cross section shows the board pad thickness is 62.5 microns. The board pad nominal artwork length and width are 1.2192 x 0.6858 mm. The board pad side area pertinent to the whisker density is computed as 0.1955 mm^2 using two times the side length area plus one times the toe width area. Only one toe area is used because the back of the pad is covered with solder mask. After 1,000 hours of 85 °C/85RH, the maximum whisker count for the SOT5 (copper alloy 194 at 0-0 cleanliness level (see Table 18) yielded a whisker density average for the board pad edge of 936 whiskers/mm^2 (see Table 19).

The whiskers did not grow from the lead where the solder was thicker than ~25 microns. For the side of the lead, the area of location "1" where the solder is thin is shown in Figure 25(C). The points shown in Figure 26 are used to form the triangular area approximating the side area of the lead. By doubling this area the relevant area needed to compute the whisker density is obtained. Using the whisker count from Table 18, the whisker density average for location "1" of 69 whiskers/mm^2 (see Table 20).

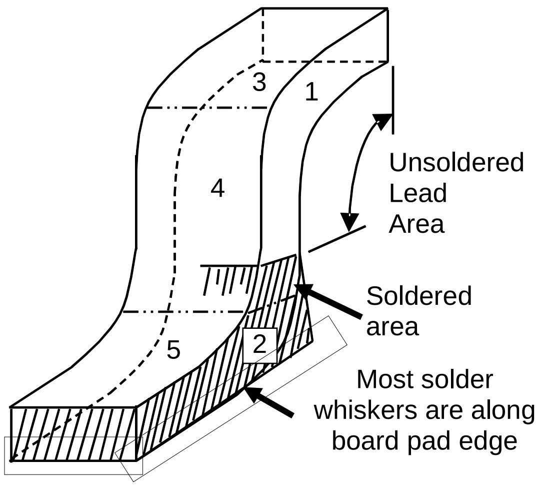

Figure 24: Whisker growth reference locations

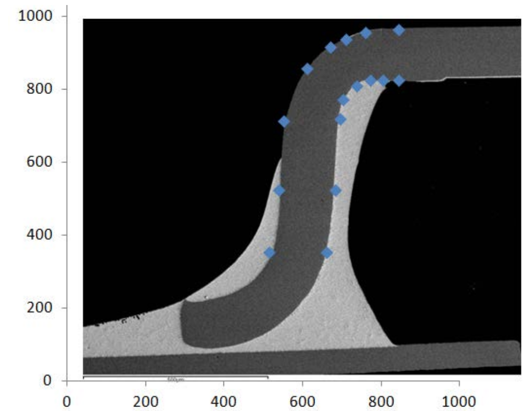

Figure 26: Points used to form the triangles used for the SOT5 lead side area calculation where the solder is thin (scale in microns).

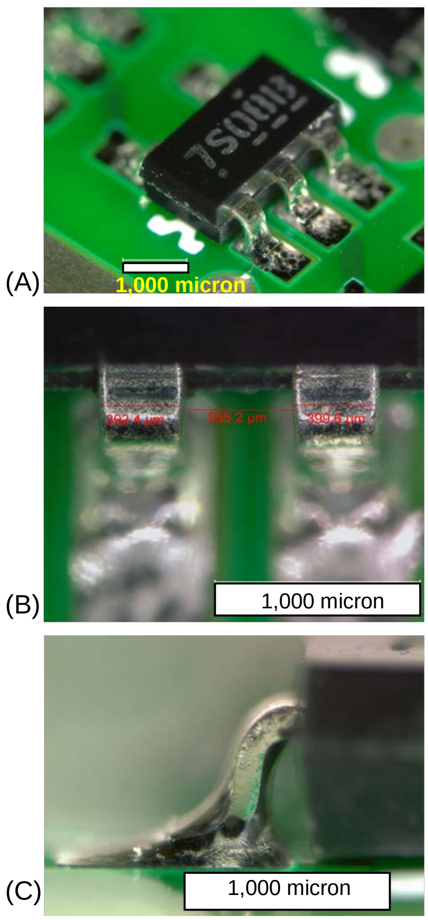

Figure 25: Isometric (A), top (B) and side views (C) of the SOT5 (NC7S08M5X) soldered to the board.

Table 18: Whisker count for the SOT5 at a 0-0 cleanliness level after 1,000 hours at 85 °C/85RH.

					Location (Note 1)					
Comp Bias	Board	Comp #	# per comp	Lead	L1	L2*	L3	L4	L5	TOTAL
Biased	Board 2	3	1333	1	6	239	0	5	36	286
				2	7	194	0	0	112	313
				3	17	220	0	3	90	330
				4	0	243	0	0	42	285
				5	2	107	0	1	9	119
		15	1600	1	8	254	0	0	48	310
				2	15	162	0	1	164	342
				3	0	284	0	0	67	351
				4	7	205	3	0	42	257
				5	2	240	15	2	81	340
		21	1277	1	14	246	2	10	29	301
				2	32	199	0	26	134	391
				3	26	197	0	26	76	325
				4	0	125	0	0	7	132
				5	8	58	0	3	59	128
Unbiased		20	1321	1	23	239	0	9	20	291
				2	0	165	0	0	53	218
				3	24	211	0	52	88	375
				4	0	225	0	0	12	237
				5	1	123	0	5	71	200
		37	1388	1	10	197	0	30	67	304
				2	37	204	0	35	143	419
				3	14	172	11	9	90	296
				4	13	119	0	11	35	178
				5	15	85	9	7	75	191
		36	1428	1	44	191	0	22	40	297
				2	18	204	1	30	146	399
				3	18	176	0	0	91	285
				4	16	172	2	1	8	199
				5	9	195	0	1	43	248

Note 1 Location 2* = whisker were in the solder located at the board pad edge.

Table 19: Whisker density of whiskers growing from the solder at the board pad for the SOT5 at a 0-0 cleanliness level after 1,000 hours at 85 °C/85RH.

	Whiskers per board pad	Whisker density (whiskers/mm^2)
Minimum	58	297
Maximum	284	1454
Average	182.8	936

Note: Board pad side area = 0.1953-mm^2

Table 20: Whisker density of whiskers growing from the side of the lead where the solder is thin for the SOT5 at a 0-0 cleanliness level after 1,000 hours at 85 °C/85RH.

	Whiskers per lead on the side	Whisker density (whiskers/mm^2)
Minimum	0	0
Maximum	44	236
Average	12.9	69

Note: Board pad side area = 0.1863-mm^2

Whisker length distribution

The correlation between whisker length and environmental exposure and time is not well understood. Experiments performed by Panashchenko [6], indicate that environmental tests (temperature/humidity and thermal cycling) may over-predict, under-predict, or show little distinguishable growth as compared to ambient-stored plated tin. While environmental tests are not a reliable method of assessing future whisker growth, some experiments have yielded relatively long whisker growth and can be useful for assessing potential whisker short circuit risk (see Table 21). The lognormal mean, μ, in microns is converted to millimeters by subtracting ln(1,000) which is 6.9078. The lognormal shape is dimensionless and requires no conversion.

Table 21: Whisker distributions considered for risk modeling

<table>
<tr><th>Tin source</th><th>Thickness (microns)</th><th>Substrate</th><th>Environmental exposure</th><th>Maximum observed whisker length (microns)</th><th>Lognormal μ (ln mm)</th><th>Lognormal σ</th><th>Density (whiskers /mm^2)</th><th>Ref</th></tr>
<tr><td rowspan="2">SAC305 solder</td><td>3 to 25</td><td>Copper board pads (clean parts and board)</td><td rowspan="2">1,000 hours 85°C/85 %RH</td><td>76</td><td>-4.978</td><td>0.710</td><td rowspan="2">297 to 1,454</td><td rowspan="2">[5] Fig. 18</td></tr>
<tr><td>3 to 25</td><td>Copper board pads (contaminated parts and board)</td><td>186 (Note 1)</td><td>-4.795</td><td>0.6962</td></tr>
<tr><td rowspan="2">Plated Sn</td><td>5 to 9</td><td>Copper C194</td><td rowspan="2">2.5 years room, 1,000 cycles - 55 to 85°C, 2 months 60°C/85%RH</td><td>39</td><td>-4.571</td><td>0.9866</td><td>2,192 to 3,956</td><td>[6] Fig. 45</td></tr>
<tr><td>7 to 9</td><td>Nickel plating over Copper C194</td><td>greater than 200 (Note 1)</td><td>-4.306</td><td>0.8106</td><td>126 to 3,573</td><td>[6] Fig. 44</td></tr>
<tr><td rowspan="2">Plated Sn</td><td rowspan="2">5</td><td rowspan="2">Copper plated brass (specimen 11)</td><td rowspan="2">15.5 years: 3.5 years room temp. and humidity, 12 years in a dessicator with dry room air</td><td>1,000 maximum specimen 11 length</td><td>-2.651</td><td>0.9212</td><td rowspan="2">Not available</td><td rowspan="2">Dunn samples [13] evaluated in [12]</td></tr>
<tr><td>733 average of specimen 11 maximum lengths at various locations</td><td>-2.783</td><td>0.8592</td></tr>
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Note 1: Distribution does not model the longest observed whiskers very well.