Tin Whisker Risk Mitigation for High-Reliability Systems Integrators and Designers

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Integrators and designers of high-reliability systems exert little or no control over component-level plating processes that affect the propensity for tin whiskering. Challenges of how to assure long-term reliability, while continuing to use COTS parts plated with pure tin, continue to arise.

An integrated, quantitative, standardized methodology is proposed whereby mitigation levels can be selected that are appropriate for specific applications of pure tin for given end-uses. A system of hardware end-use classification is proposed, together with recommended appropriate risk mitigation approaches. An updated version of the application-specific risk assessment algorithm is presented together with recommended thresholds for acceptability within the context of the hardware classifications.

Introduction

As a result of worldwide consumer electronics' demand for lead-free products, component manufacturers increasingly are converting to lead-free materials. A popular choice for material finishes is tin except for the steel finish on mechanical parts where a common finish choice is zinc.

Pure tin and zinc finishes can be susceptible to the spontaneous growth of single crystal structures known as *"tin or zinc whiskers,"* which can cause electrical failures. Ranging from parametric deviations to catastrophic short circuits, tin and zinc whiskers may interfere with sensitive optical surfaces or the movement of micro-electromechanical systems (MEMS). Though studied and reported for decades, tin and zinc whiskers remain a potential reliability hazard, particularly for space applications and for equipment subjected to long-term dormant storage and use (e.g. missiles and expendables).

There is no pending US legislation mandating lead-free electronic products, and should such legislation arise, military, aerospace and medical equipment manufacturers would likely be exempt. Nevertheless, the Department of Defense and NASA believe that the use, and therefore the risk, of pure tin finish (tin which contains less than three percent Pb by weight shall be considered "pure" for this purpose) on electronic components will increase because: 1) the commercial industry has stated initiatives to eliminate lead (Pb) from electronics, 2) defense and aerospace industry trends show increasing usage of commercial components, and 3) continuing reductions in circuit geometry and power mean that even small whiskers may cause catastrophic failures.

High-Reliability Industry Response

Even with all these recent changes, there is still no commonly used industry standard for pure tin finishes on applications. Most individual companies are developing their own standard of acceptability of tin and zinc finishes used on parts.

Some companies have responded to current industry pressure by completely changing to pure tin and zinc finishes, yet not incorporating new part numbers to reflect this change in material. This practice only leads to confusion in the procurement process. Parts will have to be inspected upon arrival; wasting a lot of time and money.

One past approach to help alleviate these problems was to place tin and zinc on a list of prohibited materials. This approach will not work anymore, as the wholesale move to pure tin renders some usage unavoidable.

Although there is no current mandate at this time, some guidelines have been provided. The GEIA standard released in November 2003 outlines the problems of tin whiskering and how to minimize the risks of pure tin usage on applications. The GEIA standard does not outline a common framework for mitigation strategies for companies facing whiskering issues. The GEIA standard lists options, but does not give clear direction on how to select alternatives to the use of tin. The lack of a standard framework leads to mitigation that is not appropriate for the need, resulting in excess cost, and reduced reliability.

Solution –

In response to the current situation, a Level I-V classification standard is being proposed to harmonize the potential risk with appropriate mitigation for tin and zinc whisker issues. The whisker mitigation levels should be defined for each hardware system or subsystem. The levels should be agreed upon by the customer and design agents during the contract process. Ideally, the levels should be specified in Statements of Work issued during the Requests for Proposals process and then whisker mitigation level requirements can ultimately be cascaded down to subcontractors and designers. This should serve to level the playing field among competing contractors.

Table 1 summarizes the five proposed Whisker Mitigation Levels, providing a brief description, the type of control, plus the recommendation of systems types to utilize each level.

Table 1 – Whisker Mitigation Levels

Level	Description	Controls	System Types
V	Complete ban on pure Sn and Zn finishes	No pure Sn or Zn, no exceptions	Space-based Implanted Medical Devices
IV	Use of Sn and Zn finishes as last resort	Permit use on a case-by-case basis, if no alternative, if risk is negligible	Avionics Missiles
III	Use of Sn and Zn permitted under pre-set conditions	Blanket permission for classes of use, and on a case-by-case basis, if risk is minimal	Surface-based Radar and Communications Hi-Rel Commercial (Medical, Safety-critical)
II	Use of Sn and Zn restricted only under pre-defined conditions	No general restrictions. Use may be banned in limited high-risk places	Commercial transportation, Military test equipment
I	No Restrictions	None	Consumer Electronics

Levels of Control (Table 1)

Level V provides for the *highest* level of control that is practical to obtain. No pure tin or zinc finishes are permitted for use. (Tin which contains less than three percent Pb by weight shall be considered "pure" for this purpose.) This level of control requires inspection verification of the metal finishes on parts received for use in manufacturing.

This level of control will lead to a significant reduction in the ability to use widely available components without modification. This will result in increased cost and lead times for obtaining special parts, or for performing post-processing on parts.

Level V should only be applied to the most sensitive systems. Typical systems where Level V would be appropriate include: space-based systems, strategic missile vehicles, and implanted medical devices.

A customer may demand Level V controls for other system types, if they require the lowest risk of tin and zinc whisker failure, and are willing to accept the increased cost and schedule burdens.

Level IV provides a *high* level of control. Pure tin and zinc finishes may not be used, except on a very limited basis. Special exemptions may be granted to permit pure tin or zinc use on a case-by-case basis. Exemptions can be granted only when there is no practical alternative, and the risk of whisker-related failures is deemed negligible. Exemptions must be reviewed in accordance with a standard internal process, and then presented to and approved by the customer.

The controls of suppliers, inspection processes, review of drawings, etc., are performed as with Level V. A listing of exemptions must be maintained, and the documents relating to them clearly marked so that their identity and their limited usage can be controlled.

Typical end uses where Level IV would be appropriate include: tactical missiles, safety-critical avionics, etc.

Level III provides a *moderate* level of control. Pure tin and zinc finishes are only permitted when the risk of failure can be reasonably determined to be minimal. Permission for the use of tin and zinc can be granted on a case-by-case basis as with Level IV. In addition, blanket permission can be granted for usage that meets pre-set criteria. These criteria must be reviewed internally and agreed upon by the customer.

Level III control allows for a wider use of standard components, provided that appropriate consideration has been given to the risks of metal whisker failures. Some reduction in the ability to use widely available components without modification will result.

Level III should be applied to a wide range of high-reliability systems. Such systems would typically permit repair and replacement of failed assemblies as a normal part of their logistic plan.

Typical systems include: surface-based military radar and communications systems, and critical commercial applications.

Level II provides for a *minimal* level of control where pure tin and the zinc finishes are restricted from use only in specific applications. Unless otherwise indicated, pure tin and zinc are considered acceptable for use.

This level of control permits the use of standard parts in all but a small fraction of applications. The intent is that some known or suspected problem applications can be restricted when the need arises. Only minimal cost and schedule impacts should result.

Typical systems where this level could properly apply include: military test equipment, industrial electronics, and transportation.

Level I classification provides for *no special controls* for pure tin or zinc finishes. All components may be used without regard to issues of tin or zinc whiskering. This is essentially a “best commercial practices,” or COTS approach. This will result in the lowest cost and no imposition of schedule of delay, but provides no mitigation of whiskering risks.

Typical systems where Level I would be appropriate for use include: consumer electronics, and non-deliverable prototypes.

Figure 1 shows a graphical representation of the application of the levels. As the risk of whiskers rises, the level rises.

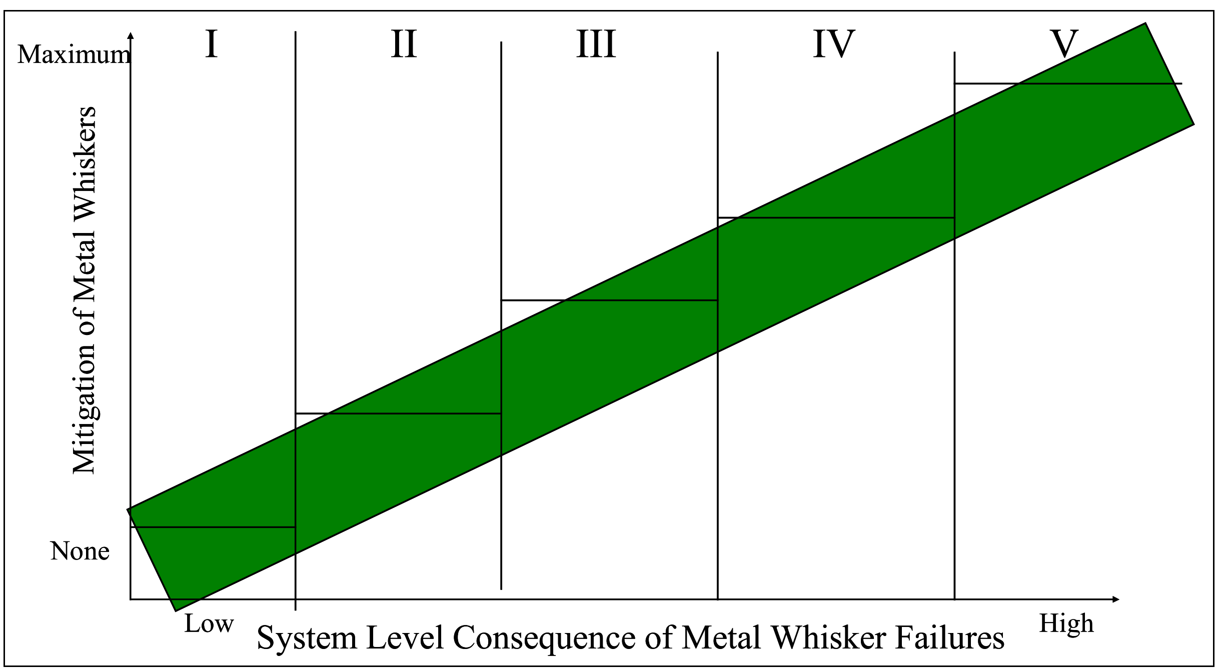

Figure 1 – Mitigation vs. Need – Levels Applied

Benefits of Standard Whisker Mitigation Level Usage
Using a leveling standard, such as the one being proposed, provides for many benefits. One of these benefits is the efficiency in communication among customers, contractors and subcontractors. This level system provides a common framework for discussion.

Whisker mitigation level usage also improves the ability to select and control the tradeoff between risk and cost. One standard way of thinking facilitates internal processes for design, purchasing, inspection, and manufacturing across programs and customers.

Algorithm Updates
Research into tin whiskers is continuous and risk mitigation tools currently in use are enhanced to accommodate information to come. Unfortunately, no similar tool is available for use on zinc whiskers at this time.

Arithmetic changes have been made within the tin whisker risk assessment algorithm to better reflect the mitigating affects of conformal coat usage. The complete algorithm is as follows:

R(growth) = [SUM(R(i)+R(d)+R(cte)+R(ex)]*r8
R(geom) = r1 + (r10*r11*r12)
R(i) = (r2*r3*r4*r7)
R(d) = (r2*r5*r7)
R(cte) = (r2*r6)
R(ex) = (r2*r9)
R(total) = R(geom)*R(growth)
=LOG [R(total)]
Output = 8.9 + LOG[R(total),10]

Minor changes have been made to two of the "r" factors, "R(growth) and "R(geom.)." The change to "R(growth)" reflects that the annealing of the tin plating provides no meaningful mitigation. The change to "R(geom)" expands the possible options for conformal coat coverage. (See former release of algorithm for differences)[1]

The tin whisker risk assessment algorithm was created to help determine the risk of whisker growth. Currently, we use this algorithm to perform literally hundreds of tin whisker assessments.

Based on a logarithmic scale of 10, the algorithm surveys different aspects of how the tin will affect associations within the part or assembly.

Risk factor data is collected on the "Data Collection Sheet" (Figure 2). Explanation of the individual risk factors is as follows:

Conductor Spacing – r1
The conductor spacing is the minimum spacing between the tin-coated surface and the nearest conductor that could be at a different electrical potential as measured in units of mils (0.001 inches). Nearby conductors that are covered by insulation are not considered as a possible short destination for a whisker. If both conductors are tin-coated, multiply the separation by 0.6 for entry into this factor.

Pb content (wt %) – r2
The lead (Pb) content is the percentage by weight of lead (Pb) that is present as an alloying element with the tin. Other elements are not considered for this risk factor.

Process - r3
r3 is a description of the process by which the tin was deposited. Electro-deposits are typically described as either "bright" or "matte," which relates to the resultant appearance. Immersion tin is deposited by an electroless plating process. Hot dip involves the submerging of the part into a bath of molten tin. If the deposition process is unknown, assume "bright," as this is the worst-case for whiskering propensity. For Pb-free solder material or BGA's use "hot dip".

Tin thickness - r4
Tin thickness is based upon the thickness of the deposit in microinches (0.000001"). If a range of thickness is present or may be present, choose the highest possible risk factor. For example, if the plating is known to range between 100 and 300 microinches in thickness, r4 should be given a 1.0 rating, rather than a 0.7. For Pb-free solder material or BGA's use the maximum thickness setting.

Material directly beneath the tin- r5
The material directly beneath the tin is often underplating that is different from the base material, although tin is also deposited directly onto some base materials. If the material is a copper alloy termed "brass" or "bronze," or contains less than 95% copper by weight, use the "Brass/Bronze" rating. Low expansion Fe-Ni or Fe-Ni-Co alloys such as Alloy 42 or Kovar should be given the "Ferrous" rating. The "Nickel" rating should be used with a nickel underplate or with any low alloy nickel. For Pb-free solder material or BGA's use the "Nickel" rating, regardless of the actual composition of the material beneath the solder.

Substrate controlling the CTE – r6
Substrate controlling the CTE should be the base metal of the component in question, but often is not. Some judgment will be necessary to determine which material in a complex stack-up will dominate the CTE that is imposed onto the tin deposit. The term "Low Expansion Alloy" is used to describe metals such as Alloy 42 or Kovar that have been formulated to exhibit a low CTE that is compatible with ceramic and glass. All other alloys where the majority constituent is iron (Fe) should be classed under a "Ferrous" rating. For Pb-free solder material or BGA's use the minimum value, regardless of the actual substrate material.

Plating fused – r7
If the deposit was fully melted and re-solidified, use the "Fused" rating. (Note: solder re-flow operations will not necessarily fuse a pure tin deposit. Use the "Fused" rating only if full melting of the plating is known to have occurred.) Otherwise, use the "none" rating.

Conformal Coat – r8
Conformal coat refers to organic coating applied directly over the tin deposit. If a coating is known to be urethane, in excess of 1 mil thick or silicone in excess of 1 mil thick, use the appropriate ratings. If Parylene is used, apply that rating (no minimum thickness). If a different coating type is used, or if a urethane or silicone coating of less than 1 mil is used, apply the "Other" rating. If no coating at all is used, apply the "None" rating (not the "Other" rating).

Use of Mechanical HWD – r9
Use of mechanical hardware is used to rate the amount of mechanical force that is applied to the surface of the tin deposit. If any mechanical component is in contact with the tin surface such that compression of the tin could occur, use the "Fasteners" rating. Components soldered onto the surface do not count for this risk factor. If no such components bear on the tin surface, use the "None" rating. (Note: the factor for "None" is not zero because some mechanical damage is assumed to always be present on the surface due to normal handling, etc.)

Where was assembly performed? – r10
The assembly performed factor is used to assess the overall vulnerability of the system to dysfunction as a result of the presence of small pieces of conductive contaminants. The concept behind this risk factor is that a device that is assembled in a clean room is likely to be very susceptible to contamination-related failure (or the expense of clean room operations would not be justified). Conversely, an assembly that is made under field conditions is likely to be fairly immune to conductive contamination (or it would never function). Another way to view this is to consider how the addition of a few loose whiskers would affect the total amount of conductive contamination present. For a clean-room build assembly, this would be a significant increase, while the same number of whiskers could represent a negligible increase for a system that is assembled in the field.

If the assembly that contains the tin-coated part is assembled in a clean room of any rating, use the "Clean-Room" rating. If the assembly occurs in a special "clean" area that has no specific rating, (like a closed room with laminar-flow benches) use the "Special Clean Area" rating. If the assembly occurs in a normal factory environment, (indoor, temperature-humidity controlled, workers in street clothes, etc.) use the "Typical Factory" rating. If the assembly is performed in an uncontrolled location (outdoor, open hangar, garage, etc.) use the "Field Assembly" rating.

Use of CC on conductors in enclosure – r11
The use of conformal coating within the enclosure is to help determine the risk of failure due to a loose whisker causing a "secondary" short. To determine the proper setting one must consider which electronics the whiskers could possibly reach. In general, all electronics with a path through the air from the tin plated surface should be considered. For example, if the tin surface is within a sealed box, only those conductors within the box would be at risk for secondary shorting. For the purpose of this factor, conformal coat of all types and thickness are equivalent. If all exposed conductors are coated, apply the "All" rating. If no coatings are used, apply the "None" rating. Often, some, but not all conductive surfaces will be coated. In this case select "Nearly All," "Most," or "Some" ratings. Use the "Nearly All" rating if all but a handful of conductors are coated, the "Most" rating if a clear majority conductors are known to be coated, otherwise apply the "Some" rating.

Air flow within assembly – r12
The airflow within the assembly is to rate the risk that whiskers will break off and migrate to other regions of the assembly at a distance from their site of growth. If air is forced over the tin-coated component by use of fans, etc., then use the "Forced Air" rating. If the assembly is used in a dynamic environment such as flight or ground vehicles, or large stationary machines with many moving parts, use the "Dynamic Environment" rating (unless the higher "Forced Air" rating applies). If cooling is achieved by passive means only and the application is in a fairly static environment, select the "None" rating.

DATA COLLECTION SHEET:

1) Conductor spacing (minimum distance that could be bridged by a whisker to a nearby conductor that could be at a different potential) in mils (thousand's of an inch) __________

(Note: if adjacent conductors are both tin plate, multiply the spacing by 0.6)

2) Pb content (% by weight), if the "tin plating" is not pure tin ___________

3) Process description for the tin plate: **Bright** **Matte** **Immersion** **Hot dip**

4) Tin thickness (plating thickness in micro-inches) ______________

5) Material directly beneath the tin: **brass/bronze** **copper** **ferrous** **nickel**

6) Substrate controlling the CTE: **ceramic** **low expansion alloy** **copper** **ferrous** **aluminum**

7) Was plating reflowed? **NO** **YES**

8) Conformal coat: **none** **urethane> 1 mil** **silicone> 1 mil** **parylene** **acrylic**

9) Use of mechanical hardware: **fasteners compressed into surface** **none**

10) Where is assembly performed? **Clean room** **special clean area** **typical factory** **field assembly**

11) Use of conformal coat on conductors in enclosure: **none** **some** **most** **nearly all** **all**

12) Airflow within assembly. **Forced Air** **Dynamic Use** **None**

Figure 2 – Data Collection Sheet

Special Instructions for Pb-free solders and BGA's
The vast majority of applications for nearly pure tin in electronics have been as plating atop other metals. Therefore, the risk assessment algorithm was developed to assess such applications. However, the advent of Pb-free solders will soon introduce bulk tin into electronics. Therefore, it is necessary to provide guidelines for use of the risk assessment algorithm in such instances.

The value of r1, which is dependent upon conductor spacing, and r2, which is dependent upon the Pb content, will remain essentially unchanged.

The value of r3, which depends upon deposition process, should be chosen with the value associated with hot-dip coatings. This is because the solder will have formed by solidification.

The value of r4 should be chosen with the value associated with the thickest possible deposit (the lowest value), because solder joints and BGA balls are generally quite thick relative to platings.

The values for r5 and r6, which are intended to account for the role of intermetallic growth and delta-CTE effects, will have no simple correspondence with a solder joint application. The ability of reactions at the interface between a solder joint and a pad to induce the stresses within the bulk of a joint will be minimal. Therefore, r5 should be set to its minimum value, corresponding to a nickel underplate, whether or not any nickel is actually present. Similarly, because stresses induced by delta-CTE affects are inversely proportional to the cube of the thickness of the layer under stress, the local stress level in the much thicker solder joint will always be much lower than the stress level in tin-plating. Therefore, r6 should also be set to its minimum value, corresponding to copper or aluminum, whether or not any copper or aluminum is actually present.

The values for the remaining factors will be unchanged relative to platings. Some care should be taken in determining the appropriate value for r7, which depends upon whether or not the ball is reflowed. Lead-free solder and BGA contacts formed from lead-free solder may or may not be subject to re-flow, depending upon the detailed process conditions used.

Table 2 – BGA Specific Ratings

r-factor	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10	r11	r12
setting	nc	nc	min	min	min	min	nc	nc	nc	nc	nc	nc

nc = no change from standard assignment rules
min = lowest value setting for this factor selected from the table

Risk Assessment Calculator

The risk factors are then given a rating from 0-1 on the "Risk Assessment Calculator" (Figure 3). The rating given is then calculated and the output is considered the overall risk.

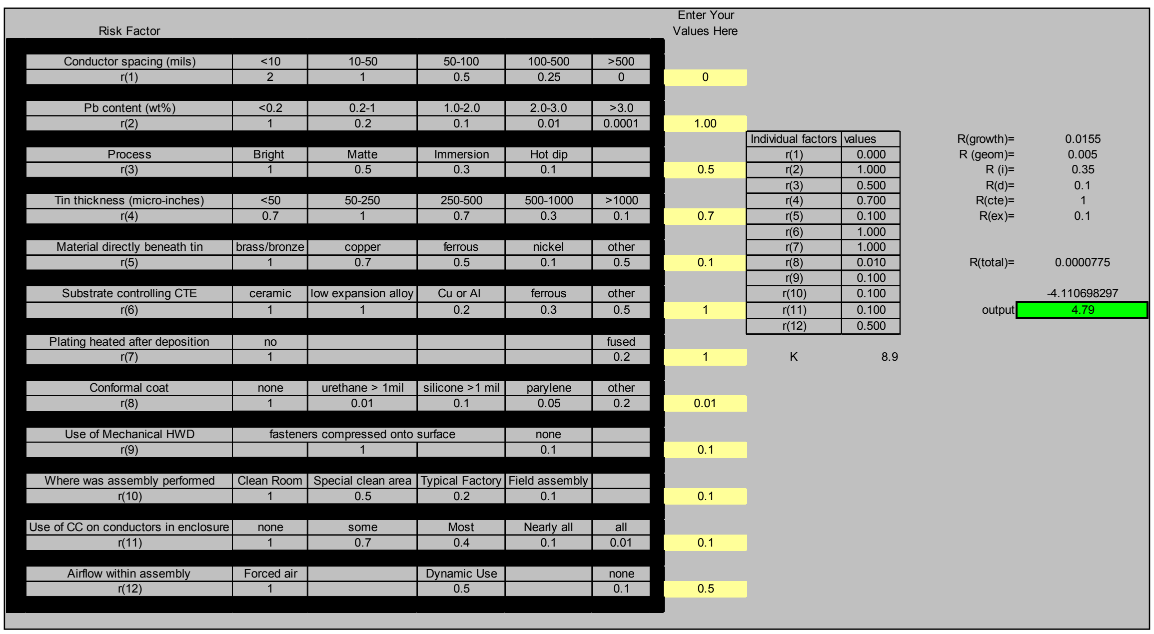

Figure 3 – Risk Assessment Calculator

For more information on the Tin Whisker Risk Assessment algorithm, please refer to the "Tin Whisker Application Specific Risk Assessment Algorithm" paper presented at the 2003 Military and Aerospace/Avionics COTS Conference[2].

Integrated System for Tin Use Evaluation

Determination of the suitability of a specific application of tin for use in a given piece of hardware requires an integrated approach.

The use of standard whisker mitigation levels provides the framework to flow requirements from the "top-down." The application specific risk assessment algorithm provides information from the "bottom-up." Integration of these two methodologies provides the requisite integrated approach.

Using the results from the tin whisker risk assessment algorithm, a threshold value can be assigned for each whisker mitigation level. This provides the guidance sought by designers to their basic question: "Can I use this part in this application, in this system?"

The suitability of tin finishes in applications will vary depending upon the program requirements. Similarly, within a given piece of hardware, some tin usages will be acceptable, while others will not.

This will result in a more complex situation than existed in the past, where finishes were globally classed as either "good" (Sn-Pb) or "bad" (Sn). Therefore, the controls and processes required for implementation will be more complex, rendering obsolete the simplistic approaches of the past.

Table 3 provides a listing of required application specific risk assessment threshold values for each whisker mitigation level. No values are provided for whisker mitigation Levels I and V as tin is always either acceptable or prohibited in these levels.

Table 3 – Recommended Thresholds

Whisker Mitigation Level	Recommended Risk Metric Limit
V	N/A (No pure Sn permitted)
IV	7.0
III	7.5
II	8.0
I	N/A (No restriction on pure Sn usage)

The values in this table are gauged to drive the use of design practices appropriate for different applications. These values have been checked using hundreds of evaluations. However, it is the responsibility of designers to verify that the results provided are acceptable to their particular customers.

Because no "bottom-up" approach exists for zinc whisker risk assessment, no integrated approach is possible at this time. However, the use of zinc in electronic components is not experiencing the explosive growth seen with tin. Therefore, the need for an integrated approach for zinc is not as urgent.

References

[1] Pinsky, David, "Tin Whisker Risk Algorithm Spreadsheet", paper presented at the 2003 Military and Aerospace/Avionics COTS Conference

[2] Pinsky, David , "Tin Whisker Application Specific Risk Assessment Algorithm", paper presented at the 2003 Military and Aerospace/Avionics COTS Conference