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PRE-STANDARD

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Process management for avionics – Aerospace and defence electronic systems containing lead-free solder –
Part 2: Mitigation of the deleterious effects of tin

IEC/PAS 62647-2:2011(E)

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Process management for avionics – Aerospace and defence electronic systems containing lead-free solder –
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PROCESS MANAGEMENT FOR AVIONICS – AEROSPACE AND DEFENCE ELECTRONIC SYSTEMS CONTAINING LEAD-FREE SOLDER –

Part 2: Mitigation of the deleterious effects of tin

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The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document
Draft PAS	**Report on voting**
107/108/PAS	107/116A/RVD

Following publication of this PAS, which is a pre-standard publication, the technical committee or subcommittee concerned may transform it into an International Standard.

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This PAS shall remain valid for an initial maximum period of 3 years starting from the publication date. The validity may be extended for a single period up to a maximum of 3 years, at the end of which it shall be published as another type of normative document, or shall be withdrawn.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

This PAS is intended for use by those procuring, designing, building or repairing electronic assemblies that will use items with Pb-free tin finishes to document processes they use to assure performance, reliability, airworthiness, safety, and certifiability of those assemblies. It provides a framework to communicate and agree on the processes to be used to control and mitigate the use of Pb-free tin in these applications.

The Aerospace Industries Association (AIA), the Avionics Maintenance Conference (AMC), and Government Electronics and Information Technology Association (GEIA) formed a joint working group with the express purpose of generating a series of industry standards documents for the use and handling of Pb-free solder, piece parts, and boards in aerospace and high performance applications. This PAS – originally published as GEIA-STD-0005-2 – was prepared by that group. It was balloted and approved by GEIA G-12 (Solid State Subcommittee) and GEIA Avionics Management Conference (AMC Subcommittee). According agreements between GEIA and IEC, this PAS is extended at international level.

This PAS is intended to work in concert with IEC/PAS 62647-1 (based originally on GEIA-STD-0005-1), GEIA-HB-0005-1 [1], GEIA-HB-0005-2 [2]. This PAS may be referenced in proposals, requests for proposals, work statements, contracts, and other documents. It may be used as a stand-alone standard or as part of compliance with IEC/PAS 62647-1.

This PAS addresses the risk of tin whiskers. However, the state of research into tin whisker risk still does not allow accurate quantitative estimates of the risk and reliability. It defines three baseline control levels that detail the amount of attention that should be paid to the risk of tin whiskers: no restrictions on tin use, some restrictions on tin use, and prohibition of tin use.

There are three informative annexes in this PAS:

– Annex A provides guidance on selecting control levels and performing risk assessments;
– Annex B describes mechanisms of formation, properties, and potential deleterious effects of tin whiskers;
– Annex C provides some background on various mitigation methods.

Due to a variety of real and potential health issues, many constituent materials used in the production of electronic products have come under scrutiny. The European Union (EU) has enacted two directives; 2002/95/EC Restriction of Hazardous Substances (RoHS) and 2002/96/EC Waste Electrical and Electronic Equipment (WEEE) that restrict or eliminate the use of various substances in a variety of products that are produced after July 2006. One of the key materials restricted is lead (Pb), which is widely used in electronic solder and electronic piece part terminations, and printed wiring boards. While these regulations may appear to only affect products for sale in the EU, due to the reduced market share of the Aerospace and High Performance Industry in electronics, many of the lower tier suppliers are changing their products because their primary market is consumer electronics. Additionally, several U.S. states have enacted similar “green” laws, and many Asian electronics manufacturers have recently announced completely “green” product lines.

The restriction of Pb use has generated a transition by many piece part and board suppliers from tin-lead (Sn-Pb) surface finishes to pure tin or other Pb-free finishes. Lead-free tin finishes can be susceptible to the spontaneous growth of crystal structures known as “tin whiskers” which can cause electrical failures, ranging from parametric deviations to catastrophic short circuits, and may interfere with sensitive optical surfaces or the movement

1 A future IEC/PAS 62647-21, based on GEIA-HB-0005-1, is in preparation.

2 A future IEC/PAS 62647-22, based on GEIA-HB-0005-2, is in preparation.

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of Micro-ElectroMechanical Systems (MEMS). Though studied and reported for decades, the mechanism behind their growth is not well understood, and tin whiskers remain a potential reliability hazard. Furthermore, the growing number of piece parts with pure tin finishes means there are more opportunities for whiskers to grow and to produce failures.

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PROCESS MANAGEMENT FOR AVIONICS – AEROSPACE AND DEFENCE ELECTRONIC SYSTEMS CONTAINING LEAD-FREE SOLDER –

Part 2: Mitigation of the deleterious effects of tin

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1 Scope

This PAS establishes processes for documenting the mitigating steps taken to reduce the harmful effects of tin finishes in electronic systems.

This PAS is applicable to Aerospace and High Performance electronic applications which procure equipment that may contain Pb-free tin finishes.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply:

2.1
assemblies
electronic items that require electrical attachments, including soldering of wires or component terminations; examples include circuit cards and wire harnesses. This may include soldered assemblies

2.2
bright tin
tin finish with higher internal stresses and smaller grain size of 0,5 μm to 0,8 μm and carbon content of 0,2 % to 1,0 %

2.3
critical
item or function, if defective, will result in the system's inability to retain operational capability, meet primary objective, or affect safety

2.4
customer
entity or organization that (a) integrates a piece part, soldered assembly, unit, or system into a higher level system, (b) operates the higher level system, or (c) certifies the system for use. For example, this may include end item users, integrators, regulatory agencies, operators, original equipment manufacturers (OEMs), and subcontractors

2.5
energy dispersive (X-ray) spectroscopy
EDS
method for material composition analysis

2.6
high performance system or product
system or product which requires continued high performance or performance on-demand, or equipment downtime cannot be tolerated, or end-use environment may be uncommonly harsh and the equipment must function when required, such as life support or other critical systems

2.7
lead-free
defined as less than 0,1 % by weight of lead in accordance with Waste Electrical and Electronic Equipment (WEEE) guidelines

2.8
matte tin
tin finish with lower internal stresses and larger grain sizes typically of 1 µm or greater and carbon content less than 0,050 %

2.9
Pb-free tin
tin defined to be pure tin or any tin alloy with <3 % lead (Pb) content by weight. This means that some Pb-free finishes other than pure tin, such as tin-bismuth and tin-copper, are considered to be “tin” for the purposes of this PAS. Many of these alloys have not been assessed for whiskering behavior

2.10
Pb-free tin finish
Pb-free tin final finishes or underplates either external or internal to a device, board or other hardware. This includes all leads and surfaces, even those coated, encapsulated, or otherwise not exposed. It may include finishes on electrical piece parts, mechanical piece parts, and boards. It does not include Pb-free bulk solders, assembly materials, solder balls, or those devices where the Pb-free tin finish has been completely replaced

2.11
piece part
electronic component that is not normally disassembled without destruction and is normally attached to a printed wiring board to perform an electrical function

2.12
rework
act of reprocessing non-complying articles, through the use of original or equivalent processing in a manner that assures full compliance of the article with applicable drawings or specifications

2.13
repair
act of restoring the functional capability of a defective article in a manner that precludes compliance of the article with applicable drawings or specifications

2.14
sub-contractor
organization, within the given high-reliability industry, that supplies, maintains, repairs, or supports electronic systems, and is not the direct supplier to the customer or user of those systems

2.15
supplier
entity or organization that designs, manufactures, repairs, or maintains a piece part, unit, or system. For example, this includes original equipment manufacturers (OEMs), repair facilities, subcontractors, and piece part manufacturers. In some cases, a single organization may be both a customer and a supplier. They should follow the requirements for suppliers when addressing their customer’s contracts and should follow the requirements for customers when flowing down requirements to their lower tier suppliers

2.16
system
one or more units that perform electrical function(s)

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2.17
tin whisker
spontaneous crystal growth that emanates from a tin surface. They may be cylindrical, kinked, or twisted. Typically they have an aspect ratio (length/width) greater than two, with shorter growths referred to as nodules or odd-shaped eruptions (OSEs). See Annex B for further description of tin whiskers and their physical attributes

2.18
unit
one or more assemblies within a chassis to perform electrical function(s)

2.19
X-ray fluorescence
XRF
method for material composition analysis

3 Requirements

3.1 Determination of levels

The customer is responsible for determining the control level they are seeking and identify it in their request for proposal when this PAS is imposed. They should also determine the level of oversight and review the program will require. For some programs, different control levels may be required for different products. In these cases, the customer is responsible for defining these different levels and their applications or define a process by which they and the supplier will determine the levels.

The customer and supplier shall agree on the control levels and shall document this agreement in appropriate control documents.

There will be cases where errors will be made in the finish determination or in the application of mitigation methods. Customers and suppliers should have processes in place to document and assess the impact of these errors. Already existing deviation or waiver processes may be acceptable if technical experts on tin whiskers are consulted.

3.2 Requirements for control levels

3.2.1 General

Each program or system has the responsibility of determining the appropriate control level for their product. This document is not intended to imply that any category of aerospace or high performance application is more or less reliable or critical than any other category; nor is it intended to imply that any aerospace or high performance system will be more or less reliable, depending on the control level that is selected from the above list. Reliability is assured by a wide range of design, production, use, and support decisions and activities, of which tin whisker mitigation is only one. It is expected that, whatever level of mitigation category is used, the system reliability will be assured by the totality of all the methods available to the producer and user of the system.

There are many aspects to tin whisker control. For the purposes of this PAS, the activities have been grouped into four categories:

– documentation of uses of Pb-free tin;
– detecting and controlling Pb-free tin introduction;
– tin whisker risk mitigation;
– tests and analyses of tin whisker risk and mitigation effectiveness.

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If only Level 2, with no sub-level, is identified in a control document, the default level *shall* be assumed to be Level 2A.

3.2.2 Control Level 1 requirements

3.2.2.1 Requirements for documentation of uses of Pb-free tin

There are no requirements. The supplier should provide general information regarding types of platings, finishes, and solder used and plans for process controls on those processes in accordance with 3.3.1. If the supplier is unable to determine some materials, this shall be stated.

3.2.2.2 Requirements for detecting and controlling Pb-free tin finish introduction

No requirements.

3.2.2.3 Requirements for tin whisker risk mitigation

No requirements.

3.2.2.4 Requirements for tests and analyses of tin whisker risk and mitigation effectiveness

No requirements.

3.2.3 Control Level 2A requirements

3.2.3.1 Requirements for documentation of uses of Pb-free tin

There are no supplier requirements. The supplier should provide general information regarding types of platings, finishes, and solder used and plans for process controls on those processes in accordance with 3.3.1. If the supplier is unable to determine some materials, this shall be stated.

The customer is responsible for listing any applications where Pb-free tin is not allowed.

3.2.3.2 Requirements for detecting and controlling Pb-free tin finish introduction

No requirements.

3.2.3.3 Requirements for tin whisker risk mitigation

The supplier shall provide descriptions of any mitigation methods assumed to be in use for the tests and analyses in 3.2.3.4. The supplier shall provide descriptions of any mitigation measures taken for hardware.

The customer is responsible for defining any mitigation measures that are required or disallowed.

3.2.3.4 Requirements for tests and analyses of tin whisker risk and mitigation effectiveness

The supplier shall provide an analysis addressing the risk of tin whiskers in accordance with 3.3.4. This analysis is expected regardless of whether mitigations are applied. If no mitigations are applied, the analysis should demonstrate why they are not needed. If mitigations are applied, the analysis should demonstrate that they are effective.

For Level 2A, these analyses may be performed at the process level. For example, the analysis might address all devices with a particular mitigation technique employed.

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3.2.3.5 Exceptions

Specific piece parts, soldered assemblies, units, or applications may be required to meet a higher level of control. These requirements shall be specified in contractual documents.

3.2.4 Control Level 2B requirements

3.2.4.1 General

For Level 2B hardware, these control plans may cover families of piece part types or applications. Separate assessments and control plans for each individual item are not required. For example, one assessment might allow use of all tin-plated capacitors in a variety of applications.

3.2.4.2 Requirements for documentation of uses of Pb-free tin

The supplier shall provide lists of families of tin-finished piece parts and/or location and material information for categories of applications where they would like to use Pb-free tin in accordance with 3.3.1.2. If there are other uses of tin, the supplier shall provide a list of additional specific applications of Pb-free tin that fall outside these families in accordance with 3.3.1.3. If the supplier is unable to determine some materials, this shall be stated.

The customer is responsible for listing any applications where Pb-free tin is not allowed.

3.2.4.3 Requirements for detecting and controlling Pb-free tin finish introduction

The supplier should provide a plan for monitoring materials on a sample basis, including method of test and sampling scheme, in their product in accordance with 3.3.2.1.

3.2.4.4 Requirements for tin whisker risk mitigation

The customer is responsible for defining any mitigation measures that are required or disallowed.

The supplier shall implement the mitigating measures contractually required by the customer.

It is recommended that at least two mitigation measures in accordance with 3.3.3 be required and performed.

3.2.4.5 Requirements for tests and analyses of tin whisker risk and mitigation effectiveness

If a specific risk algorithm or other method for evaluation measure is required, the customer is responsible for describing them in the request for proposal. The customer is also responsible for communicating any documentation review or oversight requirements to the supplier.

The supplier shall have documentation covering the following elements:

– the mitigation measures taken for each family of piece parts or applications of Pb-free tin finish in the product;
– the tests or analyses performed for each family of piece parts or applications using Pb-free tin finishes, to determine risk of whisker growth in accordance with 3.3.4;
– if there are other uses of Pb-free tin outside the families, the mitigation measures taken for each piece part or application of Pb-free tin finish in the product outside the families;
– if there are other uses of Pb-free tin outside the families, the tests and analyses performed for each of these piece parts or applications to determine risk of whisker growth in accordance with 3.3.4;

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– provide the risk assessment and mitigation measures to the customer for their review, as requested or required by customer.

3.2.5 Control Level 2C requirements

3.2.5.1 General

For Level 2C hardware, separate assessments and mitigation plans are required for each instance of Pb-free tin finish use. For example, instead of one assessment and mitigation plan covering all tin-plated capacitors, each capacitor type and application must be reviewed and approved, even if the same strategy is applied to each situation.

3.2.5.2 Requirements for documentation of uses of Pb-free tin

The supplier shall avoid use of Pb-free tin whenever possible. The supplier shall not allow use of Pb-free tin finishes without prior written permission of the customer and shall provide the customer with a list of all uses of Pb-free tin. Each individual use shall be reviewed and approved or disapproved by the customer.

The supplier shall provide a plan for passing the requirement to lower level suppliers in accordance with 3.3.1.4.

3.2.5.3 Requirements for detecting and controlling Pb-free tin finish introduction

The supplier shall provide a plan for monitoring materials in their product in accordance with 3.3.2.1. The supplier and customer shall reach an agreement regarding this plan.

For critical piece parts, assemblies or systems, the plan should include sampling at least one part per lot of all piece parts not approved for tin.

3.2.5.4 Requirements for tin whisker risk mitigation

The customer is responsible for defining any mitigation measures that are required or disallowed in their request for proposals and contractual documents.

The supplier shall implement at least two mitigation measures in accordance with 3.3.3.

3.2.5.5 Requirements for tests and analyses of tin whisker risk and mitigation effectiveness

The customer is responsible for describing the risk algorithm or other methods for evaluating mitigation measures in the request for proposal, if applicable. The customer is also responsible for communicating any documentation review or oversight requirements to the supplier.

The supplier shall have documentation covering the following elements:

– the mitigation measures taken for each piece part or application of Pb-free tin finish in the product;
– the tests and analyses performed for each piece part or application using Pb-free tin finishes, to determine risk of whisker growth in accordance with 3.3.4;
– provide the risk assessment and mitigation measures to the customer for their review, as requested or required by customer.

3.2.6 Control Level 3 requirements

3.2.6.1 Requirements for documentation of uses of Pb-free tin

The supplier shall not allow use of Pb-free tin finish.

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The supplier shall provide a plan for passing the requirement to lower level suppliers per 3.3.1.4.

The supplier shall maintain records of their monitoring of materials in their product.

3.2.6.2 Requirements for detecting and controlling Pb-free tin finish introduction

The supplier shall monitor the material in their product per 3.3.2.2.

3.2.6.3 Requirements for mitigation of tin whisker risk and mitigation effectiveness

Not applicable, as Pb-free tin finish is not allowed.

3.2.6.4 Requirements for tests and analyses of tin whisker risk and mitigation effectiveness

Not applicable, as Pb-free tin finish is not allowed.

3.3 Implementation requirements

3.3.1 Documentation of uses of Pb-free tin

3.3.1.1 Documenting general materials and processes (applies to Level 1, Level 2A)

Documentation of general materials and processes should describe the types of finishes and solders used in the products and the processes corresponding to the manufacturing or installation of products with Pb-free tin finishes. If different materials and processes are used for different applications, the application and the corresponding materials and processes should be listed. Although Levels 1 and 2A do not impose any Pb-free tin finish controls, the supplier may have processes that limit but do not prohibit the use of Pb-free tin finishes in some applications.

3.3.1.2 Documenting uses of Pb-free tin finishes by family (applies to Level 2B)

Documentation of specific uses of Pb-free tin finishes shall include a list of each family of piece parts with a tin-finished surface, which surfaces are tin, and a description of the finish composition. A family of piece parts might include multiple part numbers of a particular type of piece part, for example, capacitors or it might include all piece parts from a particular supplier. The supplier shall also provide a list of what applications will include piece parts from the family.

3.3.1.3 Documenting specific uses of Pb-free tin finishes (applies to Level 2B and Level 2C)

Documentation of specific uses of Pb-free tin finishes *shall* include a list of each individual piece part with a Pb-free tin-finished surface and a description of the finish composition, and a list of what applications will include that piece part.

3.3.1.4 Flowing requirements to lower level suppliers (applies to Level 2B, Level 2C, and Level 3)

Requirements for tin whisker control, analysis, and mitigation are applicable to all purchased and subcontracted elements and materials for the program. This may require flowing down these requirements to lower level supplier or performing extensive analysis of purchased material. The supplier should be prepared to document how they addressed the risk from purchased equipment if requested or required by the customer.

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3.3.2 Detecting and controlling Pb-free tin finish introduction

3.3.2.1 Sample monitoring plans (applies to Level 2B and Level 2C)

A monitoring plan, including method of test and sampling scheme, *should* be agreed to by the customer and the supplier for Level 2B and shall be agreed for Level 2C.

For Level 2B, the monitoring plan and sampling scheme should focus on critical hardware where Pb-free tin usage approvals have not been obtained.

For critical hardware following Level 2C where Pb-free tin usage approvals have not been obtained, the monitoring plan described in 3.3.2.2 should be used.

Some testing methods and their limitations are described in the Annex C.

3.3.2.2 Lot monitoring requirements (applies to Level 3)

A lot screening program is required for all items with metallic finishes. Items containing metallic finishes shall be tested by a method agreed to in writing by the customer, at least one sample per lot or batch received, unless otherwise specified by the customer. A minimum of 3 % Pb by weight is required. Some testing methods and their limitations are described in Clause C.1.

Customer may allow an exception for monitoring if material specification defines all finishes as gold with no Pb-free tin finishes and a visual inspection of the device shows it to be gold-colored. This exception should be stated in contractual paperwork if used.

3.3.3 Methods for mitigating impact of Pb-free tin (applies to Level 2B, Level 2C)

3.3.3.1 General

Since the failure mechanisms for whisker growth are not fully understood, no single method is an assurance against whiskers in all applications, environments, and lifetimes. The method or methods used shall be documented in the Pb-free tin finish mitigation plan.

Many mitigations methods have been proposed in the literature and are summarized in Clause C.2. Additional information can be found in JP002. Recommended mitigations, and some information on circumstances where they might be most useful, are presented below. The categories in this section represent four independent approaches; multiple actions taken in one category are not considered separate mitigations. Other mitigations methods may be applied but documentation regarding their effectiveness shall be provided.

The selection of the appropriate mitigation techniques will depend on the assessment of the application and data regarding the mitigation strategies. The discussion of risk assessments provided in Clause A.3, may help in selecting appropriate mitigation combinations. Some combinations of mitigations may be more effective and make more sense than others. The combination for a particular application should be carefully evaluated to make sure that the mitigations will successfully work together to reduce the risk of whiskers.

3.3.3.2 Design to reduce whisker impact

Although design for reduced whisker impact could include several areas, such as piece part selection and process changes, for the purposes of this PAS it means board design to reduce the chance of whiskers causing shorts even if the whisker has grown. Design mitigations could include the spacing of surfaces on which a whisker could bridge and cause shorts and the use of physical barriers.

Empirical studies over the past several decades have shown the distribution of lengths and density of tin whisker population can span wide ranges. For example, many tin finishes

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seemingly may never grow whiskers while others may grow large numbers of whiskers in excess of several millimetres in length. In extremely rare cases maximum lengths on the order of 10 mm have been documented. Intuitively, the risk of tin whisker induced shorting decreases as the minimum shorting distances in the circuit design increase. More information on whisker growth rates and lengths is provided in the informative Annex B.

The spacing requirements are left to the discretion of the customer and supplier, as different applications may be tolerant of different levels of risk.

Placement of a physical barrier can prevent whiskers from growing from one conductive surface to another. Because whiskers can grow through oils, greases and softer lacquers, care must be taken in selecting the material of the barrier; the harder materials are much more effective, provided they remain intact. While a barrier may prevent a whisker growing from one conductive surface to another, it cannot mitigate the risks associated with free-floating whiskers unless a combination of barriers fully encase the tin-finished area.

3.3.3.3 Select lower risk Pb-free tin finishes

Although all tin finishes (including those with >3 % Pb content) have some risk of whiskers, some finishes have greater risk than others. Selection of a matte tin, preferably with a nickel underplate, or a Pb-free tin alloy with nickel underplate are generally considered lower risk finishes than bright tin or tin finishes over copper. Impact of underplate thicknesses and other lower risk finishes is under review in the literature. Groups such as International Electronics Manufacturing Initiative (iNEMI) may have additional guidelines on finish selection.

There are also an increasing number of suppliers who provide Pb-free tin finishes that are warranted against whiskers. Use of these finishes is considered mitigating if the application environment and product life length are compatible with the warranty.

If this mitigation method is applied, references or documentation supporting selected finish performance shall be provided.

For the purposes of this PAS, heat treatments are considered to be in the category of lower risk finishes. Heat treatments could include reflow, fusing, or annealing at the piece part or board levels. More information on the impact of these processes is provided in C.2.2.4 and C.2.2.5.

3.3.3.4 Tin finish replacement

As stated in the definition, if all Pb-free tin finishes on the device have been replaced through replating or solder-dipping then the device is no longer considered to be tin-finished. However, if only some tin-finished surfaces have been reworked, then the actions are considered to be mitigations. For example, if tin-finished leads are solder dipped in Sn-Pb, but the dipping does not reach the piece part body, the dipping is only a mitigation and not a full replacement. If there are tin-finished surfaces that cannot be reworked because of encapsulation, then the replacement of exposed Pb-free tin finishes is only a mitigation.

Replacement of finish may lead to suppliers no longer guaranteeing the performance of piece parts. Therefore, some analysis and possibly qualification of the re-processed piece parts may be needed to verify that they will function as intended. It is recommended that customers require objective evidence that the functionality of the piece part has not been compromised by the aftermarket processing. This is an area of active research, and several groups are working on best practices to avoid damaging the piece parts.

3.3.3.5 Conformal coat

The use of conformal coating does not eliminate the potential for whisker failure entirely; however, it is a mitigating measure. For most coatings, tin whiskers have been shown to eventually grow through thin coatings. Although there is believed to be low risk of a whisker

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penetrating the coating of an adjacent surface, whiskers could still short to other uncoated surfaces in the area. For some piece part types, it is difficult to entirely encapsulate the individual interconnects so there remains a direct path for shorting due to whisker growth. Other drawbacks include bubbles between tightly spaced leads and connector mating pin overspray contamination. Coating materials and processes should also be carefully reviewed to ensure their compatibility with the hardware design and application. For example, excessively thick coatings and/or mismatches of coefficients of thermal expansion may reduce life expectancy of solder joints or crack piece parts.

It is recommended that an assessment of the conformal coating process be performed to assure that coverage and thickness are adequate and consistent. It is also recommended that the conformal coat process be regularly evaluated and that the evaluation results be available for customer review.

3.3.4 Methods for analysis and evaluation of tests and mitigations for tin whisker risk and mitigation effectiveness

3.3.4.1 General

The customer and supplier should evaluate their products, applications, and environments and evaluate how test data and mitigation strategy applies to those conditions. A number of different analyses might be appropriate for this requirement. Determination of the appropriate analysis should be made by the supplier and customer.

3.3.4.2 Analysis of application tolerance

Analyses of application tolerance might include descriptions of spacing distances versus distribution of whisker sizes and whisker density, examination of barrier locations or conformal coat coverage, or Failure Modes and Effects Analyses (FMEA) of the impact of shorts, plasma events, and possible micromechanical dysfunction.

Tolerance analyses might determine that tin whiskers have no impact or that there is some level of impact. If there is possible impact, the supplier and customer should evaluate those risks and impacts and determine if they are acceptable.

In some cases, the analysis may involve a discussion of the overall reliability model or unit design. For example, it may be that the application has adequate margin, a redundancy, or a maintenance schedule to allow for a probability of whiskers without impacting mission performance. It may also be the case that field data on particular tin-finished piece parts in similar environments exists, and can be used to support a low risk of whisker impact.

3.3.4.3 Analyses of whisker propensity tests

Although the mechanisms for tin whisker growth are still unknown, there are several test methods being used by suppliers in the industry. Industry standard tests do provide a common method and comparable data.

Many piece part suppliers are involved with developing tin whisker test methods and finish qualification methods. Some examples include JESD22-A121 "Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes" and JESD201 "Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes." Tests typically include aged samples being put through thermal cycling, humidity, high temperature, and ambient testing. Acceptable test results alone should be considered adequate only for Level 2A hardware.

If qualification or other test data is included, the analysis should include a discussion of why the test was representative and how the results were generalized to the application environment and product life length. Note that, until the fundamental mechanisms of tin whisker growth are understood and acceleration factors established, customers with environmental exposures longer than the test length should be cautious about extrapolating

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the test results too extensively. This is particularly true for systems with greater than 20 or 30 years of storage and mission life, harsh temperature cycle environments, or harsh humidity environments. Even tests that show whisker growth rate slowing should be applied with caution as periods of dormancy have been observed on whiskers.

3.3.4.4 Analyses of field data

Suppliers' field data of historic reliability on hardware using tin piece parts may provide insight into the risk of tin whiskers. Historic failure databases of these tin piece parts in these applications might include some tin whisker failures, if failures were possible, but their cause may not have been traced to a whisker.

However, care must be taken in extrapolating field data results. Different plating processes, from different suppliers, may have different propensities to whiskering. A growing number of piece parts with Pb-free tin finishes means there are more opportunities for whiskers to grow and to produce failures. The similarity of the field data to future use must be addressed in any analysis taking this approach.

3.3.4.5 Other analysis issues

Analyses should also discuss any applied mitigation strategies. If the design has a mitigating feature, criteria for appropriate spacing and barriers should be agreed upon. If lower risk finishes have been selected, the finishes should be described and any available data or references supporting improved performance presented. If some Pb-free tin finishes have been replaced, the analysis should include a discussion of any remaining Pb-free tin finishes and evidence supporting that the aftermarket processing did not damage the device. Conformal coat mitigation should include a description of the coating type, data and references supporting the effectiveness of the coating at limiting whisker growth, and any measures taken to qualify and monitor the coating process.

Analyses might also include use of a risk algorithm. Although there is no industry consensus on a specific algorithm to be called out in this PAS, more information regarding these evaluations is provided in Clause A.3.

Unlike many failure mechanisms, tin whiskers grow equally well, if not better, under storage conditions as compared to application environments. If the application is likely to have a long period of storage, it is recommended that customers require suppliers to address risk from this period or include it in any life-time calculations.

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Annex A
(informative)

Guidance on control levels, risk assessment, and mitigation evaluation

A.1 Introduction

The determination of the suitability of the use of Pb-free tin must be performed on an application-by-application basis. Unfortunately, the current state of our understanding of the tin whisker phenomenon does not permit the quantification of the probability of failure due to tin whiskers for any particular application, even under extremely well controlled circumstances. Nonetheless, customers and supplier must choose tin control levels, mitigation strategies and weigh those decisions against the risk of tin whiskers.

Potential applications of high reliability electronic systems vary from "single thread" systems where no failures can be accepted for very long periods of time, often exceeding 20 years, to systems where it is necessary to be single failure tolerant and it is necessary to mitigate the effects of single failures utilizing multiple techniques including redundancy and field support actions. A guiding principal should be that it is not possible to have a single channel electronic system that will never fail. Thus, for high reliability electronic systems, multiple provisions and techniques are required to achieve application specific reliability and availability. These principles apply to both the risk from tin whiskers as well as other failure mechanisms that have long been considered in risk and reliability assessments.

A.2 Level determination

There are three basic levels: no controls on tin finishes, some controls on tin finishes, and prohibition of tin finishes. Level 2, some controls on tin finishes, has three sub-levels. The differences between the three sub-levels may seem subtle, but the differences were carefully established to allow flexibility between different program types. Full requirements are provided in the normative sections of this PAS, but it may be helpful to review the following summary of requirements when selecting a program’s level.

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Table A.1 – Summary of control level requirements

	Documentation of tin use	Detection and control	Mitigation	Risk analysis
Level 1	Supplier: general information on finishes used	None	None	None
Level 2A	Supplier: general information on finishes used Customer: list of any applications where tin is not allowed	None	None. However, if mitigation methods were assumed for the purposes of analyses, the supplier shall report those assumed mitigations.	At the process level: analyses showing application tolerance to whiskers, OR analyses of tests to demonstrate propensity of whiskering, OR field data analysis demonstrating requirements will be met even if no mitigations are applied.
Level 2B	Supplier: list of families of tin-finished piece parts and categories of applications where they would like to use tin Customer: list of any applications where tin is not allowed	It is recommended that the supplier and customer develop a sampling plan for confirming materials received.	It is recommended that at least two mitigation methods be employed.	At the family level: analyses showing application tolerance to whiskers, OR analyses of tests to demonstrate propensity of whiskering, OR field data analysis demonstrating requirements will be met. Some individual uses may need to be analyzed at the instance level.
Level 2C	Supplier: list of all instances of pure tin Customer: list of any applications where tin is not allowed	A sample monitoring plan is required but its specifics are left to an agreement between supplier and customer. For critical piece parts, assemblies or systems, the plan should include sampling at least one part per lot of all piece parts not approved for tin.	At least two mitigation methods are required.	At the instance level: analyses showing application tolerance to whiskers, OR analyses of tests to demonstrate propensity of whiskering, OR field data analysis demonstrating requirements will be met.
Level 3	Supplier: documentation of lot screen results	At least one sample per lot of all items containing metallic finishes must be tested by a method agreed to by the customer and supplier.	None. Not applicable. No tin is to be used, so no mitigation is required.	None. Not applicable. No tin is to be used so no risk analysis is required.

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As part of the determination of which tin whisker control level is appropriate for a specific application, factors to be evaluated could include the following:

– what techniques are currently utilized to achieve acceptable failures levels for identical or similar applications?

– are these techniques sufficiently effective to assure that tin whiskers will not be an issue?

– some customers and suppliers may have been utilizing electronic piece parts with Pb-free tin finishes in safety critical applications for many years and this experience may help inform decisions about future Pb-free tin use. Does field data exist for the types of environments for the application in question? Is the data on piece parts, soldered assemblies, or units similar to those used in the application in question? Is the failure rate due to tin whiskers sufficiently high that specific corrective action is necessary, or is it sufficiently low that it is adequately addressed by the multiple techniques already implemented? Note that field data on tin finished piece parts likely is on boards where the piece parts were soldered with Sn-Pb attach. The suitability of this data when there is increased use of tin finished piece parts or the piece parts are used with Pb-free solder needs to be examined;

– has the failure rate due to tin whiskers been evaluated relative to the failure rate resulting from processing and handling during the replacement of the Pb-free tin on the piece part? Historical data indicates that handling induces latent failures. For extremely complex integrated circuits, the possible inability to do functional testing subsequent to the tin removal process contributes an additional risk factor.

A.3 Risk assessments

In order to make a final determination of a control level or a particular mitigation strategy, many programs will require a risk assessment. Although quantitative risk calculations and probabilities may not be possible, qualitative risk assessments will need to be performed if reasoned decisions are to be made concerning the use of tin.

Tin whiskers can induce failures by various mechanisms. All mechanisms that are applicable to the circumstances under assessment must be considered.

a) The vast majority of reported tin whisker-induced failures have resulted from the growth of the tin whisker from one conductor so that it bridged the gap to an adjacent conductor at a different electrical potential, including the possibility of whisker-to-whisker shorts. The bridging creates a short-circuit between the two conductors, often resulting in destruction of the whisker in the manner of a fuse element. For low pressure or high voltage applications, plasma events may result from the shorting.

b) A second failure mechanism has also been reported. With this mechanism a whisker grows in one location, becomes dislodged, and is transported to another location where it bridges between two conductors creating a short circuit. (This failure mechanism has been widely reported to have been induced by zinc whiskers.)

c) Whiskers that become loose within an assembly that is highly sensitive to contamination can pose a variety of risks, depending upon the system including: disruption of optics, disruption of micromechanical function, blockage of extremely small orifices, etc.

d) Whiskers that grow from the surfaces of RF waveguides into the region of space where the RF fields are propagating can affect the performance of the device, without necessarily contacting a second surface.

The performance of these assessments must take into account the various factors that affect the risk of occurrence of these tin whisker-induced failures. There are five principal factors that must be considered in assessing such risks. These are the following.

Factor 1: The propensity of the Pb-free tin surface in question to grow whiskers of a given length, in a given abundance, in a given time frame.

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Different coatings of Pb-free tin will produce whiskers of various densities and length distributions [77, 78]. In general, shorter whiskers are more numerous than longer whiskers. Various mitigation techniques are applied with the goal of producing low densities of whisker growths that do not include long whiskers. The intent of testing methods for whisker growth, such as JESD-201, is to verify that coatings do not produce long whiskers. Care must be taken when performing a risk assessment to be sure that assumptions on whisker length and densities can reasonably be applied to the Pb-free tin coating under consideration. One area of concern is that whisker growth data and testing is typically performed at the piece part level, but the risk must be assessed after higher-level assembly. Manufacturing processes at the OEM that induce stress into the surface (lead forming, lead sharing, connector mating, handling damage, etc.) may increase the propensity for whisker formation.

Whisker growth has been reported to occur over a wide range of growth rates. Whisker growth kinetics are typically described as occurring in three phases: latency, growth, and saturation. Growth rates from 0,03 mm/yr to 9 mm/yr have been reported. Latency periods have been reported to range from days to years [27, 30, 33]. It will therefore be difficult to use abbreviated service life as a justification for assuming that only short whiskers will exist. Additionally, an observation that whisker-free performance has been observed for a few years may not imply that long whiskers will not be present in the future.

Factor 2: The ability of whiskers growing from that surface to create an electrical short directly to an adjacent metallic surface.

The principal factors for consideration here are the distance between conductors, and existence and nature of any intervening barriers.

Whiskers must be sufficiently long to bridge a gap to create a failure risk. Therefore, the risk of failure decreases rapidly with increasing gap size. Conductor spacing must be assessed together with assumptions on the ability of the Pb-free tin coating to produce whiskers of that length, as described above.

Since whiskers are known to grow from their base, only those surfaces that are within a direct line of sight of the whisker origin, considering all possible growth angles, are at risk for direct contact from a growing whisker. Kinks and bends in the whiskers should be considered, but since growth occurs at the base, it is difficult for whiskers to grow around barriers. Substantial mechanical barriers (washers, spacers, hard staking compound materials, etc.) may reasonably be assumed to prevent whisker penetration. Barriers that are soft or thin (conformal coating, grease, oil, lacquer, etc.) may not be completely effective in preventing the penetration of a growing whisker [11, 12, 41]. Therefore, when such materials are used as barriers their ability to stop whisker penetration needs to be considered in detail.

Factor 3: The ability of whiskers to break off and to migrate to a different location in the system, where they could create electrical shorts or act as general contaminants in especially sensitive assemblies.

Although there is a significant body of experience related to failures induced by migrating zinc whiskers, there is much less data regarding failures due to migrating tin whiskers. Because of the small scale for tin whiskers, shock and vibration excitation will be far less efficient than fluid flow or electrostatic excitation to produce whisker motion. The risk associated with creating electrical shorts will relate to the conductor spacing within the assembly as related to the length of the whiskers that have formed. In this case the conductor spacing of highest concern would be the smallest spacing found within the assembly that contains the Pb-free tin coated surface.

Factor 4: The vulnerability of the system to suffer performance degradation due to electrical shorts such as might be created by tin whiskers.

Whisker-induced shorts can either be transient, due to whisker fusing, or persistent. The amount of current conducted by whisker, and for how long, will depend upon the applied voltage, length of the whisker in the air pressure [8, 23,

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35]. A determination that a particular whisker-induced short will be transient (e.g., due to whisker fusing or melting) does not generally provide sufficient justification to conclude that system-level dysfunction will not result.

Factor 5: The vulnerability of the system to suffer performance degradation to the presence of whiskers as general contamination.

Considerations here apply to extremely sensitive systems where very high degree of cleanliness is required for reliable functionality. Such systems would normally be assembled using clean room controls. Examples of these include optical, micromechanical, and some fluidic systems. In this case assessment of the anticipated whisker growth should be compared to be system limits for contamination to determine whether the anticipated growth could produce contamination of a size and quantity that could affect system performance.

The detailed contributors to these factors are discussed in reference [71].

It is important to note when performing risk assessments that the certainty that a whisker will fuse open does not imply that there is zero risk of failure. Certainty of fusing only implies that any failure condition is likely to be intermittent. There are numerous examples and literature of whiskers which fused, but still cause the system-level failure (see [72] and [73]).

The rationale supporting risk assessments will need to be recorded, to preserve traceability for audit purposes. This requirement, together with typical industry quality requirements (such as ISO 9000) creates a strong incentive for the establishment of standardized approaches for risk assessment within each organization, at the minimum.

There are three basic approaches to standardized risk assessment in this context.

First approach: Assignment of "cognizant subject matter experts" to review, record rationale, and signoff each risk assessment.

Second approach: Establishment of a set of rules-based criteria that define conditions under which the risks are deemed to be acceptable.

Third approach: Development of an algorithm that encompasses risk factors of concern that can be used to define a metric of risk on a standard basis.

In practice, some combination of these three approaches may be used in concert.

An example of a rules-based criterion that might be used for establishing a risk threshold could be: "Circuit cards which are 100 % covered by urethane conformal coat to a thickness of 100 μm minimum shall be considered to provide acceptable mitigation against tin whisker risks for whisker mitigation level 2B hardware." (Arbitrary example, not intended as a recommendation.)

Examples of algorithms for use in calculating a risk metric are described in reference [74] and [75]. Users may consider applying these existing algorithms without modification, modifying them to suit specific needs, or using them as a basis for the development of new algorithms. (The algorithms described in these references are available for use in the public domain, without restriction.)

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Annex B
(informative)

Technical guide on tin whiskers

B.1 Common tin whisker attributes

The following paragraphs provide an overview of some of the observed characteristics of tin whiskers. These features are discussed in more detail in the following references: [1, 2, 3, 8, 9, 16, 19, 20, 23, 25, 27, 28, 30, 33, 35, 43, 68].

- **Shapes and surface features:** Whiskers are approximately cylindrical, needle-like crystals that can grow either straight or kinked. The surface is usually striated longitudinally. Whiskers may grow directly out of the surface or from pyramid-shaped nodules on the surface. Nodules, which may grow tens of microns in length, may also appear without whiskers. Because of their shorter length and larger diameter, they do not usually pose a reliability risk in and of themselves. There are also odd-shaped eruptions which are typically short, curled objects that may or may not eventually lead to whiskers.
- **Incubation (dormancy) period:** Experimenters report an incubation period ranging from days to years before whiskers appear. This period is likely related to the amount of compressive stress [27]. This period is of particular concern because experiments to determine the propensity for a particular process to form whiskers may need to span very long periods of time. This property also complicates decisions about whether applications with short storage and usage lives are at risk for tin whiskers.
- **Growth rate:** Growth rate of tin whiskers is also variable: rates from 0,03 mm/yr to 9 mm/yr have been reported. Some experiments also document non-linear growth rates and times when the growth has stopped all together [27, 30, 33]. Interrelated factors such as substrate materials, grain structure, plating chemistry, and plating thickness may influence growth rate.
- **Whisker length:** Tin whisker length obviously depends on growth rate and sustained periods of growth. Whisker lengths observed in tests and field experiences range from a few microns to as much as 10 mm. The majority of whiskers are short [8, 23].
- **Whisker diameter:** Whiskers are typically very thin with diameters between 1 micron and 5 microns [8, 30], yet diameters between 0,006 μm and 7 μm have been recorded [33]. Whiskers are not always the same diameter throughout their entire length [33]. Despite some early hypotheses to the contrary, some whiskers have developed cross-sectional areas greater than either the grain size of the original Pb-free tin or the thickness of the plating [8].
- **Density of growths:** Although whisker densities up to $10^4/cm^2$ have been observed, this measurement also varies greatly in the literature [8]. Variation may be due to an inconsistent definition of what length should be counted [30] or to differences in the compressive stresses in the Pb-free tin or substrate layers [8]. Experiments also have recorded changes in whisker density from both radiation [34] and plating thickness [29].
- **Current-carrying capacity:** Under normal atmospheric conditions, the capacity typically measures between 10 mA and 32 mA [23, 35]. However, capacities as high as 75 mA have been observed [8]. The capacity depends on the thickness of the whisker and on the environment. Because air can provide cooling which might lead to higher current capacity, lower current capacity might be expected in a vacuum or low-pressure environment. Here the dangers of fusing a whisker in a low-pressure environment should again be noted. In a low-pressure environment, under certain voltage and current conditions, the vaporizing of the tin may initiate a plasma that can conduct hundreds of amps. The plasma may continue until all the available tin from surrounding areas is consumed or the supply current is interrupted [8].
- **Mechanical strength:** Their crystalline structure makes tin whiskers surprisingly strong in the axial direction. High forces in vibration and mechanical tests may be needed to

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damage or break free whiskers [35]. These experimental results may not match all experiences, however, as there are known examples of whiskers detaching and creating short circuits or jamming mechanical mechanisms [8]. Shear strengths may be lower, particularly in long whiskers [8].

B.2 Tin whisker growth mechanisms

The mechanisms by which tin whiskers grow have been studied since the 1950s. From the earliest papers, research agrees that the growth occurs at the base of the whisker, not the tip [30]. The exact mechanism of tin whisker growth is not understood. Many researchers contend that stress levels within the tin film may be critical, however research remains inconclusive. References that discuss growth mechanisms in more detail include: [1, 2, 3, 4, 5, 8, 9, 10, 14, 15, 16, 19, 20, 23, 25, 33, 43, 58, 68].

Many factors can contribute to these stresses and the formation of whiskers, and the relative importance of the factors has not been determined. A list of what appears to be the most important drivers in tin whisker growth is below.

- **Residual stresses within the tin finish:** These residual stresses are caused by factors within the plating chemistry and process such as impurities, grain size, plating thickness, and current density. Electro-deposited finishes are considered at greater risk because higher current densities have been observed to produce higher residual stress and more whiskers. Bright tin finish has a greater propensity to whisker formation than does matte tin finish, perhaps due to the organic impurities used as brighteners. Tin with smaller grain sizes has more whiskers than does tin with larger grain size [43]. Platings between 5 μm and 10 μm also seem to maximize whisker growth [8, 14, 29, 44]. However, there have been no proven cases of Pb-free tin finish, regardless of process or brightness, that are fully resistant to whiskers over the long term.
- **Intermetallic formation:** Certain under-plates may diffuse into the tin. The intermetallics formed may change the lattice spacing and create compressive stresses.
- **Mechanical loading:** Spring fixtures or turning of nuts or screws can introduce localized mechanical stress. Bending and lead forming can also lead to whisker growth. These mechanical loads may contribute to whisker formation, although experimental results have been mixed [5, 8, 15, 23, 33, 45].
- **Damage to the surface:** Bending, stretching, scratching, or nicking of the plating, either purposely or through handling damage, can create points that seem to serve as nucleation point for whiskers [5, 8, 13, 23].
- **Coefficient of thermal expansion mismatches:** Differences between the thermal expansion of the substrate or under-plate and the Pb-free tin finish can create stress at the interface [5, 8, 23].

B.3 Environmental factors

There is a great deal of uncertainty regarding environmental factors that might affect whisker formation. To date, there are no accepted test methods for evaluating whisker propensity, so determination of causal relationships has been difficult. Much of the experimental data compiled to date has produced somewhat contradictory findings regarding which factors accelerate (or retard) whisker growth [1, 2, 3, 8, 10, 16, 19, 25, 49].

- **Temperature:** Elevated temperature increases diffusion and formation of intermetallics, so it might accelerate whisker formation. However, high temperatures can also relieve internal stresses. There is a growing consensus that temperatures of approximately 50 °C may be optimal for tin whisker formation (the recrystalization temperature of tin is 51 °C – 52 °C), but whiskers can grow well, and some experiments report faster, at room temperature (22 °C to 25 °C). There may be a maximum temperature for whisker formation, perhaps above 150 °C [20], but a lower bound on formation temperature has not been found as whiskers have been observed to grow at temperatures as low as –40 °C [8].

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- **Barometric pressure:** Pressure seems to have little effect on whisker growth. Whiskers have been observed to grow in both earth-based atmospheric pressures and low-pressure (vacuum) environments [8, 20]. Some theories have been proposed that oxidation may contribute to whisker growth [48], but because whiskers have been shown to grow under low-pressure (oxygen starved) conditions, it is clear that oxidation is not required for whiskers to form.
- **Humidity and moisture:** Experiments examining the effects of humidity have been inconclusive. Some results have shown increased growth rate in high humidity (85 % - 95 % RH), but others show no change [8, 20, 50, 61].
- **Thermal cycling:** There is also no consensus on whether temperature cycling affects tin whisker growth. Some experiments, typically cycling between –40 °C to +90 °C, have shown higher growth rates, but others have not demonstrated any effect. It may be the case that the impact of thermal cycling on growth is related to the plating material below the tin. Under-plates with higher thermal mismatches with tin may be influenced by cycling while better matched materials may not [4, 8, 30, 46, 61].
- **Electric field:** Unlike dendrites, whiskers grow without an applied electric field. There have been studies suggesting that electric field can change the growth rate [53]. However, several studies found that whisker growth is not related to electric bias [9, 44, 56]. However, electric fields can create electrostatic attraction between whiskers and other surfaces and may increase the likelihood of whisker-induced shorts.
- **Sequential environments:** While no extensive studies exist yet to characterize the effects of multiple environments to represent actual equipment life cycle environments, some studies exist that provide data to indicate the potential significance of these effects [4, 60]. In particular, it is generally recognized that preconditioning of finishes does lead to different whisker growth rates; this particular issue is addressed in JESD22-A121 and JESD201. Since most applications of electronics include exposure to multiple environments over their lifetime, an effective assessment of tin whisker growth should consider the effect of sequential and simultaneous environments.

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Annex C
(informative)

Technical guide on detection methods, mitigation methods, and methods for limiting impact of tin

C.1 Methods of detecting tin

C.1.1 General

Subclause 3.3.2 requires monitoring of products for Pb-free tin finishes. This annex presents some common methods used for such detection. These methods were not developed specifically to identify pure tin and can also identify other materials, such as lead, zinc, cadmium, copper, and lead-free solder materials.

For Level 3 hardware in particular, care should also be taken to take material readings on multiple surfaces of the devices. Magnification should be used to look for areas where the final surface may not have covered completely and any exposed material should also be analyzed.

C.1.2 X-ray fluorescence (XRF) spectroscopy

The most common method for Pb-free tin detection is X-ray fluorescence (XRF). XRF is a non-destructive material analysis technique that has been used for a number of applications, beyond lead-free, for many years. Its elementary interaction mechanism is the photoelectric effect. The fluorescence radiation used for the analysis is emitted as a result of the ionization of inner shell electrons of the elements in the sample under investigation. The energy of this fluorescence radiation is characteristic for each element. The intensity distribution of the radiation energy ("spectrum") detected by a detector becomes the foundation for the analysis of the chemical composition of the sample.

XRF-analysis can be used to identify and analyze all solder alloys, including substrate solder alloys, termination solder materials and finishes, as well as assembly solder alloys used in the given application and for both original manufacturing and repair. It provides a non-destructive, non-contact means of reliably determining elemental concentration of alloys.

There are non-portable and portable detectors available that can produce results in seconds [51]. However, care must be taken with XRF as sometimes there can be false readings as material content of lower plating levels or surrounding areas are averaged into the results. There are techniques for minimizing these effects, but they may require use of bench-top XRF equipment rather than hand-held. Particular equipment should be reviewed to make sure it has the capability of reviewing layered materials; some equipment can only perform bulk measurements and may not be appropriate for reviewing finish material. Small spot size collimation should also be available. It may be difficult to tell where a hand-held device is making its measurement for small spots. Misleading measurements are also a possibility if the measurement surface is not relatively flat. If the surface is not close to flat the data will reflect back at an angle and miss the detector. When this happens, measurements just represent noise.

Some of the comparable benefits of XRF over other detection methods are as follows:

- fast
- non-destructive
- less expensive
- user friendly - low skill level is required to operate

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- good for large solid surfaces of one material type
- good for small parts with multiple materials if the XRF has a magnified video capability to ensure the XRF beam is hitting the area of interest.

Some of the comparable drawbacks of XRF to energy dispersive (X-ray) spectroscopy (EDS) are as follows:

- plating thickness and part size can affect reading accuracy, unless care is taken in developing appropriate software and techniques;
- buried materials (i.e. lead inside a part) can be picked up indicating lead is present when the actual plated surface is pure tin, unless care is taken in developing appropriate software and techniques;
- there must be a base-line or expected material. Analysis compares actual material to an expectation. Calibration and software may depend on the accuracy of this expectation;
- it may be difficult to perform on some very large surfaces (particularly on large mechanical or structural materials) and on very small samples (<50 µm);
- verification of results by EDS may be required and is often recommended for ambiguous results.

C.1.3 Energy dispersive (X-ray) spectroscopy (EDS)

For situations where XRF results are ambiguous or close to the required limits, it is recommended that another analysis technique, such as EDS, be used and compared. These tests take longer than would be practical for a general screening but can provide more precise results in confusing situations. Most people consider the XRF test to be the more rudimentary test and they often use EDS to verify XRF results.

EDS uses the same physical principles as XRF to create fluorescence radiation in a material; the fundamental difference is that the fluorescence radiation is produced by excitation of the sample to be analyzed with an electron beam vs. an X-ray beam. EDS uses low energy X-ray lines, therefore requiring operation in vacuum, and is only sensitive to 1-2 µm depth. EDS also can be considered a non-destructive analysis method; however extensive sample preparation may be required.

Some of the comparable benefits of EDS over XRF are as follows:

- capable of higher accuracy reading (typically the energy resolution is better, more elements can be detected, and the analysis software is more sophisticated on EDS systems);
- measures a surface depth in microns so it is not influenced by underlying base layers. However for an analysis beyond the surface, a cross section of the sample is required.

Some of the comparable drawbacks of EDS to XRF are as follows:

- lower detection efficiency, except for light elements such as O, Mg, Na;
- smaller sample volume results can be influenced by the microstructure, surface roughness, and surface contamination;
- more expensive;
- longer analysis time;
- needs a skilled operator - interpreter/analyzer;
- Method may be destructive to device.

There may be concerns for both methods for accurately giving a percentage of the element that is identified. <u>Calibration and technique can lead to variation.</u> The elemental analysis gives a relative indication of the content of one element vs. the others, but does not give a definitive percentage, so trying to identify 2 % versus 4 % lead content is not always reliable.

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For Level 3 hardware in particular, care should also be taken to take material readings on multiple surfaces of the devices. Magnification should be used to look for areas where the final surface may not have covered completely and any exposed material should also be analyzed.

C.1.4 Precautions

Proper ESD precautions must be in place when testing ESD sensitive items, unless the tested item will be scrapped. For moisture sensitive parts, appropriate precautions should be applied, unless the tested item will be scrapped. There are also opportunities for mechanical handling damage, such as to leads and seals, as devices are removed from packaging and tested.

C.1.5 General test experiences

One original equipment manufacturer (OEM) reported that they used XRF to check their part receipts and subcontractors for the presence of prohibited materials, including tin, cadmium, and zinc. Out of 17 341 lots scanned, prohibited materials were found in 318 of them or 1,8 % [68]. Tin was 76 %, zinc was 12 %, and cadmium was 12 %. The highest frequency of prohibited material finds by part type was terminal (152) and connectors (35). Of the lots found with tin, the majority of them were found on parts that were supposed to be Sn-Pb plated per the engineering documentation. They also reported that four out of six subcontractors were found to have prohibited materials in flight inventories.

C.2 Methods to reduce the risk of tin whisker-induced failures

C.2.1 General

Below is a discussion of individual methods and other information to help reduce the risk of failure due to tin whisker formation. The effectiveness of the mitigation strategies presented here has been demonstrated to varying degrees, but their relative effectiveness has not been quantified. Until the growth mechanisms are understood, no accelerated test for whiskers can be developed. A reliable, repeatable accelerated test will be needed before the risk to a system or the effectiveness of a mitigation strategy can be accurately and quantitatively calculated. The only sure strategy to prevent tin whisker induced failure is to avoid using Pb-free tin, but a mixture of mitigation strategies may allow for the use of Pb-free tin finishes for some applications or lifetime requirements. Strategies, along with references to research evaluating them, are presented in the sections to help users qualitatively evaluate their particular circumstances.

C.2.2 Parts and material selection

C.2.2.1 General

The mitigation methods described in this section are methods that must be addressed at the time the parts and materials are selected. In some cases, equivalent parts will be available with or without these features. In other cases, parts with these mitigating features may incur additional costs.

C.2.2.2 Physical barriers

Perhaps the most obvious method to prevent whiskers from shorting out adjacent conductors is creation of an insulating physical barrier between them. Placement of non-conductive washers, spacers, staking compound materials, etc. as a physical barrier can prevent whiskers from growing from one conductive surface to another. Because whiskers can grow through oils, greases, and the softer lacquers, care must be taken in selecting the material of the barrier. In this context, the harder or more durable materials (e.g., epoxies) are much more effective, provided they remain intact [8, 19, 25]. While a barrier may prevent a whisker growing from one conductive surface to another, it cannot mitigate the risks associated with free-floating whiskers.

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C.2.2.3 Choice of underplating or substrate material

The formation of intermetallics between the base metal and the Pb-free tin finish may create stresses that promote tin whisker growth. By controlling the underplate or substrate, the risk of whiskers may be greatly reduced.

The chemistry, thickness, surface finish, grain size, surface cleanliness, and internal stress of the substrate are all factors that may affect intermetallic compound (IMC) formation and growth. The diffusion of the materials and the IMC create compressive stresses in the Pb-free tin finish, particularly along tin grain boundaries. If the stress reaches a critical level, tin may be extruded from the surface, relieving the stress and creating a whisker [5, 8, 9, 10, 14, 33].

A thin layer of nickel over the copper substrate should, in theory, reduce IMC diffusion and stress. Studies investigating the effectiveness of nickel underplating on whisker growth have been mixed. Some studies have shown a reduction in number and length of whiskers on tin plated nickel than on tin plated copper [7, 9, 49, 59, 65]. However, studies have also shown that whiskers will grow despite a nickel barrier [22, 23, 24, 66]. The effectiveness of nickel barriers to prevent whiskers may depend on the properties of the base material and the process used for depositing the tin, explaining the differences in the experimental effectiveness of the barrier. A minimum layer thickness of 0,5 µm is recommended for devices subjected to Pb-free reflow assembly conditions [37].

Silver underplate (>2 µm) may also be a mitigating feature, but data is much more limited [36]. There is, however, the potential for this mitigation practice to be effective, and further investigation of the effectiveness of this technique should continue.

It is still unclear what impact alloying materials other than Pb have on the formation of tin whiskers. Several studies have shown SnCu alloys to produce more whiskers than pure tin [44, 45]. Other studies have shown tin-bismuth to whisker readily [64, 67]. One study has also suggested that SnAg alloys have whiskering problems [65]. However, many Pb-free alloys, including SnAgCu and SnAg, have not been fully studied for their propensity for whiskering.

C.2.2.4 Select a matte or low stress Pb-free tin finish

"Bright" tin finish contains additives that can cause internal stresses in the tin. A "matte" tin finish, or a relatively dull finish, is preferred because it does not contain these additives [3, 8]. Generally, matte tin is a tin film with lower internal stresses and larger grain sizes than bright tin. Matte tin is defined to have carbon content of 0,005 % to 0,05 % and grain size of 1 µm to 5 µm.

Although a matte tin is preferable to a bright tin, some researchers report it may not prevent the formation of whiskers. One study found whiskers up to 2 mm long on matte tin-plated steel [22, 23, 24]. Other researchers have suggested that matte tin may be very effective, particularly when combined with other mitigations [8, 9, 14]. The effectiveness of matte tin may be dependent on process controls during plating and the particular environment during use. Matte tin should be considered an improvement over bright tin, but the specific process and application should be carefully reviewed before use.

C.2.2.5 Plating process considerations

Several other aspects of the plating process beyond underplate selection and brightness of finish appear to influence the occurrence of tin whiskers [8, 18, 52, 55]:

- **plating baths:** process controls on the plating baths can help reduce the risk of whisker formation. Contamination in the bath creates nuclei for internal stresses promoting whisker growth. By controlling contamination and refreshing the baths often, these stresses can be limited. Process control is also recommended for current density, temperature, and plating speed. Higher current densities, and therefore quicker plating, may be more prone to greater whiskering [15];

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- **hot-tin dipped coating:** hot-tin dipped parts should also come from controlled production lines. Even though the layer of tin during dipping, theoretically, should be less stress inducing than electroplating, variation in plating thickness and handling damage from multiple processing steps can introduce stresses [10, 15];
- **reflowing, fusing, and annealing:** heat treatments have been promising in preventing whisker formation, but test results are not consistent. It has been hypothesized that reflowing the tin (taking it above its melting point) or even fusing or annealing it (heating but not above its melting point) should reduce the risk of whiskers because the high temperatures involved should help to reduce the internal stresses and increase grain sizes. The heating should be done in an inert atmosphere and followed by a slow cooling to minimize stresses reforming. A variety of temperature and time conditions are recommended in the literature. Although many seem to increase the incubation time or reduce whisker density and length, they have not yet been proven to permanently prevent whiskers [1, 2, 3, 8, 13, 15, 19, 38, 39, 44, 50, 60, 65, 69, 70];
- **handling:** because nicks and scratches have been shown to be common sites for whiskers to initiate, contacts with probes, vacuum chuck pickup heads, and tweezers (anything but low-pressure bars) should be minimized or eliminated [9, 10, 15, 57].

C.2.2.6 Tin thickness

There is some data suggesting that thicker Pb-free tin finishes show a lower propensity for tin whiskers and/or a greater incubation time before tin whiskers occur. It is recommended that the tin thickness for piece parts without a nickel or silver underlayer be 7 μm minimum with 10 μm nominal or thicker preferred. When a nickel or silver underlayer plating is used, the minimum tin thickness should be 2 μm [40, 60].

C.2.3 Material and assembly processing

C.2.3.1 General

The mitigation methods described in this section are methods that can be addressed after market. The most effective of these solutions involve completely replacing the Pb-free tin finish, not merely covering it, and ensuring that no Pb-free tin remains exposed. However, some of these solutions, particularly those that involve replacing the Pb-free tin finish, may lead to suppliers no longer guaranteeing the performance of piece parts. Therefore, some analysis and possibly qualification of the re-processed piece parts may be needed to verify that they will function as intended. It is recommended that tin control plans require objective evidence that any aftermarket processing intended to replace the Pb-free tin finish is a complete replacement and that the functionality and reliability of the piece part has not been compromised.

C.2.3.2 Solder dip tin-finished surfaces

Hot solder dipping (sometimes referred to as HSD) of tin-finished leads and surfaces using a Sn-Pb-based solder will help reduce whisker formation by relieving stress in the tin. The heat can increase grain size, and the Sn-Pb alloy is less prone to whisker formation. Under ideal practices, solder dip of tin-finished terminations, using Sn-Pb solder, will virtually eliminate whisker formation by dissolving and replacing the tin-finish with a Sn-Pb alloy. There is also exploration of using tin-silver-copper (SAC) and other lead-free alloys for solder dipping. It is unclear how effective these processes will be in reducing the risk of tin whiskers.

Solder dip for whisker mitigation differs from traditional solder dip in that the lead must be coated over its entire length, right up to the package interface. During hot solder dip, the piece part undergoes an unavoidable amount of thermal shock. Differential temperatures during solder dip are significantly greater than those present during typical board-level assembly. In addition, the fluxes used during the dipping process can be drawn into minor delamination commonly found in plastic piece parts, which can lead to reliability issues. To avoid these concerns, the hot solder dip process must be qualified and carefully controlled. Essential process monitors and controls include: solder thickness, solder composition, solder pot contamination, hermeticity, delamination, temperature profile, chemical exposure, and

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electrostatic discharge. However, care must be taken that the methods used are adequate and do not damage the piece part [42].

Because many parts, particularly those with glass-to-metal seals, can be damaged through thermal shock during the solder dip, solder dipping is most suitable for use on non-electrical parts or on electronic piece parts that have leads as terminations. However, processes are being developed for virtually all types of electronic piece parts. Studies evaluating the suitability of robotic solder dip processes on several common electronic packages and devices have demonstrated favorable results. If the device cannot be dipped all the way to the body, the standoff distance, usually between 10 mils and 50 mils, would still be at risk for whisker growth. There is also a risk of whiskers on any Pb-free tin inside the device that could not be solder dipped [1, 2, 3, 8].

C.2.3.3 Re-plate whisker prone areas

Some manufacturers may be willing to strip the Pb-free tin plate from finished products and re-plate using a suitable alternative plating material such as Sn-Pb or nickel. Stripping and refinishing is generally not suitable for electronic piece parts, but may be reasonably applied to a range of mechanical piece parts. If applied to electronic piece parts, such processes should be reviewed to determine the potential for affecting the reliability of the original product (e.g., chemical attack on piece part materials) [1, 2, 3]. Stripping and replating is a common process performed by the metal finishing industry.

C.2.3.4 Pb over-plating

Another option for replacing the pure tin finish involves plating of Pb on the surface of the tin and then baking the part to promote complete interdiffusion. This option may be most suitable for use on small chip-style passive devices.

C.2.3.5 Conformal coat or foam encapsulation over whisker prone surfaces

If piece parts with Pb-free tin finish must be used, government and industry subject matter experts strongly recommend the application of a conformal coating. Conformal coat reduces the risk of whisker failure by retarding possible tin whisker growth, containing many whisker growths within the coat, preventing any whiskers from shorting exposed conductors, and limiting the availability of tin to reduce the probability of creating a plasma event in low pressure environments. The use of conformal coating does not eliminate the potential for whisker failure entirely, however. For most coatings, tin whiskers have been shown to eventually grow through the thin coating and potentially short any other whiskers that have grown similarly [1, 2, 3, 8, 12, 15, 42].

Obvious limitations of using conformal coating or foam encapsulation over Pb-free tin finish are the possible variability in the quality and thickness of the coating coverage. Experts warn that when applying conformal coating to dense assemblies, the coat should not bridge the gap from one surface to another, providing a direct path for potential whiskers. Coating fully under-mounted piece parts such as pin grid arrays (PGAs), ball grid arrays (BGAs), and chip scale packages (CSPs) may also be difficult. When conformal coating is applied in a spray process, the coat must be sprayed from several angles to prevent shadow areas created by high profile piece parts [3, 20].

Experiments using Uralane 5750 conformal coating indicate that the coating reduced the growth rate, and therefore whisker length, but whiskers still grew and were strong enough to grow through conformal coating. A NASA-GSFC experiment reported whiskers growing through 0,25-mil-thick Uralane 5750 after 2,5 years of storage at room ambient. No whiskers penetrated a 2-mil-thick coat after 3 years [11]. Another experiment showed whiskers growth under coating. It found penetration on almost every coating tested after almost a year of ambient storage followed by a year of exposure to 50 °C / 50 % RH. In this experiment, Parylene C (>1 mil) was the best coating for suppressing whisker growth. A silicone, three acrylic-urethane hybrid materials, and a straight acrylic were not as effective in suppressing whisker growth with the acrylic being by far the worst performer. In addition, Parylene C was

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