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PUBLICLY AVAILABLE SPECIFICATION

PRE-STANDARD

Process management for avionics – Aerospace and defence electronic systems containing lead-free solder –
Part 22: Technical guidelines

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FOREWORD

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IEC PAS 62647-22 has been processed by IEC technical committee 107: Process management for avionics.

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**
107/131/PAS	107/139A/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.

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a single 3-year period, following which it shall be revised to become another type of normative document, or shall be withdrawn.

This PAS is based on GEIA-HB-0005-2 and is published as a double logo PAS. GEIA, Government Electronics and Information Technology Association, has been transformed into TechAmerica Association.

INTRODUCTION

0.1 General

This PAS is intended for use by Aerospace and High Performance (AHP) electronics system Customer, i.e., aerospace and defence vehicle integrators, operators, and regulatory organizations, and their Suppliers, i.e., system Original Equipment Manufacturers (OEMs) and system maintenance facilities as they incorporate Lead-free (Pb-free) solder or Pb-free piece-parts and board finishes.

This PAS is intended to work in concert with IEC/PAS 62647-1 (GEIA-STD-0005-1), IEC/PAS 62647-21 (GEIA-HB-0005-1), and IEC/PAS 62647-2 (GEIA-STD-0005-2). Part way through this documents creation, it was evident that three additional documents were needed. As a result, IEC/PAS 62647-3 (GEIA-STD-0005-3), IEC/PAS 62647-23 (GEIA-HB-0005-3) and the reliability assessment document GEIA-HB-0005-4 have been added to address testing, rework, and reliability prediction respectively.

This PAS may be referenced in proposals, requests for proposals, work statements, contracts, and other aerospace and high performance industry documents.

0.2 Transition to Pb-free

The global transition to Pb-Free electronics impacts the aerospace and other industries having high reliability applications in various ways. In addition to the perceived need to replace the Tin-Lead solders used as an interconnect medium in electronic and electrical systems, the following variations to established practice will need to be considered:

- components and printed circuit boards will need to be able to withstand higher manufacturing process temperatures;
- printed circuit boards will need to have robust solderable Pb-Free surface finishes;
- manufacturing and inspection techniques are needed that yield repeatable reliability characteristics;
- at least initially, Pb-free alloys used within the equipment should be restricted to those that are compatible with Tin-Lead soldering systems;
- a maintenance strategy should be developed that will facilitate the support repair of new and existing equipment throughout a 20+ year life.

This PAS will establish guidelines for the use of Pb-Free solder and mixed Tin-Lead/Lead-free alloy systems while maintaining the high reliability standards required for aerospace electronic and electrical systems. Currently the largest volume of Lead (Pb) in many of these electronic systems is in the Tin-Lead eutectic (Sn-37Pb) and near eutectic alloys (Sn-36Pb-2Ag, Sn-40Pb) used in printed circuit board assemblies, wiring harnesses and electrical systems. High-Lead solder alloys are not specifically addressed in this PAS; however, many of the methodologies outlined herein are applicable for their evaluation.

A good deal of the information desired for inclusion in this technical guidelines document does not exist. A large number of Pb-Free investigative studies for aerospace and high reliability electronic and electrical systems are either in progress or in the initiation stage. The long durations associated with reliability testing necessitates a phased release of information. The information contained herein reflects the best information available at the time of document issuance. It is not the goal of this PAS to provide technical guidance without an understanding of why that guidance has technical validity or without concurrence of the technical community in cases where sufficient data is lacking or conflicting. The PAS will be updated as new data becomes available.

Further complicating matters is the fact that no single alloy across the supply base will be replacing the heritage Tin-Lead eutectic alloy and that it is not likely that qualification of one alloy covers qualification for all other alloys. Given the usual requirement for long, high performance electronic service lives, any Pb-Free alloy must have predictable performance when mixed with heritage Tin-Lead alloys. Pb-Free alloys containing elements such as Bismuth (Bi) or Indium (In) that can form alloys having melting points within the equipments operating temperature range must be considered very carefully before use. Although Pb-Free solder alloys are still undergoing some adjustments, it appears that the Sn-Ag-Cu family of alloys will be used for surface mount assembly and either Sn-Ag-Cu, Sn-Cu or Sn-Cu-Ni (Sn-Cu stabilized with Nickel) alloys will be dominant in wave solder applications. In addition, some applications are using the Sn-Ag alloy family [1] [2] [3].

The majority of the Pb-Free solder alloys being considered have higher melting temperatures than Tin-Lead eutectic solder. In order to make use of the Pb-Free solders, changes to the molding compound, die attach and printed circuit board insulation systems are being introduced to accommodate the 30 °C to 40 °C higher (54 °F to 72 °F higher) processing temperature. Thus, not only is the Pb-Free transition changing the solder alloy, but a significant portion of the electronic packaging materials are changing as well. The higher melting point, greater creep resistance and higher strength of the Pb-Free alloys have driven a significant amount of study into the thermal cycling and mechanical vibration/shock assessments of these new alloys.

The consumer electronics industry has invested considerable resources to ensure that Pb-Free solder will perform adequately for their products. Creep resistance of Pb-free alloys can vary considerably from heritage Tin-Lead solders. The creep/stress relaxation performance of the solder depends on the stress level, temperature and time for a specific solder material and joint composition. Therefore, one needs to establish what the acceleration factor is between a particular test condition and application. The interpretation of the results of a head-to-head testing needs to be assessed in terms of the anticipated service conditions with respect to these acceleration factors. Thermal preconditioning prior to thermal cycling should be considered in the Pb-free solder assessment plan particularly as it relates to changes in solder microstructure. Modeling/Analysis is needed to properly compare the Tin-Lead and Pb-Free alloy performance and correct for the stress relaxation differences obtained for the various piece-parts and thermal cycling conditions.

While there is much data on near eutectic SAC (e.g., 305 and 405) Pb-Free thermal cycling, there is less information regarding Pb-Free vibration and shock performance. Fortunately, the vibration and shock performance data can be obtained relatively quickly. During vibration/shock testing, the near eutectic SAC Pb-Free solder behaves more rigidly than the Sn-Pb solder transferring greater loads to the interfaces between the solder alloy and the substrate interfaces. The increased amount of Tin in Pb-Free alloys increases the intermetallic thickness when Copper substrates are used. In addition, when Nickel or electroless Nickel (Nickel – Phosphorous) substrates are used, the increased Copper in the SAC alloy can result in the formation of intermetallics on the nickel interface, which are less robust than Sn-Cu or Sn-Ni intermetallics that are typical of Tin-Lead solder joints. Mechanical test results to-date suggest that a robust assessment of Pb-Free alloy assembly in vibration and shock environments will need to include thermal aging for interface and microstructural stabilization prior to any dynamic mechanical testing. Alloys other than SAC should be assessed to determine their vibration and shock performance characteristics.

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

Part 22: Technical guidelines

1 Scope

This PAS is intended for use as technical guidance by Aerospace system Suppliers, e.g., Aerospace system Original Equipment Manufacturers (OEMs) and Aerospace system maintenance facilities, in developing and implementing designs and processes to ensure the continued performance, quality, reliability, safety, airworthiness, configuration control, affordability, maintainability, and supportability of high performance aerospace systems (subsequently referred to as AHP) both during and after the transition to Pb-Free electronics.

This PAS is intended for application to aerospace products; however, it may also be applied, at the discretion of the user, to other products with similar characteristics, e.g., low-volume, rugged use environments, high reliability, long lifetime, and reparability. If other industries wish to use this PAS, they may substitute the name of their industry for the word “Aerospace” in this PAS.

The guidelines may be used by the OEMs and maintenance facilities to implement the methodologies they use to ensure the performance, reliability, airworthiness, safety, and certifiability of their products, in accordance with IEC/PAS 62646-1 (GEIA-STD-0005-1), “Performance Standard for High Performance Electronic Systems Containing Pb-Free Solder.”

This PAS also contains lessons learned from previous experience with Pb-Free aerospace electronic systems. The lessons learned give specific references to solder alloys and other materials, and their expected applicability to various operating environmental conditions. The lessons learned are intended for guidance only; they are not guarantees of success in any given application.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/PAS 62647-1, *Aerospace and defence electronics systems containing lead free solder – Part 1: Lead free management*

IEC/PAS 62647-2, *Aerospace and defence electronics systems containing lead free solder – Part 2: Mitigation of the deleterious effects of tin*

IEC/PAS 62647-3, *Aerospace and defence electronics systems containing lead free solder – Part 3: Performance testing for systems containing lead-free solder*

IEC/PAS 62647-21, *Aerospace and defence electronic systems containing lead free-solder – Part 21: Program management – Systems engineering guidelines for managing the transition to lead-free electronics*

IEC/PAS 62647-23, *Aerospace and defence electronic systems containing lead free solder – Part 23: Rework and repair guidance to address the implications of lead-free electronics and mixed assemblies*

GEIA-STD-0005-1, Performance standard for aerospace and high performance electronic systems containing lead-free solder

GEIA-STD-0005-2, Standard for mitigating the effects of tin in aerospace and high performance electronic systems

GEIA-HB-0005-1, Program management / Systems engineering guidelines for managing the transition to lead-free electronics

GEIA-HB-0005-3, Rework and repair handbook to address the implications of lead-free electronics and mixed assemblies in aerospace and high performance electronic systems

GEIA-HB-0005-3, “Aerospace and defence electronics systems containing lead free solder – Part 23: Rework and repair handbook to address the implications of lead-free electronics and mixed assemblies

GEIA-HB-0005-4, Guidelines for Performing Reliability Assessment for Lead Free Assemblies used in Aerospace and High-Performance Electronic Applications

GEIA-STD-0006, Requirements for Using Solder Dip to Replace the Finish on Electronic Components

ARINC Project Paper 671: Guidelines for Lead-free Soldering, Repair, and Rework, March 16, 2006.

ASTM B117-3 Standard Practice for Operating Salt Spray (Fog) Apparatus, October 2003

ASTM G85 Standard Practice for Modified Salt Spray (Fog) Testing, Annex A4 Salt/SO2 Spray (Fog) Testing 2002.

MIL-I-46058C Insulating Compound, Electrical (for coating printed circuit assemblies), Inactive for new design, July (1982)

IPC/JEDEC JP002, Current Tin Whiskers Theory and Mitigation Practices Guideline, March 2006.

IPC/JEDEC J-STD-001D, Requirements for Soldered Electrical and Electronic Assemblies, Feb. 2005.

IPC/JEDEC J-STD-002B, Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires, February 2003

IPC/JEDEC J-STD-006B, Requirements for Electronic Grade Solder Alloys and Fluxed and Not Fluxed Solders for Electronic Soldering Applications, January 2006.

IPC/JEDEC J-STD-020C, Moisture/Reflow Sensitivity Classification for Non-hermetic Solid State Surface Mount Devices, July 2004.

IPC/JEDEC J-STD-033B, Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices, October 2005

IPC/JEDEC J-STD-609, Marking of Symbols and Labels of PCB Assemblies and Piece Parts to Identify Lead (Pb) and other Materials

IPC-A-610, Acceptability of Electronic Assemblies, Revision D, February (2005)

IPC-CC-830, Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies, Revision B, August (2002)

IPC-TM-650, Test Methods Manual Method 2.6.25 Conductive Anodic Filament (CAF) Resistance Test: X-Y Axis November 2003

IPC-1066 Marking, Symbols and Labels for Identification of Lead-Free and Other Reportable Materials in Lead-Free Assemblies, Components and Devices, January 2005

IPC-1752 Materials Declaration Management, February 2006

IPC-2221A, Generic Standard on Printed Board Design, May 2003.

IPC-4552, Specification for Electroless Nickel/Immersion Gold (ENIG) Plating for Printed Circuit Boards, October 2002.

IPC-4553, Specification for Immersion Silver Plating for Printed Circuit Boards, June 2005.

IPC-4554, Specification for Immersion Tin Plating for Printed Circuit Boards

IPC-7095A, Design and Assembly Process Implementation for BGAs, October, 2004.

IPC-9701 Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments, January 2002, and Lead-Free Appendix B

JESD97 Marking, Symbols, and Labels for Identification of Lead (Pb) Free Assemblies, Components, and Devices, May 2004

3 Terms and definitions

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

3.1
alloy composition
all alloy compositions are stated as weight percent. For instance 63Sn-37Pb corresponds to a mixture of 63 % by weight of Tin(Sn) and 37 % by weight of Lead(Pb)

3.2
alloy 42
refers to a nickel-iron controlled-expansion alloy containing 42 % nickel that is often used as a lead-frame material in electronic packages

3.3
Ag, Au, Bi, Cu, Ge, In, Ni, Pb, Sb, and Sn
refer to the elements Silver, Gold, Bismuth, Copper, Germanium, Indium, Nickel, Lead, Antimony, and Tin, respectively

3.4
AHP
Aerospace, High Performance Systems

3.5
assemblies
are electronic items that require electrical attachments, including soldering of wires or component terminations; examples include circuit cards and wire harnesses

3.6
AR
acrylic resin conformal coating

3.7
CAF
refers to Conductive Anodic Filaments that form in printed wiring boards. See IPC-TM-650 Method 2.6.25

3.8
CALCE
the University of Maryland Center for Advanced Life Cycle Engineering (CALCE) consortium

3.9
CLCC
refers to a Ceramic Leadless Chip Carrier electronic package

3.10
critical
item or function, if defective, will result in the system's inability to retain operational capability, meet primary objective, or affect safety

3.11
creep
refers to time dependent strain occurring under stress

3.12
CSAM
refers to C-Mode scanning acoustic microscopy, which is a method for evaluating electronic packages for internal delamination using high frequency sound waves

3.13
CTE
refers to the coefficient of thermal expansion of a material. PCB CTE (x-y) is measured in the direction in the plane of the piece-part mounting surface and is used to quantify the stresses in the solder joint arising from the differences in CTE between the piece-parts and the PCB during thermal cycling. CTE(z) is measured in the "thickness" direction and is typically used to quantify plated through hole stress

3.14
customer
refers to an 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

3.15
dicy cure
refers to the use of dicyandiamide (dicy), as a curing agent for epoxy resins

3.16
EM
refers to electromigration of the PCB metallization. Resistance to electromigration testing is typically performed between electrically biased conductors at elevated humidity and temperature

3.17
ENIG
refers to Electroless Nickel Immersion Gold Printed Wiring Board Finish

3.18
ER
epoxy resin conformal coating

3.19
eutectic
a eutectic or eutectic mixture is a mixture of two or more metals at a composition that has the lowest melting point, and where the phases simultaneously crystallize from molten solution at this temperature. A non-eutectic mixture will exhibit a pasty range during cooling where both liquid and solid phases are present prior to reaching the mixture's solidus temperature

3.20
FR4
refers to Flame Retardant laminate made from woven glass fiber material impregnated with epoxy resin

3.21
Fick's law
refers to the classic diffusive mass transport model where the mass diffusion is proportional to the concentration gradient in the material

3.22
fillet lifting
refers to a separation that occurs between a solder fillet and a PCB pad where the solder fillet has the appearance that it has lifted off the PCB pad. The fillet lifting is caused by the formation of a low melting point phase (often a ternary alloy) or liquid phase in an alloy having a large pasty range. The thin layer of liquid present adjacent to the PCB pad results in a layer that allows the solidified solder above it to pull off the PCB pad [38] [73]

3.23
high performance system or product
requires continued performance or performance on demand, or equipment down time 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

3.24
HALT and HAST
refers to highly accelerated life test and highly accelerated stress test, respectively

3.25
HASL
refers to the Hot Air Solder Level PCB surface finish

3.26
incubation period
in the context of Tin Pest formation refers to the time required at cold temperature to initially form the brittle gray (α) Tin phase from the ductile white (β) Tin phase

3.27
inoculation
in the context of Tin Pest formation refers to practice of facilitating the white (β) Tin to gray (α) Tin phase transformation by using seed particles of the gray Tin phase on the white Tin to reduce the nucleation barrier energy associated with the transformation

3.28
ICP
refers to Inductively Coupled Plasma/Mass Spectrometry based chemical analysis

3.29
Imm Ag or Im Ag
refers to an immersion silver printed circuit board finish

3.30
JCAA
refers to the Joint Council of Aging Aircraft Organization within the US Department of Defense. JCAA and JGPP have performed extensive Pb-free solder reliability testing

3.31
JGPP
refers to the NASA lead Joint Group on Pollution Prevention. The NASA JGPP group began the Pb-free solder testing that was completed with the support of JCAA

3.32
Kirkendall void formation
refers to voids induced in a diffusion couple between two metals that have different interdiffusion coefficients

3.33
lead
for the purposes of this document, if the element “Lead” is implied, it will be stated either as Pb, as Lead (Pb), or as Tin-Lead. If a piece-part terminal or termination “lead” is referred to, such as in a flat pack or a dual-inline package, the nomenclature lead/terminal or lead-terminal will be used

3.34
Lead-Free or Pb-Free
is defined as less than 0,1 % by weight of Lead (Pb) in accordance with Waste Electrical and Electronic Equipment (WEEE) guidelines

3.35
LRU
is a line replaceable electronic unit

3.36
May
indicates a course of action that is permissible within the limits of this document

3.37
MSL
is the moisture sensitivity level rating of a plastic encapsulated electronic device as it relates to soldering

3.38
Non-Eutectic
See Eutectic mixture definition

3.39
OSP
refers to Organic Solderability Preservative finishes used on PCBs

3.40
PCB
stands for Printed circuit board, which is also commonly referred to as a Printed Wiring Board (PWB)

3.41
PEM
refers to a plastic encapsulated microcircuit

3.42
peritectic
in a peritectic reaction, a solid phase and a liquid phase react on cooling to produce a new solid phase

3.43
piece-part
is defined as an electronic piece part that is not normally disassembled without destruction and is normally attached to a printed wiring board to perform an electrical function

3.44
PWB
stands for Printed Wiring Board, which is also commonly referred to as a Printed Circuit Board (PCB)

3.45
PTH
stands for the plated through holes used on printed circuit boards for interconnecting between layers and for component attachment

3.46
repair
is the act of restoring the functional capability of a defective article in a manner that precludes compliance of the article with applicable drawings or specifications

3.47
rework
is the 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

3.48
RMA
refers to solder flux type: Rosin, Mildly Activated

3.49
RoHS
refers to the legislation enacted by the European Union on the Restriction of Hazardous Substances, EU Directive 2002/95/EC, which places a restriction on the use of certain hazardous substances in electrical or electronic equipment sold or used in the European Union after July 1, 2006. These substances are lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls, and polybrominated diphenyl ethers

3.50
SAC
refers to the family of Pb-Free alloys containing Tin, Silver and Copper used in surface mount technology or sometimes in wave solder processes. The alloys typically have a composition near the eutectic (Sn95,6Ag3,5Cu,9)

3.51
SAC-L
refers to low Silver content SAC alloys that are not eutectic compositions. These alloys have increasingly been used for BGA interconnects

3.52
should
indicates that, among several possibilities, one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required; or that (in the negative form) a certain course of action is deprecated but not prohibited

3.53
SIR
refers the Surface Insulation Resistance measurements performed on PCBs. These electrical resistance measurements are often performed after periods of humidity exposure

3.54
SMT
refers to surface mount technology circuit card assembly technology

3.55
SMTA
refers to the Surface Mount Technology Association, with headquarters in Edina, MN

3.56
Sn-Cu
solder or alloy refers to Pb-Free alloys that are comprised of Tin-Copper (Sn-0.7Cu)

3.57
Sn-Cu-(Ni)
solder or alloy refers to Pb-Free Tin-Copper with trace Nickel concentration alloy (Sn-0.7Cu-0.05Ni). Some formulations also include other minor additions such as Ge

3.58
Sn-Pb
solder generally refers to the family of Tin-Lead alloys at or near the eutectic composition with or without Silver added (Sn-37Pb, Sn-40Pb, or Sn-36Pb-2Ag)

3.59
solder ball technology
identifies a family of components that employ solder balls or bumps to make mechanical and electrical connections between components and printed circuit boards. Examples are ball grid arrays (BGA), flip chip, and chip scale interconnections

3.60
soldered assembly
is an assembly of two or more basic parts interconnected by a solder alloy. A Lead(Pb)-based soldered assembly is one in which the solder alloys are solely Lead(Pb)-based. A Lead-free soldered assembly is one in which the solder alloys are solely Lead-free

3.61
supplier
refers to an entity or organization that designs, manufactures, repairs, reworks, or maintains a piece part, unit, or system. For example, this includes original equipment manufacturers (OEMs), repair and rework facilities, Subcontractors, and piece part manufacturers

3.62
system
is defined as one or more units that perform electrical function(s)

3.63
T_d
is the decomposition temperature of a PWB laminate

3.64
T_g
is the glass transition temperature of a PWB laminate

3.65
tin whisker
is a 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)

3.66
TSOP
refers to a thin small shrink outline electronic device package

3.67
um
is a unit of length measure defined to be a micro-meter or one millionth of a meter and is commonly referred to as a micron

3.68
unit
is defined as one or more assemblies within a chassis to perform electrical function(s)

3.69
UR
urethane resin conformal coating

3.70
XY
paraxylylene resin conformal coating (Also known by the trade name Parylene)

4 Approach

The guidelines given here are intended to be used in conjunction with IEC/PAS 62647-3 (GEIA-STD-0005-3) and GEIA-HB-0005-4 to demonstrate that the solder materials and processes used in a given application will be reliable. They include

- identifying potential failure modes and mechanisms related to the solder materials, piece-part types, and processes;
- ascertaining the program environmental and operating requirements;
- reviewing the details of the assembly solder process, solder stress, metallurgy, temperature capability, and solder pad/terminal attachment strength;

- selecting data sources or designing tests to evaluate the reliability of the selected materials and processes, with respect to the potential failure mechanisms, in the application;
- analyzing data or test results, and comparing them with program criteria.

The guidelines described here address the majority of concerns regarding the use of Pb-Free solder in aerospace systems. The list is not exhaustive however, and other guidelines may be required for specific applications, service environments, and materials. The guidelines described here are not, by themselves, sufficient to assure the performance, reliability, airworthiness, safety, or certifiability of any given system in any given application. To provide such assurance, the program, including any unique functional, performance, and life tests, must be run per the program contractual requirements. The methods to convert data from one set of environmental conditions to another are described in IEC/PAS 62647-3 (GEIA-STD-0005-3) in conjunction with the guidelines given in the subsequent sections.

5 General Pb-Free solder alloy behavior

The three main Pb-free solders are based on the Tin rich Sn-Cu, Sn-Ag or the Sn-Ag-Cu (SAC) families of alloys. Sometimes small alloy additions of Ni, Ge, In, and Sb, are made to these basic alloys in an effort to alter dissolution, solidification, mechanical properties or wetting characteristics. The melting point of pure Sn is 231,9 °C (449.4 °F) and the addition of 37 %Pb to the Sn reduces the melting temperature to the eutectic point of 183 °C (361 °F). Similarly, the addition of Ag and Cu to Sn reduces the melting temperature but not to the same extent as Pb. The Sn95,6Ag3,5Cu,9 ternary eutectic SAC alloy melting temperature is 217,2 °C ± 0,2 °C (423 °F ± 0,36 °F) [4], the Sn-0.7Cu eutectic alloy melts at a temperature of 227 °C (441 °F) [5], and the Sn96,5Ag3,5 eutectic melts at 221 °C [5]. These Pb-free solder melting temperatures are considerably higher than Sn-Pb eutectic. The higher melting temperature of Pb-free alloys, results in a 30 °C to 40 °C increase (54 °F to 72 °F increase) in processing temperature as compared to the temperatures used to process heritage Sn-Pb alloys. Higher melting temperatures result in increased amounts of base metal dissolution (see section Copper Dissolution) and increased shrinkage stresses on components during cooling. An additional consideration is that the SAC alloys have generally been found to be stronger and more creep resistant than the heritage Sn-Pb solders at typical electronic use temperatures [2] [3].

The Pb-free alloy microstructure differs substantially from lamellar/colony structure of eutectic Sn-Pb. The microstructure of Sn-Ag and Sn-Ag-Cu is comprised of relatively large β phase Sn dendrites. In between the dendrites, there are arrays of β-Sn, Ag_3Sn and Cu_6Sn_5 phases [6]. In some studies large Ag_3Sn platelets have been observed. The solidification behavior strongly influences the solid microstructure. The Sn-Pb eutectic solder joint requires only 2ºC of undercooling to begin solidification [6]. In contrast, the eutectic Sn-Ag-Cu system begins solidification with the formation of the Ag_3Sn. Unfortunately, the presence of Ag_3Sn does not facilitate the nucleation of the β-Sn and significant under-cooling can occur. An undercooling of 18 °C (32 °F) was reported for β-Sn [7]. The formation of large Ag_3Sn intermetallic plates in liquid Sn was observed during slower solidification rates for SAC alloys having 3.5 and 3.8 wt % Ag and not with the 3.0 wt % Ag alloy [8] [9]. These plates are expected to change the mechanical response of the system. The Ag_3Sn intermetallic plate may stop or re-direct a crack propagating through the solder joint during environmental testing (such as thermal cycling). If the plate is in the same direction of the shear load, life can be reduced [10], but it is more common to see randomly oriented plates throughout the solderball in larger joints. The presence of Ag_3Sn plates is of greater concern for flip chip and wafer scale chip pack solder joints [11]. The volume fraction of β-Sn dendrites in the solidified solder is dependent upon cooling rate and alloy composition [12]. The grain size of the β-Sn is relatively large with respect to the solder joint size. A BGA solder joint can be comprised of as few as 10 to 30 β-Sn grains and even fewer for wafer level chip scale package and flip chip joints [13]. Since dispersed intermetallics in a SAC alloy tend to increase the hardness and stiffness of the solder, a greater volume fraction of Sn dendrites generally results in a solder joint with decreased stiffness. Reduced solder stiffness can be beneficial in some high stress shock applications because the solder does not impart as much stress on the pad intermetallic or the pad laminate interfaces. Presently, some investigators are evaluating SAC alloys with reduced Ag and Cu content (SAC-L) from the eutectic such as Sn98,5Ag1,0Cu,5 in an effort to obtain improved drop shock performance of BGA assemblies. Unfortunately, the melting temperatures of SAC-L alloys are greater than the traditional SAC alloys and their thermal cycling characteristics require evaluation.

5.1 Elevated temperature

At elevated temperatures, accelerated intermetallic growth, grain growth and redistribution of constituents within the solder joint occur via solid-state diffusion mechanisms. The majority of Pb-Free solder alloys being considered have substantially higher Tin content than the Sn-Pb eutectic solder, resulting in a greater availability of Tin to form intermetallics. The intermetallic layer development generates property discontinuities that may influence the load carrying capabilities of the solder joints during dynamic testing. Intermetallic growth on unassembled PCB's, or product that has already been fielded, can adversely affect the solderability of the PCB for initial assembly, or the entire module for repair or modification.

5.2 Low temperatures

At low temperatures, the principle concerns are the ductile-brittle transition temperature and Tin Pest (e.g., Tin Plague). The Sn-Ag, SAC, and Sn-Cu bulk Pb-Free alloys exhibit ductile-brittle transition behavior that differs substantially from Sn-Pb alloys on bulk solder samples [14]. While the fracture toughness for the bulk Pb-Free alloys tested by Ratchev were higher than Tin-Lead eutectic, the Pb-Free alloys exhibit a larger, more pronounced, change in fracture toughness with temperature as compared to Tin-Lead eutectic alloy. It is unclear if the fracture toughness characteristics observed on the bulk samples tested by Ratchev would also be evident with solder joint size geometries. Thermal cycling tests to -55 °C [15] have not revealed a brittle SAC solder fracture surface morphology. At the present time, a systematic test of Pb-Free alloy vibration and shock performance at cold temperatures is not available.

Electronic equipment that is utilized in applications having prolonged low temperature exposure may be susceptible to tin pest. The allotropic transformation of white (β) Tin, which has a body-centered tetragonal structure, to gray (α) Tin, which has a cubic crystal is known as Tin Pest or Tin Plague. This transformation occurs below 13,2 °C. Above this temperature, white (β) Tin is the stable form. Tin Pest is potentially a menace to Pb-Free solder joints because the crystalline transformation results in a 26 percent increase in volume, crack generation, and brittle characteristics. The increase in volume and accompanying cracking usually causes the metallic Tin to develop fractured and powdery regions on the surface. The presence of the gray (α) Tin serves to promote further transformation of the white (β) Tin which can eventually cause a significant amount of the metallic Tin to convert to the brittle gray Tin. Since solder joints are inherently small in volume, reliability may be compromised with the initiation of Tin Pest. Solder with 40 % Pb is seldom affected by Tin Pest provided that inoculation with previously transformed gray Tin is avoided [16].

During the operating life of electronic piece parts, Tin-rich joints will be subjected to temperature excursions (typically between –55 °C to 125 °C) with the colder temperatures being conducive to the allotropic transformation of the Pb-free solder joints. It is likely that the incubation time is reset each time the Tin is exposed to temperatures above the transformation temperature. However, once powdery Tin Pest has formed, oxidation and a phase transformation kinetics prevent the reformation of a continuous white (β) Tin metal again.

An early reported instance of Tin Pest was described by Fritzsche [17] where the disintegration of some blocks of Banka pig Tin was observed after exposure to the Russian winter of 1867-8, when the temperature during January fell as low as –38 °C (-36.4 °F). The blocks of Tin had disintegrated into granular crystalline pieces and coarse powder. (Note: The typical composition of Banka Tin is 99.950 Sn, 0.007 Sb, nil As, trace Pb, nil Bi, 0.018 Cu, 0.045 Fe, nil Ag and nil Sulfur [18].) The growth phase of Tin Pest is typically much shorter than the incubation period. The transformation may occur after a long incubation period at temperatures below 13 °C (54 °F), the rate of transformation being highest at –30 °C (–22 °F) [16]. Subjecting the Tin material to a mechanical load that results in a residual tensile stress considerably accelerates the process. Some possible sources of tensile stress in Pb-free assemblies include bending of leads and thermomechanical stresses encountered during thermal excursions. Mechanical treatment decreases the nucleation time due to an increase in the number of reaction sites. Becker [19] noted that annealing and oxidation tend to increase the nucleation time. Becker usually made his Tin Pest observations at 0 °C (32 °F) presumably to minimize the effect that temperatures above 13 °C (54 °F) would have on the transformation nucleation and rate data. Tin Pest nucleation is encouraged through inoculation with α Tin [20] and elements or compounds having a diamond cubic crystal structure similar to α Tin such as InSb, CdTe, and Ge [19]. The transformation is dependent upon the impurities and alloying elements of the Tin. The incubation time of Tin Pest is highly variable.

Tin pest is not a new problem with Lead-free solder. Bornemann [21] found that Pb, in the amount generally found in solder, will not prevent Tin Pest from eventually occurring given enough time and cold enough temperatures. The work by Bornemann highlights some of the variability associated with the transformation. Bornemann stored four un-inoculated pure Tin specimens in clean sealed vials at –73 °C (–99.4 °F). One transformed in six months and the other three showed no visible traces of transformation after four years. Bornemann also found that Pb, in the amount generally found in solder, will not prevent Tin Pest from eventually occurring. (Note: Bornemann went through extensive effort in his second set of experiments to ensure that the Tin surfaces were oxide free.) The addition of as little as 0.1 per cent by weight of Sb or 0.05 per cent by weight Bi added to Sn-Pb alloys inhibited the transformation. There is presently one commercially available patented Pb-free alloy containing Sb, which has a composition of 96.2 % Tin, 2.5 % Silver, 0.8 % Copper and 0.5 % Antimony. There is a possibility that the results of the Bornemann's investigation lead to a change in the ASTM B32 solder specification. The role of antimony in the prevention of Tin Pest in Sn-Pb alloys is discussed in J-STD-006B Section 6.1.1.1, which concludes by stating that the minimum requirement for antimony in Tin-based alloys is not necessary, presumably because no Tin Pest has been observed in Tin-Lead alloys over the last decade.

Although Tin Pest has been found in various laboratory tests [19] - [25], the nucleation kinetics are still poorly understood and it is unclear what the incubation time is for normally processed solder joints. Tin Pest has been found under laboratory conditions in Sn-0.5Cu alloy bulk test samples [22]. Tin pest transformation was also observed on 0.010 inch thick inoculated solder joints stored at –40 °C (–40 °F) [23]. Williams [23] found that the transformation occurs more readily in joints soldered with pure Tin than in joints soldered with Sn-Pb alloy. The pure Tin joints soldered at high temperature (204 °C (367 °F) above the liquidus), dissolved more Cu and tended to transform more readily than joints formed at lower temperature (4 °C (7 °F) above the liquidus). Recent experiments by Sweatman evaluated the role of impurities in commercial purity Pb-free solder alloys (Sn-3Ag-0.5Cu, Sn-4Ag-1Cu, Sn-0.7Cu-0.05Ni, and others) on the nucleation and growth of Tin pest and found that Pb and to a lesser extent Bi and Ag impurities appeared to suppress the transformation of β-Tin to α-Tin [24]. In the first phase of the evaluation by Sweatman [24], Pb-free alloys were formulated from 99.9 percent "three nines" pure Tin, placed in contact with an α-Tin nucleant and exposed to a temperature of –45 °C for 180 days with no signs of Tin pest, while 99.99 percent "four nines" pure tin was observed to readily transform within hours. The impurity analysis of the 99.9 percent pure tin revealed that the largest impurity was Pb at a level of 0.031 % followed by Sb at 0.006 % and As and Bi at 0.004 %. The second phase of the Sweatman evaluation [24] assessed the addition of 0.01 % Pb, Bi, Ag, Zn, In, P, Au, Al, Cu, Ge, Ni, Sb, Ga, and Fe alloying materials to 99.99 % pure Tin in contact with α-Tin for up to 30 hours and found that Pb at the 0.01 % level appeared to suppress the transformation while 0.01 % Fe significantly promotes the transformation. Sweatman suggests that since Pb occurs naturally in primary Tin at around the 0.03 to 0.01 % level, which is still well below the 0.1 % limit of the RoHS directive, there can be some confidence that tin pest will not occur in a Pb-free alloy made with standard 99.9 % "three nines" pure tin. The effect of alloying additions to Tin on the promotion or inhibition of Tin Pest is provided in Section 8, Table 3. With long exposure at low temperature of electroplated pure Tin coatings on Copper, it is possible to encounter transformation, but not with hot dip coating [25]. Bornemann [21] evaluated the transformation of electrodeposited Tin and Tin alloys on steel panels. The pure electrodeposited Tin coatings 0.0002 inch thick (5 um), whether inoculated or un-inoculated began to show evidence of transformation after about four days at – 73 °C (– 99.4 °F). Becker

[19] found that reflowed electrodeposited coatings exhibited different Tin Pest formation characteristics. During exposure to –73 °C (–99.4 °F), the inoculated specimens exhibited transformation in 4 days while the un-inoculated specimen took 14 months. The Tin-Zinc electroplated samples (79.3Sn-20.7Zn, 0.0005 inch (12.7 um) thick) did not exhibit transformation after two years at –73 °C (-99.4 °F) for either the inoculated or un-inoculated samples. Later, Becker [19] attempted to directly deposit thin gray Tin films onto substrates using electro deposition or evaporation, but he was unsuccessful. Becker was however able to obtain Tin Pest on inoculated thin films of Tin.

While Tin Pest has been reported under laboratory conditions on test samples, real solder joints have not exhibited Tin Pest. Tin-Silver (Sn-3.5Ag) solder has a long history of use in high reliability applications and Tin Pest has not been an issue. Recent testing of Sn-0.7Cu-0.05Ni or the Sn-3.8Ag-0.7Cu solder joints evaluated in the JCAA/JG-PP –55 to +125 °C (–67 to 257 °F) thermal cycling testing did not exhibit Tin Pest after over 4000 thermal cycles [15]. The thermal cycling data suggests that the incubation time clock may be "reset" each time the solder is exposed to temperatures above the gray to white transition temperature. The Tin Pest resistance of real solder joints has been evaluated over a 12 month period and no Tin Pest was observed [26]. Similar evaluations have been performed by the CALCE group and they have not observed Tin Pest transformation in either inoculated or un-inoculated real solder joints [27].

In summary, Tin Pest in solder joints may be a field concern in some applications subjected to extremely cold temperatures (e.g. -40 °C) continuously for long durations (e.g., on the order of a year). These applications may require further evaluation. In practice, refining costs of lead-free solders are likely to result in Pb concentrations just under the 0.1 percent and will have some Tin Pest resistance [15] [24] [26]. The majority of high performance applications are not expected to have an issue. Long term testing of real solder joints is continuing.

5.3 Temperature Cycling

Creep-fatigue models for the various Pb-free alloys being considered are at various levels of completeness. An assessment of thermal fatigue reliability to the service environments, in many cases, presents the greatest challenge due to the long test durations. Invariably, some acceleration factor, either increased temperature difference or reduced dwell time, is required to complete the temperature testing in a reasonable amount of time. The thermal cycling performance of a Pb-Free alloy is determined by its ability to survive upper and lower temperature limits, the ramp time required to transition between the temperature limits, and the dwell time at the temperature extremes.

High performance applications have historically relied on –55 ºC to +125 ºC thermal cycling testing to provide confidence that equipment will function reliably once it is in service. It has already been established that, Pb-Free eutectic SAC solder does not perform as well as Tin–Lead under high stress thermal cycling conditions (large temperature difference and/or large thermal expansion coefficient mis-match driven solder joints) [28]. Implicit in any thermal cycling discussion is that the printed circuit board used to connect the Pb-Free technology piece-parts is reliable. The PCB plated through holes and traces must be able to withstand the higher temperature Pb-Free solder reflow and rework stresses and go on to perform reliably in test and service.

There has been, and will continue to be, considerable debate on why solders perform differently under different thermal cycling conditions. There are many factors influencing solder life that interact in complicated ways that are not completely understood. While the understanding of the Sn-Pb system has improved greatly over the years, the study of this system has revealed that several other factors may also be important contributors to solder fatigue. In addition to the obvious need to define thermal cycling temperature extremes, dwell time (at hot and cold) and ramp rate, the following must also be considered during an assessment of solder fatigue:

- solder joint oxidation
- stress distribution in the solder joint

- manufacturing process history
- conformal coat type
- non-linear package and PCB properties over temperature
- PCB surface finish, etc.

All these factors combined, influence the long-term solder life in service and may or may not be accounted for in accelerated testing and modeling of heritage Sn-Pb solder [29] [30] [31] [32]. At the present time, there is no indication that any of the aforementioned solder life factors will be eliminated with the introduction of Pb-Free technology. To the contrary, a few more factors have been added; such as Sn crystallographic orientation [13], Cu-Sn-Ni ternary intermetallics [33], and ENIG interfacial concerns [34]. In addition, some phenomena that may have always been present but were not a concern with Tin–Lead, such as voiding at the Cu/Cu_3Sn interface [35] [36] [37] [38], will need to be understood in greater detail when Pb-free solders are used.

Generally, the thermal cycling test results indicate that for high strains, Tin-Lead performs better in thermal cycling than SAC alloys and that under small strain conditions (e.g., a small temperature cycle) that the SAC alloy performs better than Tin-Lead [28] [39]. However, closer examination of the Bartelo data [28] reveals that dwell time is a significant factor in the aforementioned statement. In the case of Bartelo's 0 to 100 °C temperature range thermal cycling, SAC outperformed Tin-Lead for the 7 and 22 minute dwell times but at a dwell time of 112 minutes, SAC reliability was comparable to Tin-Lead. Generally though, long dwell time thermal cycling data is lacking and few investigators have performed testing with dwell times greater than 60 minutes, a few exceptions are Bartelo, Pan and Osterman [40]. Although modeling has been proposed to extrapolate to long dwell times [28] [39] [41] [42] [43] [44], these models continue to be updated as more package types and longer dwell time tests results become available. The nature of the mixed results observed to date suggests that a careful review of the service environments is also needed in order to avoid costs associated with unnecessarily conservative design limits.

For temperature cycling test data to be interpreted properly requires documentation of test conditions and results in accordance with IEC/PAS 62647-3 (GEIA-STD-0005-3), which utilizes guidance from IPC-9701.

5.3.1 Solder Thermal Cycling Failure Mode

Typically intergranular fracture of the solder occurs during thermal cycling. In cases where high stresses are present, failure can occur at the intermetallic interfaces when weak intermetallic layers are present [6], but this does not usually occur in a properly designed and manufactured joint.

5.3.2 Stress Relaxation Considerations

One impact of using a less ductile Lead-free SAC solder is that it can have 10 to 100 times longer stress relaxation times than heritage Sn-Pb solder depending on applied stress, temperature, and the alloy type. The result of any stress testing needs to be evaluated in the context of the acceleration factor between the test and the intended use environment. Acceleration factors of Pb-Free solders vary from conventional Tin-Lead with changes in temperature extremes, ramp rates, or dwell times. These factors must be considered in order to ensure that a representative amount of damage occurs during the cycling. The other impact is that the different piece-parts on the same assembly will undergo varying degrees of stress relaxation due to the dependence of relaxation time on the applied stress. Validated model(s) will be required to translate thermal cycling results to service environmental conditions.

5.3.3 Ramp Rate

IPC-9701 recommends that the ramp time be less than 20 °C per minute. It may be beneficial to accurately control the ramp rate between comparative tests because significant stress relaxation can occur during the ramp. In addition, thermal cycles having longer ramp times may be able to use shorter dwell times.

5.3.4 Dwell Time at Elevated Temperature

Continued testing is in process to validate model performance at longer dwell times.

5.3.5 Dwell Time at Low Temperature

Dwell time sensitivity at low temperature has not been experimentally evaluated by many researchers. Modeling suggests that the majority of damage at cold occurs due to yielding due to the slow creep rates present at low temperatures. The influence of low mean temperature on reliability is being investigated by CALCE [46]. A modeling assessment of stress relaxation time for chip components was presented by Grossman [47]. The strain remaining in a 2220 chip capacitor solder joint after 10 minutes at –40 °C (–40 °F) was 4.2 % and after 8 hours was still 1.8 %. (Note the maximum possible strain was reported to be 5.6 %.)

5.4 Rapid Mechanical Loading (Vibration/Shock)

With regards to dynamic mechanical loading such as vibration and shock, little has been done in commercial industry, mostly because these are not environments of interest for the mainstream electronic products being driven to Pb-Free. The stiffer Pb-Free SAC solders are expected to transmit higher loads to the piece-part terminals and the PCB pads, potentially causing increased incidence of failure in intermetallic layers, interfaces, and non-solder (Copper and PCB laminate) interconnect structures. In addition, there will be an increased sensitivity to the presence of voids in the solder or at the interfaces. Another aspect of using a stiffer solder is that the reliability will be more sensitive to voids located in the solder or the interfaces. Typically, vibration solder fatigue failure is not an issue on piece-parts with relatively flexible leaded terminations (as in J-Leaded parts or quad flat packs). Under rapid loading conditions, solder is quite strong and stiff and the load is transferred to the leads, which typically have a smaller cross-section than the solder, so that the leads will experience fatigue failure before the solder. Thus the majority of the concern with vibration and shock loading is with Area Array (e.g., BGAs, CSPs) piece parts, piece-parts with stiff leads, leadless devices (e.g., LCCCs), and large surface mount chip parts. Mechanical shock test performance of Pb-Free solders has been found to be less than Sn-Pb solders particularly when Nickel substrates are used [33] or where there is a tendency to form Copper voids at the pad interface [36].

From the final results from the JCAA/JG-PP vibration testing on BGAs, the combination of eutectic Sn-Pb solder/Sn-Pb balls always outperformed the combination of Pb-free solder with Sn-3.9Ag-0.6Cu balls [48]. For other component types, the results were mixed. It is the working group's opinion that, given the propensity for Pb-Free alloy to form intermetallic compounds and/or voids that could result in brittle interfaces, it seems appropriate that high performance electronics include assembly thermal preconditioning prior to dynamic mechanical testing. Unfortunately, systematic studies of thermal preconditioning times/temperatures prior to dynamic mechanical testing are still needed for a variety of device types.

6 System Level Service Environment

Given that Pb-Free solder alloy performance in a particular assembly is not guaranteed to be better than Tin-Lead solder alloy, the best way to provide an accurate assessment of the Pb-Free alloy reliability is to begin with a comprehensive understanding of the electronic service environments. The results from high performance testing such as JCAA/JG-PP [49] have yielded mixed results for some piece-part types. It is unlikely that a heritage assembly can be converted to Pb-Free solder without a re-design activity. In low stress solder joints, SAC alloy performs better than Tin-Lead eutectic. As the solder stress is increased, Tin-Lead out performs SAC. It is clear that each application needs to be individually evaluated when Pb-

Free solder alloys are being considered. It is likely that some design adjustments to reduce solder strain will be needed on some applications to implement Pb-Free solder.

6.1 Service Environment

The system level requirements imposed by the aerospace vehicle manufacturer on an OEM electronics system Supplier are intended to ensure reliable operation of the equipment in service for its expected lifetime. To demonstrate that the system environmental requirements are met, a series of tests and analyses are performed. The tests performed often stress the equipment to greater levels than would be encountered in service to ensure design margin or to accelerate testing (reduce test time). The strategies employed to establish margin or to accelerate testing must exercise the failure mechanisms expected in service without introducing non-relevant failure mechanisms.

The solder joint reliability is determined by its ability to survive accelerated life time service environments. To perform the reliability analysis, the solder joint environment is obtained from the assembly level analysis whose boundary conditions are obtained from the box level and the vehicle level environments. Extensive discussion on the thermal cycling assessment of surface mount assemblies is given in IPC-9701, Performance Test Methods and Qualification Requirements for Surface Mount Solder Joints. Many of the principles outlined in IPC-9701 are applicable to the evaluation of Pb-Free alloys. The underlying physics-of-failure concepts are also applicable; however, Pb-Free alloys have different creep behavior, stress relaxation times, and creep-fatigue models than the heritage Sn-Pb alloys as described in IEC/PAS 62647-3 (GEIA-STD-0005-3) and modeling must be used to compare Pb-free and Sn-Pb fatigue test results.

In the following paragraphs, the special considerations required for the assessment of Pb-Free solders alloys in aerospace environments will be outlined. Depending upon the individual application, there may be additional testing and analysis required to substantiate the Pb-Free alloy soldered assembly.

6.2 Electronics/Electrical Equipment Thermal Environments

Steady state and cyclic thermal environments of the equipment utilizing the Pb-Free alloy provides the basis for the reliability determination. The steady temperatures are used for intermetallic growth and Kirkendall void formation, while the cyclic environments will be used to determine the thermomechanical fatigue life of the electronic/electrical system. The LRU level thermal environments, in combination with the power dissipation and the cooling design, must be used together to determine the PCB assembly temperatures driving the solder thermomechanical fatigue.

6.2.1 Electronics/Electrical Equipment Steady Temperatures

A range of operating temperatures that includes the fraction of time the equipment will be at the various temperatures and the state of power dissipation within the box should be provided as is described in Annex A.

6.2.2 Electronics/Electrical Equipment Temperature Cycling

The thermal cycling performance of a Pb-Free alloy is determined by its ability to survive upper and lower temperature limits, the ramp time required to transition between the temperature limits, and the dwell time at the temperature extremes. A series of thermal cycling environments that captures the spectrum of cycles that equipment will be exposed to throughout its life should be provided. The thermal cycling environment should be specified for both “operating” and “un-powered storage” conditions as described in Annex A.

6.3 Vibration and Shock

Vibration and Shock performance of Pb-Free solders for some piece-part types is less than Sn-Pb. Accurate representation for the service conditions would prevent unnecessary costs during the Pb-Free implementation. Thermal preconditioning may be required as part of this service life assessment to simulate intermetallic growth.

6.4 Humidity

No special considerations beyond the normally specified humidity testing are required. Care must be used when using zinc or indium bearing solder alloys due their corrosive tendencies. In these alloys, the zinc and the indium are the species that corrode.

6.5 Other environments: Salt Spray, Fungus, Cooling Air Quality, and Fluid Compatibility

No special considerations beyond the normally specified testing are required. Silver finishes are not prone to whisker growth in most environments. However, rapid growth of silver dendrites or, in some cases, silver whiskers may form in the presence of H_2S (found in some cases where the environmental air pollution contains SO_2) [50]. Pb-free solder and finish performance evaluations in sulfur bearing atmospheres (such as salt fog testing in accordance with ASTM G85 Annex A4) has not been extensively evaluated.

6.6 Other Special Requirements

No data is available for acoustic vibration or pyroshock performance of Pb-Free alloys.

7 High Performance Electronics Testing

The Joint Group on Pollution Prevention (JG-PP) and the Joint Council on Aging Aircraft (JCAA), conducted a multiyear evaluation of Pb-Free solder [49]. The test utilizes the best practices for printed circuit board thickness and plane layer content, assembly design, assembly and piece-part characterization, monitoring, and failure analysis as outlined in IPC-9701. The test plan includes an assessment of the standard high performance environments: Thermal Shock from –55 to +125 °C, Thermal Cycling (–20 to +80 °C and –55 to +125 °C), Vibration, Mechanical Shock, Humidity, Salt Fog, Surface Insulation Resistance, Electrochemical Migration Resistance, and Combined Thermal/Vibration Environments. The thermal cycling tests are utilizing 30 minute hot and 10 minute cold dwell times (after assembly temperature stabilization). Although preliminary results are available, the principal investigators are cautious about drawing conclusions from the data until the failure analysis and modeling activities have been completed. As has been observed in previous studies, the results are mixed. Sometimes Pb-Free exhibits better performance than Sn-Pb and sometimes the opposite was found to be the case. Modeling will be needed to properly compare the Sn-Pb and Pb-Free alloy performance and correct for the stress relaxation differences observed on the various piece-parts and thermal cycling conditions. A summary of JCAA/JGPP testing associated with Sn-Pb and Pb-free finish/solder alloy mixing is given in Section 8.5, after the mixing of alloys discussion.

In 2006, the results of thermal cycling test performed by CALCE were presented in a SAC modeling paper [51]. The test design of experiment (DOE) matrix included temperature differences, mean temperatures, and dwell times. The study evaluated the performance of ceramic leaded chip carriers on glass epoxy PCBs with three solder alloys, Sn95,5Ag3,8Cu,7, Sn96,5Ag3,5,) and Sn63Pb37. Dwell times of 15 and 75 minutes were evaluated for various temperature cycling ranges and mean test temperatures (e.g,. cycles of 0 to 100 °C (32 to 212 °F), –25 to 75 °C (-13 to 167 °F), 25 to 125 °C (77 to 257 °F), etc.). Sn-Pb outperformed Pb-free solder at the highest tested cyclic mean temperatures, which had a peak temperature of 125 °C (257 °F). However, Pb-free solder was more reliable than Sn-Pb solder at peak temperatures under 100 °C (212 °F) regardless of dwell time. Finally, the reliability of Pb-free solders showed much stronger dependence than the Sn-Pb solder on the cyclic median temperature.

The thermal cycling performance of A30C5 and A40C5 for –55 to +125 °C (-67 to 257 °F) thermal cycling exposure was assessed on ENIG finished PCBs for a variety of component types [45]. The thermal cycling performance of A40C5 was better than the A30C5. The Land Grid Arrays package (LGA 64) exhibited some degree of interfacial fracture at the ENIG board interface with the ENIG exhibiting signs of a moderate level of black pad corrosion.

8 Solder Joint Reliability Considerations

The reliability of a solder joint is dependent upon the integrity of the solder in the joint and the metallurgical interfaces to the leads and pads. Particularly for SMT assemblies, due to the limited solder volume present, the solder joint reliability is strongly influenced by the final solder alloy composition and microstructure, the shape of the solder surface and the terminal-to-solder interfacial strength. Mixing of Pb-free and Sn-Pb finishes are a significant consideration with assemblies with a 20 year maintenance plan. Some issues associated with finish compatibility and mixing are introduced here and are then discussed further and summarized in Sections 9, 10, and 11.

Final Solder Joint Composition

The initial composition of the solder used to form the joint is typically modified to some extent during the soldering process as the pad metallization and the finish of the pads are dissolved into the solder joint. The amount of dissolved piece-part and pad metal typically does not significantly alter the final alloy composition but may effect the final solder joint mechanical properties. There are some pad constituents (e.g., gold in solder or Pb in SAC solder) that have a tendency to segregate to either the pad interfaces and/or grain boundaries causing a change in mechanical properties of the joint and the interfaces. In addition, contact pad metallization and finish solubility can create unanticipated intermetallic compounds near the joint interfaces. It is important to embody these effects in the test assembly ultimately used to validate the assembly performance/reliability. The effect of the pad dissolution is one of the factors considered in the test protocol section outlined in IEC/PAS 62647-3 (GEIA-STD-0005-3).

While the final solder joint composition is not significantly influenced by the component metallization on most electronic devices, BGAs and CSPs need to be considered differently. With BGA and CSP devices the final solder joint composition is strongly influenced by the ball composition because the ball volume is large compared to the solder provided by the printed solder paste used during the assembly process. There are also reliability concerns when mixing Sn-Pb and Pb-free alloys during manufacture and/or repair.

In addition, some Pb-free alloy formulations contain other constituents. It is commonly recognized that Zinc and Indium bearing Pb-free alloys tend to corrode readily in moist environments and should be evaluated carefully before use [52]. Solder alloy composition may need to be defined more accurately if ternary or quaternary alloy systems are used. As the industry transitions from Sn-Pb to Pb-free, additional measures may be critical in assuring that the proper materials are utilized. X-ray Fluorescence (XRF) spectroscopy measurement techniques are presently being used as a means of verifying alloy and finish compositions. While the Pb-free alloy's structural properties influence the reliability of the assembly, the wetting characteristics of Pb-free alloys also need to be considered.

Solder Wetting and Final Joint Shape

The solder stress-strain distribution within the joint is often determined by the final solder joint shape, which is defined by the solder wetting and the resulting solder free surface shape. The wetting angles for Pb-Free alloys are greater than Sn-Pb alloys [53][54]. Greater wetting angles are indicative of poorer spreading and less metallurgically bonded area resulting in potentially weaker joints. The addition of Ag to Sn and Sn-Cu alloys significantly decreases wetting in solder drop spreading experiments [55]. Although Pb-free solders do not wet as well as the heritage Sn-Pb solders, not all solder configurations are impacted by this issue. Solder geometries, such as ball grid arrays, are usually not dependent upon wetting angle as long as the entire pad is metallurgically wet. In contrast, piece-parts with leads, particularly those with stiff leads, which depend upon the heel fillet geometry for strength, are expected to be more sensitive to wetting variations. Quad flat packs soldered with SAC alloy exhibited premature failures during thermal cycling from –55 to +125 °C (–67 to 257 °F) that was attributed to solder process variability (e.g,. insufficient solder volume, insufficient heel fillet, solder voids, etc.) [15] [56]. Chip piece-parts and leadless ceramic chip carrier solder joints may be less prone to wetting variation because any solder that does not wet up onto the vertical surfaces will tend to increase the solder thickness under the device. The final consideration in assembly performance is the reliability of the interfaces. Lead-free process variability should be minimized before beginning extensive reliability testing. Some quick process quality checks include: lead terminal pull testing, cross-sectioning, HALT/HAST testing, and vibration/shock.

Strength of the PCB and Component Interfaces

The piece-part and pad interface strength is typically dependent upon the intermetallic strength. The stress imparted upon the interface is dependent upon the solder alloy and the load application rate. Under slow loading conditions, such as thermal cycling, the solder tends to creep and the resulting interfacial stress is lower than during rapid loading. In the case of rapid loading such as vibration or shock, the solder does not have time to creep and greater loads will be observed on the interfaces. Nickel-Tin intermetallics are generally weaker than Copper-Tin intermetallics [57]. Another source of reduced interfacial strength is the presence of voids near the interfaces. Voids result in reduced strength by decreasing the metallurgically bonded areas. Some investigators have found voiding in the copper substrate adjacent to the Cu3Sn intermetallic [35] [36] [37] [38].

The laminate integrity under the solder pads is also impacted by these interfacial stresses and will be discussed in the piece-part and PCB sections. This topic is under considerable study in the industry at the present time. Mechanical design modifications may be needed to reduce vibration and shock loads of Pb-free solder joints to prevent damage to the underlying laminate material (e.g., PCB BGA pad cratering [58]).

8.1 Mixing of Solder Alloys and Finishes

As the Pb-free transition is occurring, metallurgy mixing is one of the biggest assembly concerns to the AHP electronics equipment Suppliers and users. Sn-Pb BGA ball metallurgy and Sn-Pb finished piece-parts are being quickly replaced by Pb-free alternatives. A special consideration for AHP applications is that Pb-free solders may be either intentionally or unintentionally mixed with Sn-Pb solder or Pb bearing finishes throughout their service life and during repair depot activity.

Some common issues with Pb-free surface finishes are given in Table 1 and in the remaining paragraphs of Section 8. The assessment of piece part and PCB finishes is extended in greater detail in Sections 9, 10, and 11. A finish process compatibility matrix and a relative process reliability summary are given in Tables 6 and 7.

Piece-parts and PCB finishes used in high performance applications often require an assessment of Tin whisker propensity and Tin pest risk. The impact on Tin whisker and Tin pest formation due to elemental additions into Pure Tin are given in Tables 2 and 3. A detailed discussion of the Tin whisker and Tin Pest propensity for the various piece-part and PCB finishes is given in Tables 4 and 5.

8.2 Pb-free Terminations in Tin-Lead Joints

One result of the WEEE/RoHS directives and the responding piece-part fabricator initiative is the introduction of piece-parts with Pb-free surface finish terminations into existing traditional Tin-Lead soldering processes. The variety and compositions of the Pb-free surface finishes being delivered into the electronics industry is extensive. Many of these piece-part materials will find their way into the inventory of aerospace and defense assembly processes under government acquisition reform initiatives. Additionally, the banning of Tin-Lead surface finishes could reduce the Supplier base and adversely affect the readiness of some critical missions. Electronics assembly design teams must be knowledgeable on the potential impact of the Pb-free surface finish piece-part and pad interface on solder joint integrity.

Recent test results indicate that Sn-Pb finished PCBs with SAC alloy solder BGAs exhibits poor thermal cycling performance [Reference [15] Figures 38 and 39] when the Pb concentrations are low (e.g., flux only rework of a SAC BGA on a Sn-Pb finished PCB pad). Earlier testing on CLCCs suggest that the fatigue life of SAC solder is improved with the addition of some Pb [74]. The addition of Pb in SAC changes the solder composition and affects the fatigue performance. The presence of Pb in SAC expands the considerations of property changes on the reliability of the solder alloy. The impact is not universal – solder joint integrity degradation can range from slight-to-severe depending upon the use environment.

The amount of Pb versus solder joint volume, the amount of stress the solder joint experiences and the overall reflow thermal profile have direct impact on the final solder joint integrity. These process interactions are not fully understood and a mixed metallurgy situation must be carefully characterized to assure that product integrity is not compromised

8.2.1 Ball Grid Array Pb-free Terminations in Tin-Lead Joints

Industry has two opposing camps on the BGA mixed metallurgy issue and whether specific factors such as PCB thickness, reflow temperature profile, and testing parameters result in a level of performance variability. A general statement on the mixing issue is not possible at this time and each application will need to determine if mixing will impact product integrity. If mixed (Pb-free/Sn-Pb) ball metallurgy is being considered, the fatigue exponents need to be developed that will allow extrapolation from accelerated tests conditions to service conditions for the range of solder joint compositions that the process will yield.

It was found during the JCAA/JG-PP testing that the mixed alloy (Sn-Pb/Pb-free) systems were not "as good or better" than either of the pure material sets for highly stressed assemblies. Both SAC BGAs soldered with Sn-Pb Paste and Sn-Pb BGAs soldered with SAC paste combinations were tested in the JCAA/JG-PP test and both mixed combinations failed very early in –55°C to +125°C (–67°F to 257°F) thermal shock (starting at a few hundred cycles) as can be seen in reference [59] Figure 14 and Table 6. In comparison, non-mixed solder BGAs (i.e., pure SAC or pure Sn-Pb) had no failures after 1000 thermal shock cycles. Early failures for these mixed metallurgy BGA combinations were also seen in the –55°C to +125°C (–67°F to 257°F) thermal cycle test (see reference [15] Figures 6 and 7). In addition, early failures were observed for Sn-Pb BGAs soldered with SAC (reference [60] Figure 8) in the –20°C to +80°C (–4°F to 176°F) thermal cycle test (Note: SAC BGAs soldered with Sn-Pb were not tested). In highly stressed chip scale package (CSP) thermal cycling testing, the mixed metallurgy combinations did not perform as well as the non-mixed soldered CSPs [61]. In addition to compositional complications associated with the addition of more elements into the solder joint, mixed metallurgy performance is also affected by processing time and temperature process controls, as discussed later in this section.

Under rework conditions, the JCAA/JGPP testing revealed some poor thermal cycling performance at the lower limit of Pb contamination in SAC BGAs. Testing of SAC BGAs soldered with flux only to Sn-Pb HASL (hot air solder level) finished PCBs exhibited poor thermal cycling reliability. The solder failed with a fracture near the pad interface where Pb had accumulated along Sn grain boundaries near the interface [See Reference [15] Figures 38 and 39].

Those tests that have evaluated the mixed metallurgy configuration have found that it is much better if the Pb-Free alloy and the Sn-Pb are well mixed. The solder process temperature and time above Sn-Pb liquidus are important considerations when assembling BGAs with SAC balls to PCBs using Sn-Pb solder paste. It has been found that, in order to have a well mixed final SAC/Sn-Pb metallurgy, solder time/temperature process parameters may need to be tailored beyond the standard Sn-Pb solder profiles. It can be very difficult to practically implement the tight process temperature windows on large complex assemblies. If mixed (Pb-free/Sn-Pb) ball metallurgy is being considered, the fatigue exponents need to be developed that will allow extrapolation from accelerated tests conditions to service conditions for the range of solder joint compositions that the process will yield.

The melting points of SAC alloys are generally toward the upper limit of the Sn-Pb solder processing temperatures. The Pb-free BGA ball composition variations influence the melting temperature. In cases where improved drop shock performance is desired, SAC with reduced Ag content (e.g., SAC with 1 %Ag, melting point = 226°C (439°F)) is used instead of the near eutectic SAC composition (e.g., SAC with 3 %Ag, melting point = 220°C (428°F)). SAC balls attached to a PCB with Sn-Pb solder can have various microstructures, depending upon the maximum soldering temperature of the solder joint, the time above liquidus, and the ratio of deposited Sn-Pb paste to the SAC BGA volume. These factors will determine the degree of SAC ball and Sn-Pb paste solder alloy mixing. It is generally desirable to have a SAC ball that is completely molten such that it will form a well mixed alloy upon solidification. As discussed below, the thermal cycling performance of the SAC Ball and Sn-Pb paste is generally lower than either the SAC Ball/SAC Paste or the Sn-Pb Ball/Sn-Pb paste combinations. However, thermal cycling fatigue life may be acceptable for assemblies having lower solder stresses.

When full mixing is not attained, the SAC Ball is partially dissolved into the Sn-Pb alloy. In some cases, the Pb migrates along the Sn grain boundaries [62]. Some of the drawbacks associated with a partially mixed joint are:

- Poor self alignment of piece-parts during reflow increasing the risk of an open circuit condition.
- Insufficient collapse of the balls during reflow making them susceptible to package coplanarity variations and abnormally formed solder joints that are difficult to inspect.
- Variation in joint microstructure homogeneity that could lead to poor fatigue characteristics.

Chung [62] and Maire [63] evaluated the thermal cycling performance of SAC BGAs that were soldered with near eutectic Sn-Pb solder where the finally solidified BGA ball was not mixed. Chung utilized Sn-Pb solder and reported no electrical failures after 1000 thermal cycles from –40 °C to +85 °C (–40°F to 185 °F). Maire used Sn-36Pb-2Ag solder and observed some amount of cracking after 1000 thermal cycles from –40 °C to +100 °C (-40°F to 212 °F), however, the observations were similar to the cracks observed on pure Sn-Pb joints. Both investigators agreed, however, that a well mixed solder ball was desirable for the reasons previously mentioned.

Non-uniformly mixed SAC BGAs attached to ENIG PCB pads were evaluated for thermal cycling life by Hillman [34]. Hillman found that this configuration exhibited poor thermal cycle reliability. Cracks rapidly formed between the solder and the ENIG pads. The JCAA/JGPP testing also showed some poor thermal cycling performance at the lower limit Pb concentration in Sn-Pb/SAC BGAs mixed metallurgy rework assemblies with Sn-Pb PCB pads during the –55 °C to +125 °C thermal cycling tests. See section on Tin-Lead in Pb-free joints.

In some cases, the Sn-Pb solder temperature profile can be increased slightly to ensure good mixing. However, there are cases where the temperature limitations of heritage Sn-Pb piece-parts may not allow solder process temperature increases. There is another way to achieve the desired results. Mixing can be achieved through a combination of increasing the amount of Sn-Pb solder paste printed onto the PCB and increasing the time above Sn-Pb liquidus during soldering. Snugnovski found that Sn-Pb solder will dissolve solid SAC BGA balls with solder temperatures below 220 °C (428°F) as long as the proper ratio between Sn-Pb paste and SAC ball mass is obtained [64].

Uniformly mixed SAC BGA balls attached to PCBs using Sn-Pb solder were evaluated in thermal cycling [65] [56]. These assemblies successfully completed 2000 thermal cycles from –55 °C to +125 °C (–67°F to 257°F).

8.2.2 Flat pack and chip device Pb-free Terminations in Tin-Lead Joints

The majority of Pb-free finishes (see Table 1 and Table 8) are compatible with Tin-Lead alloys and will not impact solder joint reliability. The most common finishes are pure Tin, high Tin content alloys with Silver and/or Copper, and Nickel/Palladium/Gold over copper alloys or low coefficient expansion leads/terminations. Detailed solder joint reliability considerations associated with several finishes are discussed next.

8.2.2.1 Pure Tin (Matte Tin and Bright Tin)

A very common Pb-Free finish is pure Tin [3]. There are many different matte Tin and bright Tin plating finishes in use in the various electronic components (microcircuits, connectors, resistors, capacitors, axial leaded devices, relays, switches, etc.). Tin plating characteristics can vary greatly from Supplier to Supplier. Process chemistry and control of these plating processes is critical in determining solderability and Tin whiskering characteristics (See IEC/PAS 62647-2 (GEIA-STD-0005-2) and JP002)). Pure Sn finishes are fully metallurgically compatible with Sn-Pb assembly solder alloys. The Sn finishes applied to the devices are thin enough that they will dissolve completely into the bulk solder during reflow even if the melting point of Sn is not attained. Since Sn-Pb eutectic solder already contains Sn, the principal effect of soldering to pure Sn terminations is a slight Sn enrichment in the final solder joint composition. The properties of Sn-Pb solders change little with a variation of a few percent in composition [66]. In bright Tin or thicker matte Tin coatings, co-deposited organics can yield solder voids during reflow in some solder joint geometries.

One should note that Tin finished piece-parts may exhibit poorer wetting than Sn-Pb finishes if they are stocked for extended times. When a “last time buy” is made of a pure Tin finished part, careful stock control should be in-place to ensure solderability at the time of assembly. Bright tin surface finishes can exhibit solderability difficulty due to the presence of co-deposited organics in the plating that can volatilize and can also exhibit degradation of the base metal solderability after extended storage.

8.2.2.2 Sn-Bi

Bismuth is typically added to tin finishes in amounts of 2-4 % by weight. Mixing Sn-Bi finishes with Sn-Pb solder is discussed in Section 8.4.

8.2.2.3 Sn-Cu and SAC

Sn-Cu and SAC finishes are metallurgically compatible with Sn-Pb solder. Similarly to matte Tin, the use of these alloys will result in minor enrichment of Sn and some added Copper and Silver to the final solder joint. There are some indications that Sn-Ag-Pb solders are more durable than Sn-Pb solders [67]. The electrodeposited Sn-Cu finish should be avoided because this finish has a very high propensity for whisker growth [68] [69].

8.2.2.4 Ni/Pd/Au

The maintenance of Au concentration in the final solder joint is still required to ensure that Gold embrittled joints do not form. There may be some instances with Pd bearing finishes, where Pd can diffuse into the solder joint resulting in the formation of brittle Pd-Sn intermetallics. Palladium has been used since 1989 as a termination finish on microcircuit leads and many Pd finished components have been fielded [70]. In some cases, the formation of a Pd-Au-Ni-Sn intermetallic near interface can reduce durability [45]. PdSn4 has the same brittle characteristics as AuSn4 intermetallic. [71]. For applications in high moisture or corrosive environment, if the Ni/Pd/Au is cracked during lead-forming, stress corrosion can result [3]. In a typical solder joint, this amount of gold contributed to the solder joint is negligible and the conventional 3 % gold concentration limit will not be exceeded.

8.3 Tin-Lead Terminations in Pb-free joints

The introduction of Tin-Lead terminated components in a Pb-free solder system is likely during the early stages of Pb-free assembly processing while the piece-part supply stream still contains Sn-Pb terminated components. In addition, fine pitch leaded piece-parts have been granted an EU exemption and will be permitted to use Sn-Pb finish [72].

8.3.1 Ball Grid Array Tin-Lead Terminations in Lead-free Joints

First it should be noted that heritage Sn-Pb BGAs were not designed to be capable of withstanding the higher Pb-free solder process temperatures and that maximum temperature capabilities of the Sn-Pb BGAs should be assessed prior to soldering at Pb-Free solder temperatures. As was mentioned in Section 8.2.1, industry has two opposing camps on the mixed metallurgy issue and that specific factors such as PCB thickness, reflow temperature profile, testing parameters result in a level of performance variability such that a general statement of the mixing issue is not possible at this time and the user needs to investigate their design more fully to determine how mixing will impact their product integrity. In contrast to JCAA/JGPP findings discussed in Section 8.2.1, Wickham's [56] evaluation of Sn-Pb BGAs soldered to PCBs with SAC solder showed comparable reliability to Sn-Pb BGAs soldered with Sn-Pb-Ag solder (Note: failures for both of these configurations were observed in the BGA die region between 1000 and 2000 thermal cycles from –55 to +125 °C (-67 to 257 °F)).

8.3.2 Flat pack and chip device Tin-Lead Terminations in Lead-free Joints

Surface mount solder fillet lifting is possible during secondary soldering processes [73], resulting in low strength solder joints. Generally however, Pb contamination of SAC solder joints did not adversely impact solder joint reliability in –55 to +125 °C (–67 to 257 °F) thermal cycling and vibration for the majority of components tested [56] [65]. Thermal cycling testing from –40 to +125 °C (–40 to 257 °F) on leadless ceramic chip carriers showed that the addition of small amounts of Pb (~0.2 to 0.9 wt % depending upon the assembly tested) improved the thermal cycling performance of Sn95,5Ag3,8Cu,7 and Sn96,5Ag3,5 but decreases the reliability of Sn-0.7Cu [74].

8.4 Bismuth Effects

The addition of Bismuth to SAC has been shown to yield a solder joint which has improved reliability [74] [75]. The principle concern is that when Bi is mixed into Sn-Pb solder, a low melting point Sn-Bi-Pb Ternary alloy can form, particularly at the grain boundaries. The melting point of the ternary alloy is 96 °C and the solder can lose strength during hot mission environments. Trace amounts of Pb were found to have a detrimental effect on solder life of Bismuth containing solders (Sn91,8Ag3,4Bi4,8 and Sn92,3Ag3,4Cu1,0Bi3,3) and resulted in catastrophic failure of Sn-58Bi solder joints where the joints essentially turned into a powder after 835 thermal cycles from –40 to +125 °C (–40 to 257 °F) [74]. Since AHP products have a 20 year service life and a repair depot infrastructure that will have both Sn-Pb and Pb-free alloy configurations for a significant amount of time, Bismuth bearing solder alloys are noted as a concern in IEC/PAS 62647-1 (GEIA-STD-0005-1). However, there are some piece-parts that are only available with a Sn-Bi lead termination finish, preliminary testing suggests that trace amounts of Bi in Sn-Pb joints are not detrimental to solder life in this case. The present J-STD-006 solder alloy specification allows 0.1 % Bi in Sn-Pb solder.

The various combinations that may be encountered are:

- Sn-Pb-Bi-X solder joint where there is sufficient amounts of Pb and Bi and the Sn-Bi-Pb ternary alloy can form. The risk that Sn-Pb-Bi ternary alloy can form is greatly reduced if Bi bearing alloys having significant Bi concentrations are not used.
- Bismuth based Pb-free solder alloys with "Pb contamination". The presence of trace amount of Pb in a Bismuth based Pb-Free solder alloys (SACB) solder joint were found to cause a measurable reduction in solder joint integrity that is most likely due to the deformation of the soft Pb phase that segregates along the Tin grains [76]. (Ref: Kayria [75] showed the phase and the segregation. The user needs to determine the level of risk.)
- Tin-Lead based solder alloys with "Bi contamination". Some piece-parts are being provided with Tin-Bismuth plating finish. The Bismuth concentration in the plating is typically 2 to 5 weight percent and only ~ 3 um (120 microinches) thick. There has

been some indication that Sn-Bi finishes used on Alloy 42 lead-frames that are soldered with Sn-Pb will exhibit some reduction in solder joint thermal cycling fatigue life compared to a Sn-Pb finished lead termination soldered with Sn-Pb solder [77] [78]. Sn-Bi finished Copper lead-frames soldered with Sn-Pb solder, have exhibited comparable thermal cycling reliability to Sn-Pb finished Copper lead-frames soldered with Sn-Pb solder [78]. Other testing has shown good thermal cycling performance with SOIC14/16 (small outline integrated circuit) packages (Note that the type of lead material was not reported) [65]. Further testing is in process [76].

Provided that uniform solder reflow processing is followed to ensure that Bi segregation does not occur, it is expected that there is little risk of forming the Sn-Bi-Pb ternary eutectic (96 °C (205 °F) melting point) with small (1-5 % by weight) additions of Bi to Sn finishes when soldered with Sn-37Pb [79] [80] [81] (Note: Segregation of low melting point phases can occur under some soldering conditions. Segregation of a 178 °C (352 °F) melting point Sn-Ag-Pb alloy has been observed during reheating of Pb bearing components attached with SAC solder alloys [73]). There is a ternary Sn-Pb-Bi peritectic that is thermodynamically stable for Bi above 6 % by weight in the component finish, and this peritectic has a melting point of 135 °C (275 °F). As long as the Bi concentration on the lead termination is less than 6 %, the peritectic should not be an issue [79] [80] [81]. With eutectic Sn-Pb solder, it is necessary to control the Bismuth content of the finish between 3-5 % so as to have enough Bismuth to help retard whisker formation without getting into the compositional range of the ternary eutectic. In addition, keeping the Bi content low is required to retain solderability of formed leads [80]. The reader is also referred to the JCAA/JG-PP Testing of mixed alloys discussed in section 8.5. Applications should evaluate Sn-Bi lead termination finish for acceptability in the given use environment.

8.5 JCAA/JGPP Testing of Mixed Alloy Combinations

Various combinations of solder alloy and solder finish were evaluated in the JCAA/JGPP Pb-free evaluation for military and high performance environments. The study evaluated Sn-37Pb, Sn-3.9Ag-0.6Cu (SAC) and Sn-3.4Ag-1.0Cu-3.3Bi (SACB) solder alloys. The following sections discuss the vibration, thermal shock, and combined (thermal cycling and vibration) results for the mixed alloy scenarios evaluated.

8.5.1 Vibration

The JCAA/JGPP Pb-free Solder Study investigated the effect that Sn-Pb component finish had on solder joints manufactured with Lead-free solder alloys (SAC and SACB). Results from vibration testing indicated that BGA-225 components with Sn-Pb balls assembled with Sn-Pb paste outperformed Sn-Pb balls assembled with either Lead-free paste (with the SAC paste showing the worst performance) [48]. With regards to the CLCC-20 components, in those cases where the CLCC finish was Sn-Pb combined with either Sn-Pb paste, SAC paste or SACB paste, the combination of SACB paste/Sn-Pb finish performed the best. Bismuth alloys combined with trace amounts of Lead (Pb) have been shown to fail prematurely in thermal cycling due to the formation of a low melting ternary 16Sn32Pb52Bi alloy (m.p. 96 °C (205 °F) [74]). Either the ternary alloy is not vibration sensitive or the formation of the ternary alloy was suppressed somehow by the large amount of Lead (Pb) in the final joints (approx. 17 % by ICP (Inductively Coupled Plasma/Mass Spectrometry) analysis). The large amount of Lead (Pb) in the solder joints is due to the large amount of Sn-Pb solder held by the castellations on each CLCC [48].

8.5.2 Thermal Shock Testing

The results from thermal shock testing, TSOP-50 component with a Sn-Pb component finish, indicated that the only TSOPs to have significant failures were those with a Sn-Pb finish and soldered with SACB. The early failure of the TSOPs soldered with SACB is presumably due to the formation of a low melting ternary 16Sn32Pb52Bi alloy (m.p. 96 °C (205 °F)). The amount of Pb in these solder joints was approximately 3 % as determined by ICP spectroscopy. This result is in contrast to the CLCC data, where large amounts of Lead (Pb) contamination had only a slightly negative effect on the reliability of SACB [59]. In those cases where the CLCCs were finished with Sn-Pb and were combined with either SAC paste or SACB paste, the Lead

(Pb) contamination in the final solder joints had only a slightly negative effect on the survival times of the solder joints (see Figure 31 of JCAA/JGPP thermal shock test report [59]). This was unexpected because Bismuth alloys combined with trace amounts of Lead (Pb) have been shown to fail prematurely in thermal cycling due to the formation of a low melting ternary 16Sn32Pb52Bi alloy (m.p. 96 °C (205 °F)). In addition, trace amounts of Lead (Pb) (0.5 %) have been shown to have a positive effect on the survival times of CLCC SAC solder joints subjected to –40 to +125 °C thermal cycling [74]. The large amount of Lead (Pb) in the CLCC solder joints in this study (approx. 17 % by ICP analysis) appears to have a very different effect on solder reliability than do trace amounts of Lead. The large amount of Lead (Pb) in the solder joints is due to the large amount of Sn-Pb solder held by the castellations on each CLCC [59]. For BGA-225 components, Sn-Pb balls assembled with SAC paste failed on six out of a total of 25 BGA's. No Weibull analysis was done since the number of failures was less than 25 % of the population. These failures suggest that using Sn-Pb BGAs in combination with SAC solder is to be avoided. In comparison, only one failure was seen when SACB paste was used with Sn-Pb balls [59].

8.5.3 Combined Environments

For Combined Environments Testing, BGA-225 components with Sn-Pb balls soldered with Lead-free solder alloys (SAC and SACB), it was shown that Tin-Lead degrades the early life performance of Tin-Silver-Copper while the number of cycles where 63 % of the samples failed (N63 values) are similar. The data results showed no effect in the reliability performance of Tin-Silver-Copper-Bismuth when used to solder Tin-Silver-Copper or Tin-Lead BGA-225 components [82]. For the CLCC-20 components, the presence of Tin-Lead appears to improve the reliability of the Tin-Silver-Copper solder joint. However, the presence of Tin-Lead appears to degrade the reliability of the Tin-Silver-Copper-Bismuth solder joint [82]. For the TSOP-50 components, the presence of Tin-Lead appears to slightly improve the reliability of the Tin-Silver-Copper solder joint. However, the presence of Tin-Lead appears to severely degrade the reliability of the Tin-Silver-Copper-Bismuth solder joint [82].

8.6 Pb-Free Solder and Mixed Metallurgy Modeling

The solder joint metallurgy is the principal factor affecting the attachment reliability of mixed Sn-Pb/Pb-free assemblies. The record for SAC balls / Sn-Pb paste assemblies under accelerated thermal cycling conditions varies. No life prediction model or acceleration factors are reported for such mixed assemblies [83]. To arrive at a validated model for mixed assemblies, we need to develop proven models for Pb-free solder joints first. Using the JCAA/JGPP data Osterman has developed a Coffin-Manson type equation that accurately predicts the reliability of Pb-free solder joints for plastic BGAs and leadless SMT devices [84]. The Norris-Landsberg acceleration model with constants similar to those of Sn-Pb solder are also shown to fit the JCAA/JGPP data [85]. Additional testing and analysis are needed before a validated model is developed for Pb-free assemblies, and later for mixed Sn-Pb/Pb-free assemblies.

Table 1 – Review Of Piece-Part Surface Finish And Potential Concerns

Surface Finish	Potential Impact Concern(s)
Palladium (Pd)	A number of piece-part fabricators utilize surface finishes that contain Pd. Pd has been shown to be flux sensitive and has a relatively slow diffusion rate into Tin-Lead solder alloys in comparison to other metals. A slight increase in solder process temperatures (e.g., 5 to 10 °C (9 to 18 °F)) and extending the solder process dwell time have been used to compensate when using Pd surface finishes in Tin-Lead soldering processes. Pd thicknesses in the 0.51 to 0.76 um (20 to 30 uinch) range has been shown to cause solder joint embrittlement due to the formation of $PdSn_4$ microstructure phase.
Gold (Au)	Gold has a long tradition of being utilized as a piece-part surface finish for some piece-part styles. Au has a propensity to embrittle solder joints due to the formation of the $AuSn_4$ microstructure phase when the Au content exceeds 3 % of the solder joint [86]. Some investigators suggest that the Au limit lies from 2 to 7 weight percent [6]. Thin Au platings used on BGAs, CSPs, and flip chip packages result in Au concentrations typically less than 1 % in the solder joints. Gold plating thicknesses in the 0.025 to 0.51 um (1-20 uinch) range can be prone to solderability problems for some piece-part types. In Lead-free solder systems, the intermetallic compound formation is more complex than in the Sn-Pb system. In smaller volume SAC joints (300 um diameter balls with 300 um diameter Au/Ni pads), re-deposition of $(Au,Ni)Sn_4$ intermetallic was closely associated with the migration of Cu from the bulk solder to the surface [87].
Tin-Silver-Copper (SAC)	The introduction of SAC solder alloys as the primary solder attachment material has also led to the introduction of SAC solder alloys as a piece-part surface finish. These SAC surface finishes are typically applied thru a “hot dipping” process. The interaction of a SAC surface finish and Tin-Lead solder is not fully understood although initial solder joint reliability studies have not revealed any major solder joint integrity problems.
Bright Acid Tin (Sn)	Bright Acid Tin contains codeposited organic materials to produce the “bright” appearance. These co-deposited organic materials have a detrimental impact on solderability and have been shown to be more prone to produce Tin whisker phenomena.
Matte Tin (Sn)	Industry studies have shown that matte Tin can produce Tin whisker phenomena under some conditions. Matte Tin also has a greater potential of having solderability problems due to the formation of Tin oxides in comparison to Tin-Lead surface finishes.
Palladium-Silver (Pd-Ag) or Palladium-Platinum-Silver (Pd-Pt-Ag)	Pd-Ag and Pd-Pt-Ag surface finishes are commonly used as surface finishes on ceramic bodied piece-parts such as surface mount chip capacitors or piece-parts utilizing castellations. These finishes can be “dissolved (e.g., leached) off” the piece-parts due to dissolution of the surface finish into the solder joint during the Tin-Lead solder process resulting in degradation of the piece-part termination/solder joint interface. Pd-Ag and Pd-Pt-Ag surface finishes exhibit reduced solderability as compared to Tin-Lead finishes.
Bismuth (Bi)	Tin, Lead and Bismuth can form low melting microstructure phases that would have a detrimental impact on solder joint reliability. The industry is currently conducting solder joint integrity investigations to determine the severity and consequences of the interaction of Bi and Sn-Pb solder in high performance electronics use conditions. Testing suggests that small amount of Bi introduced into Sn-Pb solder joints from a Sn-Bi electroplated lead termination finish (1-5 % with a thickness of ~ 3 um (120 uinches)) does not present a reliability issue. Increasing the Bi content in a Sn-Pb solder joint can result in solder joint integrity degradation. There have been concerns expressed that solidification profiles need to validated to ensure that low melting point Tin-Lead-Bismuth composition alloys would not segregate into interfacial sites.

Table 2 – Elements Promoting and Supressing Tin Whiskers

NOTES (1) References are provided immediately following Table 8-2B. (2) A minimum of 1 year of testing is needed for inclusion into the suppressor column.

Added element	Solubility Limit	Sn whisker (plating)		Experiment Duration
	(wt %) (6)	Promoter	Suppressor (2)	
Ag * 2-5 % (20) 2-4 % (9)	0.04 (12,13)	—	—	(20) > Significantly worse than Sn-10Pb after 3 months of aging at 52 °C (126 °F). (9) > Reduces whisker growth.
Cu	0.0063 (12,13)	1.0 (14), 1.5 (23), 1.4-3.7 (24) & 3.0-36.5 % (10)	—	(23) 9 days (24) 2 hours to 15 days
Bi * 2-4 % (8,9) 5-10 % (20) Not specified (21)	21.00	—	—	(8) > 3-4 months nucleation delay at RT (9) > Partially effective after 3 months of aging at 50 °C (122 °F). (20) > Similar to SnPb10 after 3 months of aging at 52 °C (126 °F). (21) > No whisker growth after 4 months of aging at 51 °C (124 °F).
Pb	2.50	—	> 3.0 % (7), ≥ 1.0 % (16)	(16) 1 year to 12 years
Ni	nil	—	12-35 % (8,11)	(8) > Sn-35Ni, no whisker nucleation after 48 months at RT.
Sb * 2-3 % (8)	10.50	—	—	(8) > 3-4 months nucleation delay at RT
Al	nil	?		
Zn	0.33	9 % (22)	—	(22) > 21 days to nucleate whiskers at 50 °C (122 °F)
Mg	nil	?		
Te	nil		?	
Co	nil		?	
Mn	nil	18-23 % (18)	—	(18) > 17 hours to nucleate whiskers at RT
Au	0.30		?	
Cd	~1.00		?	
Fe	nil	?		

* Element addition tends to delay the whisker growth, but not suppress it.

Table 3 – Elements Promoting and Supressing Tin pest

(1) References are provided immediately following Table 8-2B. (2) A minimum of 1 year of testing is needed for inclusion into the suppressor column.

Added element	Solubility Limit (wt %) (6)	Sn pest (bulk)		Experiment Duration
		Promoter	Suppressor	
Ag	0.04 (12,13)	—	0.01 % (15)	(15) > Slows down transformation during 5 months at -45 °C (-49 °F)
Cu	0.0063 (12,13)	0.01 % (15)	—	(15) Cu added to 99.99 % pure tin placed in contact with gray tin for 2 hours at -45 °C (-49 °F).
Bi	21.00	—	0.1 % (1,4), 0.05 % (3)	(3) > No visible transformation in 14 months at -73 °C (-99 °F)
Pb	2.50	—	≥ 5.0 % (1), 0.01 % (15) 0.02 % (3)	(3) > No visible transformation in 14 months at -73 °C (-99 °F)
Ni	nil	0.01 % (15)	—	
Sb	10.50	—	> 0.5 % (1,4-5), 0.27 % (3), 0.2 % (tinned Cu wire) (17)	(3) > No visible transformation in 14 months at -73 °C (-99 °F)
Al	nil	0.01 % (2,15)	—	
Zn	0.33	9.0 % (15)	0.01 % (15) 20.7 % (7.6µ & 12.7µ thick plating) (3)	(3) > No visible transformation in 24 months at -73 °C (-99 °F)
Mg	nil	small qty (2), 0.01 % (19)	—	
Te	nil	small qty (2)	—	
Co	nil	small qty (2)	—	
Mn	nil	small qty (2)	—	
Au	0.30	0.01 % (15)	small qty (2)	
Cd	~1.00	—	small qty (2)	
Fe	nil	0.01 % (15)	—	

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9 Piece-parts

9.1 Materials

The J-STD-609 specification defines an e-code system that should be used to communicate the piece-part terminal finish. Although the e-code definitions do not capture all the attributes needed to perform a Tin whisker assessment, they will allow designers to quickly identify piece-parts with pure Tin finishes. Other systems may be necessary to capture attributes such as matte Tin or bright Tin, Nickel under plating, and base lead/terminal material. (Note IPC-609 is merging JESD97 and IPC-1066 standards.)

9.2 Temperature Rating

The higher soldering process temperature requirements of Pb-Free solder alloys have driven an increase in part soldering temperature capability of surface mount devices (typically from 230 °C to 260 °C). It is not appropriate to assume that the presence of a Pb-Free piece-part and pad interface finish is always accompanied by a 260 °C maximum temperature capability. The maximum temperature capability should be verified for devices typically susceptible to solder stress damage, such as those having large silicon die, thin parts, and BGAs. Piece-part solder temperature capabilities should be communicated to the repair facility if they are below the normally expected value for a particular assembly type (e.g., a 260 °C max temperature device on a Pb-Free assembly).

Piece-parts not typically used in commercial Pb-Free assemblies such as hybrid circuits, optical device, larger multilayer ceramic capacitors, special oscillators, optocouplers, mechanical relays, special RF devices, etc. should be reviewed for their solder temperature capability.

9.3 Special considerations

As the elimination of Pb in piece-parts proceeds, Tin and Zinc finishes may be used instead of Sn-Pb plating. The substrate, the plating type, the thicknesses involved all drive Whisker formation. Tin and Zinc electroplated finishes (not hot dipped galvanized) have both demonstrated the ability to form pronounced metal whiskers particularly when the base material is steel, brass or Copper. Zinc whiskers were a problem in raised floor data centers where air conditioning was distributed via sub-floor passages and the floor tiles were made of galvanized steel. The flowing air carried Zinc whiskers to sensitive locations causing electrical shorts [88]. Piece-parts comprised of metal parts, frames or shells, should be reviewed to ensure that Tin or Zinc plating be avoided internally or externally where a metal whisker reliability risk exists.

9.4 Plastic Encapsulated Microcircuit (PEM) Moisture Sensitivity Level (MSL)

Moisture sensitivity level of the plastic encapsulated microcircuits and other plastic encapsulated piece-parts such as capacitors and resistor networks are often re-assessed for Pb-free soldering temperatures. In some cases, piece-part Suppliers may be raising MSL for Pb-free soldering and may not maintain the MSL rating for the lower Sn-Pb soldering temperature. If the assembly manufacturer is using Sn-Pb eutectic solder, they may face increased MSL maintenance cost associated with the Pb-free MSL level. Some of the parts standards related to moisture sensitivity and handling are: ANSI/J-STD-020, Moisture/Reflow Sensitivity Classification for Non-Hermetic Solid State Surface Mount Devices, and ANSI/J-STD-033, Standard for Handling, Packing, and Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices.

9.5 Terminal Finish

Devices with a pure Tin terminal finish should be stored in a humidity controlled or desiccated packaging to preserve solderability. ANSI/J-STD-002, Solderability Tests for Piece-part

Leads, Terminations, Lugs, Terminals, and Wires. The metallurgical stability of Lead-free lead/terminal finishes as compared to Tin-Lead finish is presented in Table 1.

Table 4 – Piece-part Lead/Terminal and BGA Ball Metallization Tin Whisker and Tin Pest Propensity

Piece-part Terminal Metallization (1)	Whisker Propensity (2) (3) (4)	Tin-Pest Propensity (4) (For applications with a duration greater than a year at cold temperatures.)
Sn-(3-5)Pb	Low (5)	Low (5)
Sn- (37-40) Pb	Low (5)	None
Sn Reflowed	Medium-High (6)	Low (7)
Sn Bright Electrodeposit	High (8)	High (7)
Sn Matte Electrodeposit	Medium-High (6)(9)	High (7)
Sn Matte Electrodeposit with Nickel Underplating	Low	No Data
Sn-Bi (2-4 % Bi content in terminal plating) (10)	Medium-High (6)	None Bi > 0.1
Antimony Bearing (11)	No Data	None Sb>0.5
SAC dipped	Medium (6)	Low Short Term (12)
Sn-Cu plated finish	High (8)	High (12)
Sn-Cu dipped finish	High (8)	High (12)
Ni/Pd/Au electrodeposit	None	None
CBGA/BGA/C4 Ball		
Sn-37Pb ball alloy (includes Sn-36Pb-2Ag)	None	None
10Sn-90Pb ball alloy	None	None
Sn-Cu ball alloy	Low (13)	High (12)
SAC ball alloy	Low (13)	Low (12)
Cu Wire Column (14)	No Data	No Data

NOTES for Table 4

(1) Alloy percentages given as weight percent

(2) IEC/PAS 62647-2 "Aerospace and defence electronics systems containing lead free solder – Part 2: Mitigation of the deleterious effects of tin" (GEIA-STD-0005-2) provides guidance on finishes and risk mitigation methods. There is presently significant effort being directed toward understanding the Tin whisker growth mechanism. Generally, the substrate material, plating parameters, the presence of Nickel underplating, annealing and reflowing the finish also influence the whisker growth but long term testing is still underway. For the purposes of this table, the base lead termination material is taken to be Copper. Base materials such as brass (Copper and Zinc alloy) have a high propensity for Tin whisker formation and have actually been used to create Tin whiskers in very short times. Nickel under plating is recommended if brass lead termination material is used.

(3) "Recommendations on Lead-Free Finishes for Piece-parts Used in High Reliability Products ", iNEMI Tin Whisker User Group, Herndon, VA USA, Version 4, Updated December 2006.

(4) See Tables 2 and 3 Elements Promoting and Supressing Tin whiskers and Tin pest.

(5) The risk is considered low for the heritage Sn-Pb finishes. Small Pb whiskers have been observed on the JCAA/JG-PP -55 to +125 C thermal cycling testing.

(6) Medium-High Risk corresponds to those finishes that iNEMI recommends be tested in accordance with JESD 201 to verify that the finish has a relatively low tendency for whisker growth. In some cases, other mitigations such as Nickel underplating may be necessary to reduce whiskering to a low risk level.

(7) Spergel [25] evaluated tin coated copper wire for up to 5 years at -40 °C (-40 °F) to -55 °C (-67 °F). Spergel found that fused tin finished copper wire had a low propensity for tin pest formation while the electrodeposited tin finish had a high propensity for pest formation. [see Section 5.2].

(8) iNEMI [80] suggests that dipped Sn-Cu finish may or may not be effective reducing tin whiskers. In electrodeposited layers Cu in Sn promotes rapid whisker formation [See Table 2]

(9) NEMI recommends a matte Tin plating thickness greater than 8 um for whisker mitigation however, thick matte platings may be susceptible to voiding during soldering.

(10) Bi finishes may need to be restricted on low volume Sn-Pb solder joints in cases where the total Bi content of the joint becomes 0.2 to 0.5 wt % in typical SMT solder joints. Bi also can accumulate to undesirable levels in wave solder pots.

(11) Antimony greater than 1000 ppm needs to be reported in accordance with HAZMAT as referenced in IPC-1752

(12) Alloy additions to high purity 99.99 % Tin were evaluated by Sweatman [24]. Note that both Cu and Ni demonstrated a propensity for Tin Pest formation. Long term Tin pest test data has not been published on many of the elemental additions evaluated by Sweatman.

(13) Tin whiskers have not been identified to be an issue on bulk Pb-free alloys like BGA balls or solder joints.

(14) The Copper wire column typically uses a wire that is 10 mils in diameter, 60 mils long having a finish of 0.05 um Sn. (ref. Cole, M. et.al., “Lead-free Card Assembly and Rework for Column Grid Arrays”, SMTA Journal Vol. 17-1 (2004).

9.6 Assembly stresses

Increased processing temperatures can result in increased stresses on the piece-parts during manufacturing processing and upon cooling. These stresses can result in excessive warpage or internal damage. Devices having large silicon die or large linear dimensions such as area arrays, connectors etc., should be evaluated.

9.7 Hot Solder Dipping

If the piece-part has an unacceptable Pb-free finish configuration, it may be possible to utilize hot solder dipping to refinish the leads/terminals with Sn-Pb solder. Solder dipping can result in damage to the piece-part particularly if the die is large or pre-existing delamination is present [89]. (Note: Scanning acoustic microscopy (CSAM) is typically used to determine internal package delamination between the molding compound and various internal features, e.g., the die, die paddle, and the lead-frame.) It was unclear if the devices that exhibited increased delamination would have had similar delamination tendencies after surface mount soldering. There exists a potential risk in exposure of the base-metal of the lead frame at corners, especially for etched lead frames owing to their concave geometrical shape [89]. The document GEIA-STD-0006 is being written to provide requirements for solder dipping piece-parts. A solder dipping project is nearly completed [90]. The control of preheat and cool down of piece-parts reduces the thermally induced stresses associated with the solder dipping process [91]. It is worth noting that an increasing number of components with leads are being provided with a dipped SAC finish by the Suppliers.

10 Printed Circuit Boards

Circuit cards provide the means necessary to interconnect the piece-parts mounted on them. With the industry moving to Pb-Free solder, a number of bare printed wire board issues (laminate material, trace width, plated-through-hole size, external finish, external copper thickness, etc.) must be addressed when designing for Pb-Free assembly. Higher processing temperatures are required for Pb-Free soldering. The guidance outlined by iNEMI [92] states that while laminate materials used for assembly with Sn-Pb have been used successfully in lower complexity assemblies at Pb-free (i.e., SAC) processing temperatures, there are issues in using these materials for complex, thermally challenging products at Pb-free process temperatures. Moving to higher temperatures increases materials sensitivities and a number of parameters (e.g., thermal decomposition (Td), glass transition temperature (Tg), time to delamination (see IPC-TM-650 2.4.24.1) and coefficients of thermal expansion in-plane (CTE(x-y)) and out-of-plane (CTE(z)) must be reexamined. More testing and evaluation is required before a new laminate material can claim to be compatible for assembly with Pb-free materials intended for high reliability systems. After initial material selection, the manufacturer will need to validate acceptable performance of the PCB materials under the service conditions. iNEMI provides potential test methods for validation of performance, which include conductive anodic filament (CAF), rework simulation, and thermal/temperature cycling. iNEMI recognizes that the validation methods presented are not all encompassing, as Pb-Free technologies mature and more field data is gathered, there will be a greater understanding of the Pb-Free PCB design constraints. In addition, the point application of heat and dwell time associated with hand soldering can result in printed circuit board damage such as pad, laminate and plated through hole damage. Further discussion regarding the use of supplemental PCB solder process assessment coupons is presented in Section 11.1.

10.1 Plated Through Holes

A plated-through hole (PTH) in a printed circuit board is defined as “a hole in which electrical connection is made between internal and/or external conductive patterns by plating of metal on the wall of the hole”. Some of the factors driving PTH reliability are laminate material, overall PCB thickness and PTH diameter, soldering temperature, number of rework events and the subsequent field stresses. Thermo-mechanical stresses mainly due to mismatch in out-of-plane (z-direction) CTE between the PTH metal and the laminated material can result in the failure of the PTHs. Failure of a PTH constitutes an electrical discontinuity that may be caused by fracture of the plating material at the barrel, fracture at the land-barrel junction, or delamination of the plating from the PWB.

Bare printed circuit board materials require changes from today’s typical “dicy cured” FR4 materials in order to support Pb-free assembly. The High Density Packaging User’s Group has completed a study of via reliability through air to air thermal cycling after various Sn-Pb and Pb-free reflow profiles [93]. Six different materials, with different numbers of reflow profiles were studied in this test through 6000 accelerated thermal cycles. The boards in this test were subjected to 0, 3, and 5 reflows. (Note that a repair heat cycle may require up to 3 reflow temperature excursions; one for part removal, one for site dressing, and one for part replacement). The boards were 0.125 inches thick, did not contain internal nonfunctional pads, and contained several PTHs sizes and laminate materials. After reflow, the boards were subjected to continuity monitoring for 6000 thermal cycles over a 95 °C (203 °C) temperature range from 5 to 100 °C (41 to 212 °F). Data from this testing showed that all PCB laminate materials that claimed to be Pb-free compatible exhibited considerable variation in reliability. The authors suggest that given the differences in material performance related to plated through hole reliability and the difficulty in relating material properties directly to the resulting plated through hole reliability, it is highly recommended that high reliability and/or long life applications include some quantifiable fatigue life evaluation of materials prior to specifying them on this type of product. Drill hole wall roughness and plating quality continued to be key parameters controlling plated through hole reliability. Additionally, for higher aspect ratio plated through holes, the tensile strength and elongation properties of the PTH Copper appeared to be significant variables affecting long term reliability. The number of reflow cycles used in the reference [93] assessment may not be adequate for aerospace and high performance applications. Some applications may need to consider increasing the number of reflows used in the PCB assessment in order to account for additional repair events that may occur through the life cycle of the product.

10.2 Copper Dissolution

Many of the Pb-Free solder alloys cause greater Copper dissolution than the heritage Sn-Pb alloys during soldering [94]. The phenomenon that is taking place during the dissolution is a solvent/solute interaction. Given enough time, the liquid solder solvent will dissolve the Copper solute until it reaches saturation. Although the Pb-Free SAC was formulated to contain Copper in an effort to reduce Copper pad dissolution, at a given processing temperature it has the ability to “dissolve” Copper until the solubility limit is reached. The dissolution process is basically a concentration driven diffusion/convection process. Solid metal substrate dissolution by liquid Sn is a very complex phenomena that is dependent upon the solid and liquid materials, temperature, contact time, and liquid velocity. It is not clear what role intermetallic plays in the dissolution process since the liquid solid boundary cannot be observed directly due to the opacity of the liquid metal. In some cases, transient solid phases can form and re-liquefy [95].

During surface mount soldering, the volume of liquid solder solvent is limited by the volume of the deposited solder paste and, in the case of BGAs, the BGA solder ball volume. Early in the Pb-free transition, Copper was added to Sn-Ag eutectic alloy to reduce Copper pad dissolution during surface mount soldering [96] [97]. Recently, deSousa et.al. [98] recommended increasing the Cu concentration in SAC BGAs to 1 %Cu, which the investigators felt was a level where pad dissolution was minimized but there was still enough dissolution occurring to obtain good wetting. Dissolution is not unique to Pb-free solder; some older Sn-Pb immersion dissolution studies of Copper wire [99] [100]and flat foil coupons [101] suggest that significant dissolution is also possible when liquid Sn-Pb solder exposure is prolonged.

Wave and fountain soldering are more likely to dissolve PCB pad metallization because of the larger volume of solder available for dissolution. The solder in the wave/fountain acts continuously as a solvent that will completely dissolve the Copper pad (e.g., the solute) given enough time. While the PCB is in contact with the solder, fresh solder at low Copper concentrations continuously impinges on the PCB Copper pad carrying away pad material, eroding the pad. For Pb-free SAC, it was determined that the knee of the PTH solder joint is the most susceptible Cu dissolution location [102]. The knee not only has a thinner initial Cu thickness layer compared to the pad, but the rate of Cu dissolution is greater at this (convex) surface as compared to the pad and/or the inner barrel wall. Also, it was determined that it is possible for a good solder fillet to form even when 100 % Cu dissolution occurs at the knee location. Solder bridging over the dissolved knee can in some cases result in latent failures. There are, however, many cases where there will be no impact to functionality because either (a) the solder completes the connection satisfactorily for the intended life or (b) there are no surface connections made to the periphery of the pad. PCBs intended for soldering in wave, and fountain applications should have surface land and plated through hole metallization thickness, particularly over the hole knee, evaluated for adequacy. If the item is intended to be repaired during the service life using these processes, then there must be enough metal remaining to allow for reliable depot/field repair. Different Copper plating processes from different Suppliers could potentially produce different Copper plating densities, which should be considered during testing, since they are likely to play an important role in Copper dissolution. Nickel metallization (ENIG or electrodeposited Ni) significantly improves the dissolution resistance and in combination with Gold plating can promote improved wetting characteristics. However, the ENIG finishes have historically been susceptible to a phenomenon called “black pad” (Note: “Black pad” phenomena on ENIG finishes is thought to be a function of the phosphorous content in the Nickel plating, the immersion Gold plating process, and chemical attack of the Nickel plating.). In addition, Ni-Sn intermetallics have lower strength than Cu-Sn intermetallics. In some designs, a mixture of PCB finishes on the same panel may be useful. Some Suppliers are evaluating the use of Copper pads for the SMT devices and ENIG for the plated-through-hole regions requiring high dissolution resistance. Testing of a Sn-0.7Cu-0.05Ni alloy in fountain soldering on a thermally massive PCB showed slightly greater dissolution rates as compared to Sn-Pb [103]. In some cases, improving pre-heat prior to soldering can reduce liquid solder contact time significantly reducing dissolution.

10.3 PCB Laminate Materials

Material selection will need to be carefully considered when designing for Pb-Free assemblies [93]. Lead (Pb) containing assemblies have been around for more than 50 years, are well understood, and are very forgiving during the soldering and assembly process. Pb-Free solders require higher processing temperatures and materials must be selected to assure low stress, compatibility of piece-parts to substrate material, mechanical characteristics, board finish and Tin whisker mitigation. The higher temperatures required for Pb-Free processing requires materials to be selected and matched to the thermal expansions of the assembly components. Good material selection and thermal expansion matching directly affects the integrity of the finished product. Both the glass transition temperature and the decomposition temperature should be considered when evaluating a PCB laminate material. Fiber debonding and Conductive Anodic Filament (CAF) formation should be assessed for PCB laminates subjected to increased Pb-Free soldering and rework temperatures. There has also been an issue with laminate strength under BGAs. In some cases, PCB pads exhibit laminate cracking under the BGA solder pads after soldering and/or after rapid mechanical loading [58] [104]. The cracks are typically located in the resin rich layer between the copper pad and the glass fiber bundles. In this failure mode, the copper trace connecting the BGA solder pad to the adjacent PTH eventually fractures and creates an open circuit condition. Resin fractures where the pad has been weakened but where there is still electrical continuity are difficult to detect without cross-sectioning.

10.3.1 Coefficient of Thermal Expansion

Configurations requiring controlled thermal expansion PCB construction in order to match the thermal expansion of low CTE piece-parts may exhibit greater warpage and plated through hole stresses during Pb-free soldering and rework.

10.4 Surface Finish

The PCB finish should be communicated to the repair facility using the e-code system defined in IPC-1066. Various Pb-Free finishes have emerged. The key assembly attributes for various board surface finishes such as shelf life, multiple assembly reflow cycles, SMT land surface topology, test probe characteristics, etc,. are summarized in Table 5-2 of IPC-7095A. A summary of the Tin whisker and Tin pest propensity tendencies of various Pb-Free PCB finishes is given in Table 5.

Electroless Nickel immersion Gold [IPC-4552] or electrolytic Nickel can form Sn-Ni-Cu ternary intermetallics when used with Cu bearing solder or Cu pads in close proximity. This interaction is also possible in Sn-Pb solders when a Cu pad is opposite a Ni pad (ball size = 125 um) [105] The diffusive transport of Cu through Sn is somewhat unusual and may not necessarily be governed by traditional concentration gradient based descriptions based on Fick's Law. One investigator found that Cu from a Cu plate was transported through solid Sn to an adjacent Ni plate to form a Cu-Ni-Sn intermetallic. It was noted that no Cu was found in the Sn separating the plates [106]. Some of these Sn-Cu-Ni intermetallics have lower strength than Sn-Cu or Sn-Ni binary intermetallics and maybe less durable than Sn-Pb soldered joints during mechanical shock testing. There has been some work suggesting that the thermal cycling performance of reduced Silver content SAC alloy (SAC-L) chip scale package solder joints is improved when a Nickel surface finish is used instead of Copper [107]. The Nickel surface finishes, however, typically have lower vibration and shock performance than Copper [108].

Immersion Ag [IPC-4553] is a metallurgically compatible finish to Cu, Sn, Pb, and Ag bearing solder alloys. The wettability of Pb-Free alloys in surface mount applications is such that the deposited solder alloy does not generally wet out to the extents of the pads, leaving non-solder coated Immersion Ag coating at the edges. Caution should be exercised when using Silver in assemblies exposed to sulfur bearing atmospheres. Immersion Ag is considerably thinner than typical plated Silver finishes that have exhibited Silver migration tendencies in the past under voltage biased humidity conditions. Silver thickness should be monitored and controlled. Immersion Ag surface finish performs adequately in SIR and EM tests and is not readily prone to dendritic growth in presence of high humidity. However, ENIG and OSP are superior in the water droplet conditions simulating condensation and are less likely to electromigrate under those circumstances [109]. Conformal coating should prevent liquid moisture contact with Immersion Silver finishes in most cases (Note: All polymer coatings are permeable to molecular moisture. Good conformal coat adhesion is needed. If separation between the assembly and the coating occurs, liquid moisture will eventually accumulate in the gap if sufficient moisture is present in the surrounding atmosphere).

Immersion Tin(Sn) [IPC-4554] is a metallurgically compatible finish to Cu, Sn, Pb and Ag bearing solder alloys. The immersion Sn thickness should be at least 1 um thick to ensure adequate solderability [IPC-4554]. Immersion Sn differs from electrolytic Sn used on Sn plated piece-parts. Immersion Sn has not been shown to produce whiskers when exposed to the classic acceleration methods used for electrolytic Sn. However, whiskers have been grown on immersion Sn coated features after some time at ambient conditions and not as a result of exposure to heat, vacuum, pressure, humidity or bias voltage [IPC-4554]. JP002 suggests that the primary source for whisker growth is film stresses associated with the growth of Cu_6Sn_5. Whisker length has been reported to be significant in vias, with lengths measured to be 150 um. Whiskers of much smaller lengths have been recorded growing off the edge of surface mount (SMT) component pads, as well [110] [JP002] [IPC-4554]. Immersion Sn plating Suppliers have implemented specific Tin whisker mitigation protocols as part of their chemistry (e.g., alloy elements, additives, organic content control, etc.) that are expected to reduce Tin whisker risk. The industry continues to work on a test method designed to quickly indicate the susceptibility of a deposit to whisker growth. Whiskers forming on the Immersion Sn will not be an issue in cases where Tin-Lead solder completely wets to the edge of PCB pads. While complete pad solder wetting is not an issue with Sn-Pb solders, most of the Lead-free solders do not wet much beyond the location of the printed solder paste. PCB pad and/or solder stencil print adjustments may be needed to completely cover PCB pads with solder.

As long term storage and rework/repair capability improves, OSPs may become increasingly used in the future. Although the solder joint reliability is good, this finish often leaves areas of exposed Copper [111], which may be susceptible to corrosion and present long term reworkability issues. OSPs are fully compatible with all solder alloys.

Table 5 – PCB Metallization Tin Whisker and Tin Pest Propensity

PCB Metallization	Tin Whisker Propensity See Notes (1)(2)	Tin-Pest Risk (cold applications)
Sn- 3 to 5 wt % Pb	Low	Low
Sn- 37 to 40 wt % Pb Electroplated and Fused	None	Low
Sn- 37 to 40 wt % Pb Hot Air Solder Level	None	Low
Sn-Cu HASL	High (3)	No Data (4)
Imm Ag (PCB) (5)	None (No Sn on surface)	None (No Sn on surface)
Imm Sn (PCB)	Low-Medium (6)	No Data (7)
Au/Ni Electroplate or ENIG (Electroless Ni-P/Immersion Au)	None	None
Organic Solderability Preservative	None	None

NOTES for Table 5

(1) IEC/PAS 62647-2 “Aerospace and defence electronics systems containing lead free solder – Part 2: Mitigation of the deleterious effects of tin” (GEIA-STD-0005-2)

(2) “Recommendations on Lead-Free Finishes for Piece-parts Used in High Reliability Products “, iNEMI Tin Whisker User Group, Herndon, VA USA, Version 4, Updated December 2006.

(3) iNEMI [80] suggests that dipped Sn-Cu finish may or may not be effective reducing tin whiskers. In electrodeposited layers, Cu in Sn promotes rapid whisker formation [See Table 2] G.T.T. Sheng et al., "Tin Whiskers Studied by Focused Ion Beam Imaging and Transmission Electron Microscopy," J. Appl. Phys., Vol. 92, No. 1, pp.64-69, July 2002.

(4) Cu in high purity 99.99 % Sn Promotes Tin Pest (See K. Sweatman et al [24]). Williams [23] found some tin pest transformation on 99.98 % Sn after it was soldered to copper at 204 °C (400 °F) above the liquidus and attributed this to the increased Cu content in the Sn. Spergel [25] did not observe tin pest transformation in dipped wire.

(5) Silver is susceptible to the formation of Silver Sulfide Dendrites

(6) See Section 10.4. The Tin whisker risk for Immersion Sn differs from electrolytic Sn used on Sn plated piece-parts.

(7) See Section 5.2. If the Sn coating is hot dipped on Copper, Spergel Tin indicates that the Tin pest risk is low but not with electrodeposited Sn. For thin Sn film configurations, Tin pest has been observed by Bornemann [21] and Becker [19] under laboratory conditions. No long term Tin pest testing is available for Immersion Sn finish (fused or not) over Copper.

10.5 Pb-Free PCB Qualification

PCB laminate and construction integrity qualification requirements are evolving. PCBs being considered for Pb-Free solder processing should be tested for plated through hole and inner layer integrity at the reflow temperatures expected in the proposed process and also be subjected to solder float testing with all solder alloy(s) that will be used. The Supplier should qualify the Pb-free laminate materials and the plating process to the thermal exposure levels that are expected during soldering and rework processes. Both decomposition (T_d) and glass transition temperatures (T_g) as well as time to delamination need to be considered when choosing a laminate. PCB board solder float temperature requirements for Pb-free PCBs are likely to increase from 260 °C to 288 °C (500 to 550 °F). It is expected that these requirements will eventually flow into IPC-6011 and IPC-6012. Cross-section and warpage assessments of PCBs after multiple Pb-free solder reflow exposures have shown that different Pb-free laminates have varying levels of performance [104].

10.6 PCB artwork and Design Considerations for Pb-Free solder applications

There are a number of issues to consider when designing piece-part land patterns for Pb-Free Solder. A thorough understanding of the Pb-Free solder properties and the soldering process becomes important. At the present time, the surface mount land patterns based on Sn-Pb solder have not changed significantly for Pb-free solder. Designers should address material compliance restrictions (such as RoHS restrictions) early in the design cycle and need to be aware of the Pb-free manufacturing process considerations. Design review discussions should include moisture sensitivity levels (MSL), piece-part plating options, maximum reflow temperatures for parts, thermal balance, and required printed-circuit-board (PCB) finishes. Early involvement of Manufacturing Engineering will be needed to help ensure success. There are some cosmetic aspects of the present IPC land pattern design that may change to account for the reduced spreading characteristics associated with Pb-Free alloys. In some instances, pads may require design changes to support higher temperature processing and rework. It is expected that the land pattern designs will continue to evolve.

11 Printed Circuit Board Assembly

The assembly manufacturing requirements are given in J-STD-001 with the printed circuit board design guidance being provided in IPC-2221 and IPC 7095. Many of the IPC standards have changed or are in the process of changing to provide Pb-free design guidance [112]. The introduction of Pb-free finishes and alloys has significantly increased the number of possible finish/alloy combinations. Each combination requires some level of cross-compatibility assessment. Various Pb-free finishes can be used in different solder processes and solder alloys. A high level summary of the various component and PCB process compatibility and reliability considerations is given in Tables 6, 7, 8, and 9.

11.1 PCB Process Indicator Coupons

A dissolution assessment coupon for PTH technology PCBs is a useful way to ensure that adequate dissolution resistance is verified for each lot of PCBs. The dissolution assessment coupon is one means of determining if a particular PCB can be subjected to solder fountain repair(s) after the initial assembly wave soldering process has been done. It may also be beneficial to incorporate a surface mount wettability coupon (e.g., as defined in IPC-6012B) that would be manufactured at the same time as the production PCBs. The coupon would be stored along with or remain attached to the main PCB to assess solder wettability for applications requiring long term storage. Patterns should be representative of the piece-part technology used on the board. (e.g., a decreasing pitch pattern).

11.2 Solder Inspection Criterion

IPC-A-610 has been updated to provide visual guidance for Pb-Free acceptance criterion. Not all combinations of solder, lead/terminal finish, and processes are captured for the various joint configurations. Individual programs may need to establish/define requirements regarding the suitability of the various joint configurations and appearances. Presently, fillet lifting for

PTH solder joints (not SMT) is allowed because it does not significantly reduce the solder joint strength. In some instances, the thin gap of the lifted fillet may be undesirable because it could tend to accumulate or trap contamination or be difficult to conformal coat.

11.3 Fluxes, Residues, Cleaning and SIR issues

Pb-free solder fluxes and higher processing temperatures may result in residues that are less soluble and more difficult to remove. Surface insulation resistance (ref. IPC-9201) should be used to assess cleaning effectiveness. Flux residues may also present conformal coat adhesion issues if not removed.

Table 6 – Piece-part Terminal and BGA Ball Metallization Solder Process Compatibility Risk (See Note 1)

Terminal or PCB Metallization (2)	Sn-Pb Solder	SAC Solder (SMT and Wave)	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn- 3 to 5 wt % Pb	None	Low (3, 4)	Low (4)	Low (3, 4)
Sn- 37 to 40 wt % Pb	None	Medium (3,4)	Medium (4)	Medium (3,4)
Sn, Reflowed/Fused/Dipped (5)	None	None	None	None
Sn, Bright Electrodeposit – Avoid (6)	Shelf Life (7,8) Solder Voids (9)	Shelf Life (7,8) Solder Voids (9)	Shelf life (7,8) Solder Voids (9)	Shelf life (7,8) Solder Voids (9)
Sn, Matte Electrodeposit (5)	Short Shelf (7,8) Solder Voids (9)	Short Shelf (7,8) Solder Voids (9)	Short Shelf (7,8) Solder Voids (9)	Short Shelf (7,8) Solder Voids (9)
Sn-Bi (2-5 wt % Bi content in terminal plating, which results in ~0.2 to 0.5 wt % in most final SMT solder joints) Bi finishes are not recommended for wave solder (11)	SMT Low-Medium (10)	None SMT	None SMT	None SMT
Antimony Bearing	No Data	No Data	No Data	No Data
SAC Dipped (12)	None	None	None	None
Sn-Cu electrodeposit - Avoid (13)	None	None	None	None
Sn- 0.5 to 0.9 wt % Cu-0.05Ni Plated or Dipped Avoid (13)	None	None	None	None
Ni/Pd/Au electrodeposit	Low (14)	Medium	Medium	Medium
CBGA/CCGA/BGA/C4 Ball				
Sn-37Pb (includes Sn-36Pb-2Ag)	None	Unlikely Combination	Unlikely Combination	Unlikely Combination
10Sn-90Pb	None	High (15)	Unlikely Combination	High (15)
Sn-Cu	No Data	None	None	None
SAC	Medium (16)	None	None	None
Cu wire column (17)	Low	Low	Low	Low

NOTES for Table 6:

(1) Low risk represents good processability and High risk represents poor processability. Several finishes have insufficient Tin whisker or Tin pest data; however, based on the metallurgy, they have been ascribed a risk level based on the best information available.

(2) All alloy percentages are given in weight percent.

(3) Some investigators have found that a Sn- Ag - Pb alloy can form having a melting point of 178 °C, which may impact processing [Momokawa, Y., and Ishizuka, N., “Delamination by Reheating in SMD Solder Joint Using Lead-Free Solder,” NEC Res & Devlop., Vol. 44, No. 3, July 2003 pp. 251 – 255] and Karl Seelig and David Suraski “Lead Contamination in Lead-free Electronics Assembly”, White paper AIM Solder.

(4) Pb from the finish can contaminate the wave solder bath.

(5) Organic co-deposited compounds are typically removed from the Tin coating during the reflow/fusing process.

(6) Bright Tin finish is not recommended due to Tin whisker propensity of bright Tin plating. Bright Tin is defined as having 0.2 % – 1.0 % Carbon Content with 0.5 um – 0.8 um grain size. Matte Tin is a film with lower internal stresses and larger grain sizes than Bright Tin. Matte Tin plating is defined as having 0.005 % – 0.050 % Carbon with 1 um – 5 um grain size. [“Recommendations on Lead-Free Finishes for Piece-parts Used in High Reliability Products “, iNEMI Tin Whisker User Group, Herndon, VA USA, Version 4, Updated December 2006].

(7) Co-deposited organics can limit shelf life and/or solderability.

(8) Insufficient coating thickness can result in reduced shelf life. Recommended thickness is 10 um nominal (8 um minimum) when no Nickel underplating is used. The minimum thickness should be 2 um when a Nickel underplate is used to ensure shelf life. [“Recommendations on Lead-Free Finishes for Piece-parts Used in High Reliability Products”, iNEMI Tin Whisker User Group, Herndon, VA USA, Version 4, Updated December 2006]. The lower rate of nickel diffusivity retards Nickel/Tin intermetallic formation thus limiting the stresses which would drive Tin whisker growth.

(9) In Bright Tin or thicker matte Tin coatings, co-deposited organics can yield solder voids during solder reflow for some solder joint geometries.

(10) Environmental reliability should be substantiated on the programs considering small amounts of total Bi in the final solder joint.

(11) Not recommended for pin thru hole, Bi may accumulate in wave solder pot.

(12) There may be Tin whisker risk with SAC alloy dipped finishes where they become thin around corners and edges. Note: Thicker coatings tends to isolate the intermetallic layers and dissipates whisker formation inducing stresses.

(13) Avoid Sn-Cu due to the Tin whiskering propensity of this plating. Sn-Cu provides all of the raw materials for generating the intermetallics that drive tin whisker formation. Tin whiskering propensity is high. Hot solder dipped Sn-Cu is being used in some applications. [“Recommendations on Lead-Free Finishes for Piece-parts Used in High Reliability Products”, iNEMI Tin Whisker User Group, Herndon, VA USA, Version 4, Updated December 2006]

(14) Electrodeposited plating should be analyzed to ensure that the final solder joints will not be susceptible to strength reduction associated with Gold embrittlement.

(15) Smetana, J., Horsley, R., Lau, J., Snowdon, K., Shangguan, D. Gleason, J., Memis, I, Love, D., Dauksher, W., Sullivan, B., “HDPUG's Lead-Free Design, Materials and Process of High Density Packages”, IPC SMEMA Council APEX (2003). In some cases, tilting of CCGA columns was observed after Pb-Free reflow.

(16) Mixed alloy (SAC ball/Sn-Pb paste or Sn-Pb Ball/SAC paste) combinations are not as reliable as the unmixed (SAC Ball/SAC paste or Sn-Pb Ball/Sn-Pb paste) combination. See mixing of alloys section. – Fatigue models do not exist for Sn-Pb and SAC alloy mixtures at this time. (See section on mixing of alloys).

(17) The Copper wire column typically uses a wire that is 10 mils in diameter, 60 mils long having a finish of 0.05 um Sn. (ref. Cole, M. et.al., "Lead-free card assembly and rework for column grid arrays", SMTA Journal Vol. 17-1 (2004).

Table 7 – PCB Finish Solder Process Compatibility Risk (1)

PCB Metallization (2)	Sn-Pb Solder	SAC Solder	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn- (37-40) Pb Electroplated and Fused	None	Medium (3,4)	Medium (4)	Medium (3,4)
Sn- (37-40) Pb Hot Air Solder Level (HASL)	None	Medium (3,4)	Medium (4)	Medium (3, 4)
Sn-Cu HASL	None	None	None	None
Immersion Ag (5)	Low	Low	Low	Low
Immersion Sn (6)	Low	Low	Low	Low
Au/Ni Electroplate(7)	Low	Low	Low	Low
ENIG (Electroless Ni-P/Immersion Au) (8)	Low	Low	Low	Low
OSP (Organic Solderability Preservative) (9)	None	None	None	None

NOTES:

(1) Low risk represents good processability and High risk represents poor processability. Several finishes have insufficient Tin whisker or Tin Pest data; however, based on the metallurgy, they have been ascribed a risk level based on the best information available.

(2) All alloy percentages are given in weight percent.

(3) Some investigators have found that a Sn- Ag - Pb alloy can form having a melting point of 178 °C which may impact processing [Momokawa, Y., and Ishizuka, N., “Delamination by Reheating in SMD Solder Joint Using Lead-Free Solder,” NEC Res & Devlop., Vol. 44, No. 3, July 2003 pp. 251 – 255] and Karl Seelig and David Suraski “Lead Contamination in Lead-free Electronics Assembly”, White paper AIM Solder.

(4) Pb from the finish can contaminate the wave solder bath.

(5) When using Imm Ag, thickness uniformity and porosity should be monitored. The thickness can vary with feature size [Borgesen, Unovis Area Array Consortium (formerly Universal Instruments) Year end report 2005]. The Imm Ag surface finish is susceptible to degradation by finger oils during handling. Storage precautions should be considered to ensure sufficient shelf life.

(6) The shelf life for Imm Sn is typically lower than Sn-Pb finishes. Storage precautions should be considered to ensure sufficient shelf life.

(7) Gold embrittlement may be a concern in some applications if the Gold concentration in the final solder joint exceeds 3-4 %.

(8) The “black pad” pheonomena associated with ENIG is an industry concern.

(9) The shelf life for OSP is lower than Sn-Pb finishes and there is an increased incidence of exposed Copper regions on the PCB pads where the solder does not wet to the pad extents. Storage precautions should be considered to ensure sufficient shelf life.

Table 8 – Piece-part Terminal and BGA Ball Metallization Reliability Risk (See Note 1)

Terminal or PCB Metallization (2)	Sn-Pb Solder	SAC Solder (3)	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn-(3-5)Pb	Low	Low (4)	Low (4)	Low (3)
Sn-(37-40) Pb	Low	Medium (4, 5)	Medium (4)	Medium (4, 5)
Sn (bright or matte Tin)	Low (6)	Low-Medium (6, 7)	Low (6, 7)	Low (6)
Sn-Bi (2-5 % Bi content in terminal plating typically results in ~0.2 to 0.5 % in most SMT final solder joints)	Low	Low	Low	Low
Sn-Cu, Sn-(0.5 to 0.9)Cu-0.05Ni, or SAC dipped finish	Low	Low (7)	Low (7)	Low (7)
Ni/Pd/Au (8)	Low-Medium	Low-Medium (7)	Low (7)	Low
CBGA/Column Grid/BGA/C4 Ball				
Sn-37Pb (includes Sn-36Pb-2Ag)	Low	No Data	No Data	No Data
10Sn-90Pb	Low	High (9)	No Data	No Data
SAC	Medium (10)	Low-Medium	No Data	No Data
Cu wire	-	Low-Medium	No Data	No Data

NOTES for Table 8:

(1) Low risk represents good reliability and High risk represents poor reliability.

(2) All alloy percentages are given in weight percent.

(3) SAC does not perform as well as Sn-Pb in vibration or shock loading [JCAA/JGPP 2006 test [49] results]. Thermal cycling performance of SAC is generally better than if the maximum temperature is below 100 °C (212 °F). [CALCE 2006 progress report].

(4) Pb from the finish can contaminate the wave solder bath.

(5) Some investigators have found that a Sn- Ag - Pb alloy can form, having a melting point of 178 ºC, which may impact processing [Momokawa, Y., and Ishizuka, N., “Delamination by Reheating in SMD Solder Joint Using Lead-Free Solder,” NEC Res & Devlop., Vol. 44, No. 3, July 2003 pp. 251 – 255] If delamination is present, then solder reliability will be impacted.

(6) In bright Tin or thicker matte Tin coatings, co-deposited organics can yield solder voids during reflow in some solder joint geometries.

(7) There is a possibility of forming lower strength Sn-Ni-Cu intermetallics after aging [Sinn-Wen Chen, Shou-Wei Lee and Ming-Chuen Yip, “Mechanical Properties and intermetallic compound formation at the Sn-Ni and Sn-0.7wt % Cu/Ni Joints”, J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1284-1289][Chien-Sheng Huang, Guh-Yaw Jang and Jenq-Gong Duh, Interfacial Reaction in the Edge of Pb-Sn Flip Chip Solder Bumps on Ni-Cu Under-bump metallization, J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1273-1277] [Gregorich, T., Holmes. P., Lee, J., and Lee, C., “Sn-Ni and Sn-Ni-Cu Intermetallic Compounds Found When Using Sn-Ag-Cu Solders”, IPC/Soldertec Global 2nd Int. Conf. on Lead Free Electronics, June 2004].

(8) In some cases, the formation of a Pd-Au-Ni-Sn intermetallic near interface can reduce reliability [Snugovsky,P., Bagheri,Z., McCormick, H., Bagheri, S., Hamilton, C., and Romansky, M., “Failure Mechanism of SAC 305 and SAC 405 in Harsh Environments and Influence of Board Defects Including Black Pad”, SMTA International Conference Proceedings, Surface Mount International, Chicago IL (2006)]. $PdSn_4$ has the same brittle characteristics as AuSn4 intermetallic. [Finley, D. W, et. al., “Assessment of NiPd Finished Components for Surface Mount Assembly Applications”, Surface Mount International Conference Proceedings, (SMTA, Edina, MN), 1995 pp. 941 – 953]. For applications in high moisture or corrosive environment, if the Ni/Pd/Au is cracked during lead-forming, stress corrosion can result [Ganesan and Pecht, Lead-free Electronics, CALCE.

(9) Column grid array columns, particularly for heavy parts, can become tipped after SAC reflow if the column attach alloy melting temperature is below the Pb-Free soldering temperature. [Smetana, J. et.al., “HDPUG's Lead-Free Design, Materials and Process of High Density Packages”, IPC SMEMA Council APEX (2003)]

(10) Mixed alloy (SAC ball/Sn-Pb paste or Sn-Pb Ball/SAC paste) combinations are not as reliable as the unmixed (SAC Ball/SAC paste or Sn-Pb Ball/Sn-Pb paste) combination. See mixing of alloys section. – Fatigue models do not exist for Sn-Pb and SAC alloy mixtures at this time. (See section on mixing of alloys).

Table 9 – PCB Metallization Reliability Risk (See Note 1)

Terminal or PCB Metallization (2)	Sn-Pb Solder	SAC Solder (3)	Sn-Cu or Sn-Cu-Ni wave solder	Sn-Ag solder
Sn-Pb	Low	Medium. (4, 5)	Medium (4)	Medium (4, 5)
Imm Ag	Low	Low	Low	Low
Imm Sn	Low	Low	Low	Low
Electrolytic Nickel/Gold	Low (6)	Low-Medium (6)	Low-Medium (6)	No Data
Electroless Nickel/Immersion Gold ENIG (7)	Low	Low-Medium (6)	Low-Medium (6)	No Data
SAC HASL	Low	Low	Low	Low
SnCuNi HASL	Low	Low	Low	Low

NOTES for Table 9:

(1) Low risk represents good reliability and High risk represents poor reliability. Several finishes have insufficient Tin whisker or Tin Pest data; however, based on the metallurgy, they have been ascribed a risk level based on the best information available.

(2) All alloy percentages are given in weight percent.

(3) SAC does not perform as well as Sn-Pb in vibration or shock loading [JGPP 2006 test results]. Thermal cycling performance of SAC is generally better than Sn-Pb eutectic when the maximum temperature is 100 °C (212 °F) or lower. [CALCE 2006 progress report].

(4) Pb from the finish can contaminate the wave solder bath.

(5) Some investigators have found that a Sn- Ag - Pb alloy can form, having a melting point of 178 °C, which may impact processing [Momokawa, Y., and Ishizuka, N., “Delamination by Reheating in SMD Solder Joint Using Lead-Free Solder,” NEC Res & Devlop., Vol. 44, No. 3, July 2003 pp. 251 – 255] If delamination is present, then solder reliability will be impacted.

(6) Solder joint strength can be reduced after extended baking due to the diffusion of dispersed Au from the bulk to the Ni interface to form AuSn4 in the grain boundaries near the interface or Au0.5Ni0.5Sn4 over the NiSn interface intermetallic [discussed in Mei, Z., “Microstructural Evolution and Interfacial Interactions in Lead-Free Solder Interconnects”, in Lead-Free Solder Interconnect Reliability, Ed By D. Shangguan ASM International, Materials Park, OH (2005)]. There is also the possibility of forming lower strength Sn-Ni-Cu intermetallics after aging [Sinn-Wen Chen, Shou-Wei Lee and Ming-Chuen Yip, “Mechanical Properties and intermetallic compound formation at the Sn-Ni and Sn-0.7wt % Cu/Ni Joints”, J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1284-1289][Chien-Sheng Huang, Guh-Yaw Jang and Jenq-Gong Duh, Interfacial Reaction in the Edge of Pb-Sn Flip Chip Solder Bumps on Ni-Cu Under-bump metallization, J. Elec. Materials, Vol. 32 No. 11, (2003) pp. 1273-1277] [Gregorich, T., Holmes. P., Lee, J., and Lee, C., “SnNi and SnNiCu Intermetallic Compounds Found When Using Sn-Ag-Cu Solders”, IPC/Soldertec Global 2nd Int. Conf. on Lead Free Electronics, June 2004].

(7) ENIG is susceptible to a low strength solder joint condition called “Black pad” which due to corrosion of the Ni-P by the immersion Au process [discussed in Mei, Z., “Microstructural Evolution and Interfacial Interactions in Lead-Free Solder Interconnects”, in Lead-Free Solder Interconnect Reliability, Ed. By D. Shangguan ASM International, Materials Park, OH (2005)].

12 Module Assembly Considerations

12.1 Connectors and Sockets

Little work has been published regarding Pb-free soldering of connectors. Warpage conditions of PCB edge and long SMT connectors may be exacerbated due to the higher processing temperatures.

The connector contacts and bodies should be reviewed for the presence of pure Tin and Zinc plating and assessed for Metal Whisker risk, both internal and external to the connector body. Contacting surfaces are usually not conformally coated and can be susceptible to shorting if whiskers grow between adjacent contacts. Tin plated contacting surfaces not surrounded by insulating materials should be avoided. Of particular concern are un-mated test connectors on printed circuit assemblies that may form Tin whisker shorts. Tin plated brass without a Nickel barrier is undesirable. Tin over brass has been frequently used to grow whiskers in very short times for experimental purposes. For an extended discussion regarding tin whiskers, the reader is referred to IEC/PAS 62647-2 (GEIA-STD-0005-2) and JP002.

Press fit connectors should be reviewed for Tin whisker risk because there is no solder present to mitigate Tin whiskers. In addition, compressive stresses are imparted on the Tin plating by the compliant pins pressed into the holes. It has been shown that whisker growth is stress dependent. Compliant pins act as a stress source. In these instances, the residual stresses supplied by the compliant pin energize and promote the growth of Tin whiskers. In particular, compliant pin connectors pressed into immersion Tin finished PCBs should be avoided unless suitable Tin whisker risk mitigation is used. Press fit connectors and PCBs having noble metal finishes have been shown to be successful with increased consideration for the mechanical press fit system (e.g., material compatibility, lubricity, insertion force, hole integrity, tolerances).

12.2 Heatsinks/Modules

The addition of heatsinks can substantially alter the solder stresses. Heatsinks can significantly stiffen the assembly and alter the piece-part mounting surface coefficient of thermal expansion. If the heatsink/PCB assembly is asymmetric, bending can occur during thermal cycling, which will tend to increase the stress on the piece-part solder joints. Thick stiff assemblies often have greater solder strain during thermal cycling, but usually have lower strain during vibration and shock as compared to thin flexible boards and/or piece-parts. In addition, the constraining effects of a thermal interface material used on top of an area array component can impact the thermal cycle reliability of the part. Therefore, thermal cycle qualification testing of a part that is to be used with a heat sink should be performed with the heat sink attached [113].

12.3 Conformal Coating

Conformal coating [IPC-CC-830, MIL-I-46058] application over pure Tin finished conductors is one of the Tin whisker mitigation options given in IEC/PAS 62647-2 (GEIA-STD-0005-2). Although conformal coating must be used in conjunction with other mitigation techniques, it is frequently employed in high reliability assemblies. Conformal coating can influence the solder fatigue behavior of an assembly. Conformal coatings are available in a wide range of hardnesses and Tin whisker mitigation effectiveness [114] [115]. Conformal coatings generally have a much higher coefficient of thermal expansion than solder. Conformal coating can increase solder stress during thermal cycling [30] [116] [117], particularly if the coating is rigid, the piece-part has a stiff lead termination geometry and the coating bridges the gap between the piece-part and the PCB. The relative rigidity of common conformal coating materials are shown in Table 10. Compliant conformal coating usually results in reduced solder stress as compared to the rigid conformal coating. Assemblies used for thermal cycling testing and environmental stress testing should be conformally coated if the conformal coat is expected to effect the thermal cycling reliability of the assembly.

Table 10 – Relative Rigidity of IPC-CC-830 Conformal Coating Categories

Coating Type	Rigidity/Stiffness
XY (Paraxylylene)	High
UR (Urethane)	Low to High
ER (Epoxy)	Medium to High
AR (Acrylic)	Low to Medium
SI (Silicone)	Low

The conformal coating should be evaluated for coverage, particularly on the vertical surfaces of leads/terminals and other features if intended for use in Tin whisker mitigation. Conformal coating viscosity and spray configuration are key factors in controlling coverage. Shadowing must also be evaluated. Conformal coating has been shown to extinguish whisker initiated arcing as the coating decomposes (e.g., burns) [118], but it may be possible that the decomposition by- products could support the arcing event under some conditions.

13 Manufacturing Resources

Considerable information on the application and reliability of Pb-Free soldering is available in many handbooks. A partial list follows as:

- Lead-Free Electronics, edited by S. Ganesan, M. Pecht, Wiley-IEEE, NY Press, 2006 [3]
- Implementing Lead-Free Electronics, J. S. Hwang, McGraw-Hill Professional Engineering, NY, NY, 2004. [119]
- Handbook of Pb-Free Solder Technology for Microelectronic Assemblies, K. Puttlitz and K. Stalter, Marcel-Dekker, NY, NY 2004.[120]
- Electronics Manufacturing: with Lead-Free, Halogen-Free, and Conductive-Adhesive Materials, John H. Lau, C.P. Wong, Ning-Cheng Lee, Ricky S.W. Lee, McGraw-Hill, NY, NY, 2003. [121]
- Lead-free Solder Interconnect Reliability, D. Shangguan, ASM International, Materials Park, OH, 2005. [32]

14 Aerospace Wiring/Cabling Considerations

14.1 Insulation Temperature Rating

Pb-free may not be a critical issue with cable/harness soldering. Parrish [122] suggests that because of the type of heat sources commonly used in cable and harness applications, and the intimate operator control of hand soldering operations, cable harness Pb-free soldering is not nearly as significant an issue as Pb-free PCB machine reflow soldering where temperature sensitive piece-parts and internal elements can be degraded with increased temperatures.

14.2 Cable Connectors

Cable connectors should be assessed using the same criterion that are mentioned in the module assembly Section 12.1, Connectors and Sockets. The connector contacts and bodies should be reviewed for the presence of pure Tin and Zinc plating and assessed for metal whisker risk, both internal and external to the connector body. As with the electronic module connectors and sockets, Tin plated contacting surfaces not surrounded by insulating materials should be avoided. Of particular concern are un-mated test connectors that may form Tin whisker shorts. Tin plated brass without a Nickel barrier in undesirable. Tin over brass has been frequently used to grow whiskers in very short times for experimental purposes.

14.3 Wire Terminals

It is possible to form thin solder regions over corners of terminals and wires. If the thickness of Pb-Free solder in these areas approaches the thickness obtained from fused Pb-free solder on component leads, Tin whiskers may form. In almost all cases, the large spacing between conductors associated with these configurations effectively eliminates the Tin Whisker shorting risk.

14.4 Splices

During the transition, communication with the splice Supplier will be needed to ensure that the solder alloy and surface finish are known. There are no anticipated technical compatibility issues between Pb-Free wire and splices.

14.5 Sleeving

Temperature rating of sleeving should be adequate for the Pb-free processing temperatures required for soldering.

15 Rework/Repair

Considerable effort has centered on rework/repair, which is paramount to aerospace maintenance. During the creation of the present handbook, it was decided that the rework topic required a separate document. At the present time IEC/PAS 62647-23 (GEIA-HB-0005-3) has been written to address the topic of rework and repair. Much of the text below is being considered for the rework and repair document. Upon its completion, this section will be revised. Due to higher unit costs and fewer, more complex parts, aerospace organizations must rework or repair products instead of discarding them. As a result, consortia have been studying the rework/repair issues, like JCAA/JG-PP Pb-free Solder Study which investigated the impact of rework/repair of Pb-free assemblies in contrast to Sn-Pb assemblies and the NEMI consortia on Pb (Lead) contamination.

Also to be noted is the Airlines Electronic Engineering Committee of the Avionics Maintenance Conference issuance of ARINC Project Paper 671, which states that “mixing Pb-free and Pb-based solder processes within a single soldered assembly is undesirable and should be avoided.” This is of significance to rework and repair over a 20 year service life because of the strong possibility of mixing Pb-free and Pb-based solders.

The need for a metallurgically stable solder joint under harsh environmental conditions, high stress and shear loading, and long term storage presents a set of requirements that are significantly different from most commercial applications. It is well documented that processing conditions during soldering can significantly affect the microstructure and reliability of the joint. While methods for repairing assemblies using Sn-Pb solders are well established, limited data is available for re-work and repair of Pb-free solder processing, especially when the resulting joint is a combination of Sn-Pb and Pb-free solders [123] [124] [125].

The JCAA/JG-PP study [49] looked at various configurations of reworked assemblies with the following tests:

- Thermal cycling –20°C to 80°C and –55°C to 125°C
- Combined Environments
- Vibration
- Mechanical Shock
- Thermal Shock
- Salt Fog

- Humidity
- SIR
- EMR

With regards to reworked solder joints, the following was concluded by the JCAA/JGPP study:

- Rework operations have the potential to reduce the reliability of both Pb-free and Sn-Pb solders
- Results from individual tests (combined environments, thermal cycling, and vibration testing) should not be used alone to make definitive decisions on Pb-free reliability. Results from this study should be taken as a whole.
- The impact of Sn-Pb contamination on the Pb-free solder alloy reliability is mixed. For SAC, Sn-Pb contamination can either increase or decrease reliability depending upon the amount of Pb contamination. For SACB, Sn-Pb contamination has a detrimental effect on reliability. The topic of mixing is discussed in further detail in Section 8.1, Mixing of Solder Alloys. Under high-stress conditions, Sn-Pb generally outperforms Pb-free. For low stress conditions, Pb-free outperforms Sn-Pb.

NEMI companies have also done considerable work in the rework arena. Results from the 2005 study [126], determined that elevated Pb-free SMT and rework processing temperatures can cause significant quality and reliability concerns when using existing PCB laminate systems (originally designed for conventional Sn-Pb processes). The study also concluded the following:

- The high temperature exposures necessary for Lead-free or Tin-Lead rework on high thermal-mass PCBs can induce partial reflow of adjacent piece part solder joints.
- Degradation was measured on non-reworked adjacent piece parts after accelerated thermal cycling. This likely reflects the influence of unintended joint reflow.
- High temperature exposures during the Lead-free assembly and rework thermal excursions on NiAu PCBs had a detrimental impact on the mechanical deflection sensitivity in the board resin material.
- High temperature exposures during Lead-free rework had a detrimental effect on PCB solder mask and vias.

McCall [127] acknowledged that liquid Tin is an efficient solvent that readily dissolves copper and other metals (see Section Copper Dissolution). McCall warns against the tendency to just increase the temperature during rework. The issue is not temperature, but the ability of the reworking iron and tip configuration to transfer heat to the work efficiently and the heater's ability to keep up with heat loss during the work. Without standardization of a single alloy, the use of various alloys creates potential compatibility issues between alloys. It will be impossible for a rework technician to visually identify which alloy has been used on a given PCB. Solder alloys used in initial manufacturing and on the bench-top must be compatible with one another to avoid creating an uncontrolled alloy. Adjusting an alloy piece-part by 0.5 % can change joint wetting and strength characteristics, as well as melting points.

The use of nitrogen-assisted soldering equipment mitigates some problems associated with using Lead-free solders. First, it creates an inert environment around the solder tip, reducing the potential for tip oxidation, which would reduce its ability to transfer heat and hold solder. Second, it assists with the soldering process at the PCB level by purging oxygen from the immediate area, reducing or eliminating oxidation on the worksite. This not only reduces the amount of flux required, but also helps improve wetting and spreading, and leaves a shinier, less-grainy finish. In the process, care must be taken to prevent the nitrogen flow from cooling or disturbing the solder joint. Excessive flow during solidification may cause a "cold solder joint," eliminating the beneficial aspects of the non-oxidizing shroud.