DEVELOPING A NASA LEAD-FREE POLICY FOR ELECTRONICS LESSONS LEARNED

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ABSTRACT

The National Aeronautics and Space Administration (NASA) is not required by United States or international law to use lead-free (Pb-free) electronic systems but international pressure in the world market is making it increasingly important that NASA have a Pb-free policy. In fact, given the international nature of the electronics market, all organizations need a Pb-free policy.

Note: The chemical symbol for lead, Pb is often used in this paper, to avoid confusion with termination leads. The symbol for tin, Sn is sometimes used for symmetry.

This paper describes the factors which must be taken into account in formulating the policy, the tools to aid in structuring the policy and the unanticipated and difficult challenges encountered. NASA is participating in a number of forums and teams trying to develop effective approaches to controlling Pb-free adoption in high reliability systems. The activities and status of the work being done by these teams will be described. NASA also continues to gather information on metal whiskers, particularly tin based, and some recent examples will be shared. The current lack of a policy is resulting in "surprises" and the need to disposition undesirable conditions on a case-by-case basis. This is inefficient, costly and can result in sub-optimum outcomes.

1. INTRODUCTION

On July 1, 2006 the European "Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment" or RoHS directive went into effect.[1] Even though this directive is not enforceable in the United States and is not applicable to spaceflight hardware, it was apparent that NASA would need a policy to cope with its consequences. The RoHS requires the control of six chemicals: lead (Pb), cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants. Of these, Pb has the greatest potential impact on NASA spaceflight systems. The RoHS limits the concentration of Pb to 0.1% by weight [2]. Pb has been used in the solder alloys used to assemble the electronics in every spaceflight system ever launched by NASA, at concentrations that far exceed this limit (typically ~40% Pb). Decades of mission success have been founded on the properties of SnPb solder alloys especially Sn60Pb40 and Sn63Pb37. It was clear as July 1, 2006 approached that there was no direct form, fit, function Pb-free substitute for Sn/Pb solder alloys waiting to be used.

Instead, there was an extensive array of Pb-free solder alloys, some proprietary, whose performance and long-term reliability in harsh environments continue to be the subject of ongoing research and technical debate.

2. THE CHALLENGES OF LEAD-FREE SOLDER ALLOYS

It has been known for more than ten years, that alloys based on mixtures of tin, silver and copper (SAC alloys), possess the basic properties required to make solder joints between electronic components and the printed wiring boards used to make electronic circuits. Other candidate Pb-free alloys include those containing tin-bismuth, tin-copper and tin-nickel-copper (SNiC). In the United States, the SAC alloys have become the primary choice despite having higher melting points than Sn63Pb37 and Sn60Pb40 solder. Initially the front runner for reflow applications was SAC405 (4% silver, 0.5% copper, balance tin), later SAC305 became industry's choice. According to McCormick et al of Celestica [3], this was probably driven by economics since the reduced silver content reduces the alloy cost; there is little difference in the performance of the two alloys although SAC405 may be marginally better in some respects.

The concern for the hi-reliability electronics assembler, including NASA and other space agencies is that there is very limited experience with the use of Pb-free alloys, certainly nothing equivalent to the decades for Sn/Pb. The higher melting point of the SAC alloys raises concerns about the risk of damage and reduced life time for electronic parts that have been designed to work with Sn/Pb alloys. The limited testing that has been accomplished so far, has demonstrated differences in performance between Pb and Pb-free alloys, sometimes the Pb is superior, sometimes it's the Pb-free. Given this situation, it was clear that NASA should delay adoption of Pb-free solders for as long as possible, in order for industry to work out the problems and to select the best alloys and combinations for various assembly processes and application conditions.

Pb alloys have also been used extensively to make solderable finishes on component terminations and solder pads on printed wiring boards. These applications introduce a further risk in a Pb-free world.

3. LEAD-FREE FINISHES, TIN WHISKERS AND TIN PEST

A suitable termination or solder pad finish needs to be readily solderable, tarnish resistant to remain solderable during extended storage, easy to apply, economically viable and compatible with a range of solders so as not to develop brittle intermetallics or destructive corrosion. Suitable termination finishes include gold, silver, tin and tin-lead. Obviously, there is a big difference in cost between precious metal and base metal finishes, so for most general purpose applications the choice has been between tin and tin-lead. Therefore, in a Pb-free world, the termination plating of choice is tin, essentially pure tin. However, pure tin finishes have one unfortunate property, the propensity to grow tin whiskers.

Tin whiskers are crystalline growths that grow spontaneously from tin-coated surfaces. Whiskers are generally only one to five microns in diameter but over time they have been noted to grow to lengths approaching 20 millimeters [Fig. 1].

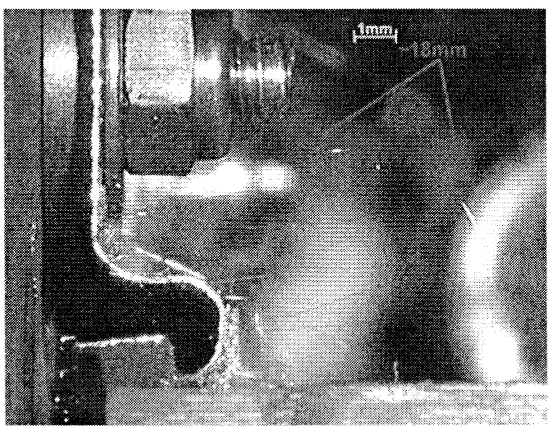

Figure 1. 18mm whisker on Space Shuttle Card Guide

They are electrically conductive and can cause circuit malfunctions ranging from intermittent glitches to catastrophic short circuits. On-orbit satellite failures due to whiskers are well documented [4]. Whiskers do not need the presence of an electrical field or humidity to grow and they grow best around room temperature [5]. There is no way to accelerate or stimulate their growth that has proven effectiveness. It is a widely held belief that whiskers are only a concern for space and other high reliability applications. This is false. Whiskers have caused failures in a broad range of electronic equipment containing pure tin termination finishes when the risk of whisker growth was not effectively mitigated. For example, various military systems have been affected by tin whiskers and a number of nuclear power stations in the United States and abroad have experienced shutdowns as a result of tin whiskers [4].

Whiskers have been studied for more than 60 years but it is still not known why they grow or exactly how they grow, so the risk of any given tin-plated surface growing whiskers is unpredictable, as is the density of the growth or the distribution of lengths and growth rate of the whiskers. The research has tried to identify ways of limiting or eliminating whisker growth and various studies have found that techniques such as use of nickel underplating, annealing at elevated temperatures and reflow of the finish to be effective; unfortunately an equivalent number of studies have shown these techniques not to be effective [6]. It is clear that these studies did not control for one or more important variables with a strong effect on whisker growth. Extensive experience has shown that the most effective way to limit the risk of tin whiskers is to alloy the tin with Pb. While Sn/Pb finishes occasionally whisker, the whiskers are short and sparse and rarely represent a reliability risk. The established industry minimum Pb content has been set at 3%, although less than 1% is probably effective [7,8]. There is very little evidence that alloying the tin with any other element than Pb is as effective at whisker suppression.

For surfaces finished with pure tin, the only proven mitigation for whiskers is conformal coating with an appropriate polymer [9] but it can be impossible or undesirable to completely coat all surfaces, especially under components. It is also difficult to apply polymer coatings uniformly to avoid producing locally thin coatings. Hot dipping tin-coated surfaces into Sn/Pb solder can also be quite effective but it is difficult to dip component leads all the way to the body without causing damage and any areas of exposed pure tin can still grow whiskers. One such example is described on the NASA Tin and Other Metal Whisker site [10]. It is interesting to note that this particular system also employed nickel underplating which is often claimed to inhibit tin whisker formation.

A large number of engineers are still unaware of whiskers but even more have never heard of "tin pest". Tin has two stable allotropes: beta (or "white") tin and alpha (or "grey" tin). At temperatures above 13°C the familiar beta phase is the stable allotrope for tin. Beta tin is a body-centered tetragonal crystal that is ductile and a good electrical conductor. At temperatures below 13°C, the alpha phase is the stable form. Alpha tin is a diamond cubic crystal that is brittle and has semiconductor properties. The transformation from beta to alpha tin is also accompanied by an expansion in volume of ~26%. This expansion and the brittle nature of alpha tin produces a wart-like, powdery conversion of the tin commonly referred to as tin pest [Fig. 2]. The maximum conversion rate reportedly occurs around -40°C [11]. There are various anecdotal, historical references to tin pest. For example the tin buttons of the uniforms of Napoleon's army are supposed to have disintegrated because of tin pest formation in the cold Russian winter during his retreat from Moscow [12].

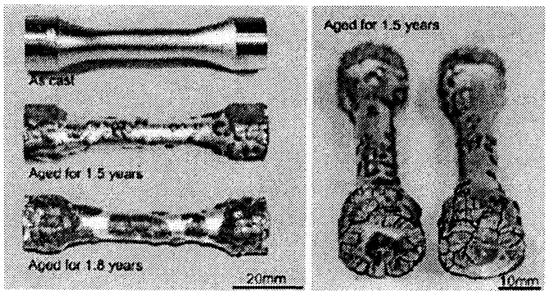

Figure 2. Transformation of Beta-Tin into Alpha-Tin in Sn-0.5Cu at T = -18°C [13]

Recent experiments have found that Pb-free tin-based alloys can exhibit pest [11,13]. The formation of tin pest seems to be affected by the presence of alloying constituents even at very low concentrations. Like tin whiskers, the most common way to reduce the risk of pest is to alloy the tin with Pb, ideally about 40% Pb. The risk of pest can probably be eliminated or reduced to acceptable levels by using Sn63Pb37 or Sn60Pb40 solder to attach the components making sure as much of the pure tin finish as possible is wetted with the solder. But one must remember that there are many types of tin-coated components that will not be assembled via soldering. For example, mechanical components such as screws, nuts, washers, brackets, shields, connector shells, braids, etc. may be tin-coated and will not be assembled using solders. In fact, sometimes applying solder to components where solder was never intended can have deleterious effects (e.g., crimping a solder coated conductor can result in intermittent electrical contact due to plastic deformation of the solder).

4. A SIMPLE PB-FREE POLICY FOR NASA

From the preceding discussion it can be seen that NASA does not have to adopt Pb-free systems and would be wise to avoid them as long as possible. It is more straightforward to avoid the use of Pb-free solder than it is to avoid pure tin finishes. At this time there is no need for NASA to accept the use of Pb-free solders except in special circumstances where the use of specialty solders has always been permitted. Such special circumstances include high or low temperature applications where tin-silver, tin-antimony, tin-bismuth or tin-indium solders may be appropriate. The situation is much more complex regarding pure tin finishes.

Pure tin is now the solderable termination finish of choice for most commercial electronic parts worldwide. As NASA often needs to utilize commercial parts in order to achieve necessary functionality, mass or size for leading-edge applications, exposure to pure tin terminations is inevitable and in fact is already quite common.

The simple NASA policy can therefore be summarized:

- Tin-Pb solders are required unless Pb-free solder alloys are necessary to meet technical needs such as high (or low) melting points, material compatibility etc.
- Pure tin termination finishes shall be avoided whenever possible and shall be carefully mitigated against the risk of whisker growth if their use is unavoidable.

5. NASA'S CURRENT SITUATION

There is currently no NASA-wide policy or position on the Pb-free issue. There are some existing requirements but they are not universally implemented. The NASA workmanship standards for soldering NASA-STD-8739.3 [14] and NASA-STD-8739.2 [15] both contain requirements to use SN60 or SN63 (Sn/Pb) solders except a tin silver alloy is an option for high melting point applications. While these standards are mandated by NASA policy document NPD 8730.5 [16], some NASA Centers continue to use their own documentation and individual project contracts may allow the contractor to use their own standards that may not specify the use of Pbed solders. The wording in the standards, combined with the well established use of Pbed solders in the industry does provide considerable confidence that NASA is unlikely to encounter Pb-free substitutions for Pbed solders for the foreseeable future. The protections against exposure to pure tin and the whisker and pest threats are not as strong.

There is no NASA-level document that currently restricts the use of pure tin finishes or that requires mitigation of pure tin finishes against the risk of whisker growth. NASA makes extensive use of US Military (MIL) specified parts and since 1994, most of the US MIL specifications have restricted the use of pure tin finishes. These restrictions have been progressively tightened and the level of detail increased. An example of the current "boilerplate" used in the MIL specs. is provided from MIL-PRF-38535 for Microcircuits: "*A.3.5.6.3 Microcircuit finishes. Finishes of all external leads or terminals and all external metal package elements shall conform to either A.3.5.6.3.2 or A.3.5.6.3.3, as applicable. The use of pure tin, as an underplate or final finish, is prohibited both internally and externally. The tin content of solder shall not exceed 97 percent. Tin shall be alloyed with a minimum of 3 percent Pb by weight.*" This means that most MIL spec. parts purchased today still utilize Sn/Pb finishes internally and externally. Of course, this language has no influence over finishes supplied on commercial parts, that is determined by market forces and those forces are currently requiring pure tin. Individual NASA Centers and the Jet Propulsion Laboratory (JPL) all have some kind of EEE parts control document. At the Goddard Space Flight Center (GSFC) it is NASA standard EEE-INST-002 [17]. At Marshall Space Flight Center it is MSFC STD 3012 [18]. Both EEE-INST-002 and MSFC STD 3012 prohibit the use of pure tin finishes however, this is unworkable in practice because of the need to use commercial parts. This situation either generates a lot of waivers or results in lots of nasty "surprises".

6. NASA PARTICIPATION IN INDUSTRY AND GOVERNMENT ACTIVITIES IN THE UNITED STATES

There have been a large number of consortia and other organizations in the United Sates which have been formed or have taken on the task of understanding the risks of going Pb-free and the development of appropriate strategies and mitigations. NASA has become an active member in many of them including:

6.1. NASA-DoD Lead-free Electronics Project [19]

This consortium was formed in 2001 under the direction of the Joint Council on Aging Aircraft/Joint Group on Pollution Prevention (JCAA/JGPP). Today it is headed by NASA with extensive support from the major military and aerospace contractors. The consortium is exploring the performance of Pb-free solders in combination with a selection of part package styles, both through hole and surface mount with a variety of Pb-free surface finishes. Sn-Pb solder and finishes are used as the control. This is the largest public study of Pb-free performance in the world, to date. Phase I is complete all but for thermal cycling of some test vehicles which have proven very robust. Results confirm that Pb-free can be superior to Sn-Pb in some circumstances but inferior in others. Phase II will look at alloys which have become popular since Phase I began such as SAC105 and will also focus on issues related to rework and repair.

6.2. The Executive Lead-Free Integrated Process Team (ELF IPT) [20]

The ELF IPT was formed in 2006 to provide a high level oversight body to promote Pb-free awareness within the United States (US) Department of Defense (DoD) and its contractors. The team is co-chaired by a US government representative and a contractor and membership is restricted to US citizens. Its charter says that the ELF IPT will: "Actively pursue the integration of the recommendations (deliverables) from the ELF IPT into existing government guidance and investment planning documents such as DoD Policy, DoD Directives, Federal Acquisition Regulations, Contract Statements of Work (SOWs) and others." The ELF IPT has assembled a comprehensive slide show to educate all parties in the supply chain about the impacts and risks of the conversion to Pb-free electronics [21]. The ELF IPT also functions as the steering organization for the Pb-free Electronics in Aerospace Project (LEAP) Working Group.

6.3. Lead-free Electronics in Aerospace Project Working Group (LEAP WG)

Formed in 2004 by Aerospace Industries Association(AIA), Avionics Maintenance Conference (AMC), and Government Engineering and Information Technology Association (GEIA), the LEAP WG is an international government/industry body with Asian and European participation in addition to its United States founders. The LEAP WG develops handbooks and standards to provide a framework for a controlled approach to Pb-free electronics. The LEAP does not perform tests, analysis or evaluations, instead it makes use of the results generated by organizations such as CAVE, CALCE, JCAA/JGPP, JEITA, iNEMI etc. This initiative has been very successful thanks to the enthusiasm and hard work of LEAP's dedicated volunteers. The standards and handbooks developed so far are being released as GEIA documents in the 0005 series, for example GEIA-STD-0005-1. Fig. 3 shows the way the various standards and handbooks are designed to work together. The focus is on the Lead Free Control Plan (LFCP) prepared in accordance with GEIA-STD-0005-1. The LFCP details how the supplier controls the use of Pb-free solders and mitigates the risk of tin whiskers and tin pest. The supplier and customer negotiate the content of the LFCP to meet their mutual needs. The other standards and the handbooks determine the content of the LFCP.

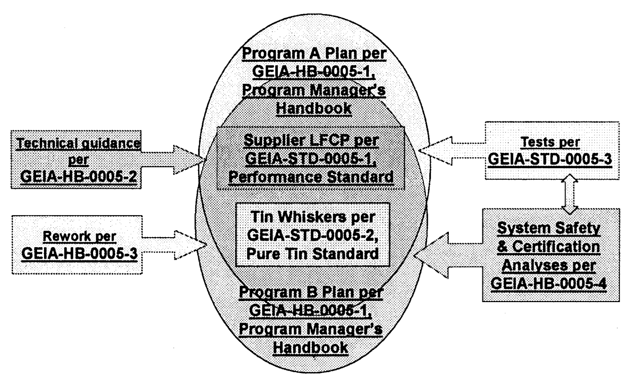

Figure 3. The Interrelationship Between the GEIA 0005 Standards and Handbooks

6.4. Government Electronics and Information Technology Association (GEIA) [23] and JEDEC Solid State Technology Association [24]

NASA has been an active government guest contributor to the GEIA G11 and G12 committees and task groups and the JEDEC JC13 task groups for many years. These organizations are forums for information exchange that also develop handbooks and standards on a broad range of topics affecting microelectronics. Both organizations have taken leadership roles in the Pb-free transition.

As previously mentioned, the GEIA has published several of the documents developed by LEAP and plans on publishing the rest of the documents in development. The drafts are reviewed by the GEIA and JEDEC participants and discussed during the meetings held three times a year. Recommendations for modifications and additional documents/topics are fed back to the LEAP WG. Tab. 1 shows the current status of the GEIA documents which have been published or are in active preparation. The plan has been to also have the IEC publish the documents as Publicly Available Specifications (PASs) but this process is unexpectedly delayed.

The G12 committee has established a task group to develop documentation to cover hot solder dipping (typically to replace Sn with Sn/Pb) and the re-balling of Ball Grid Arrays (BGAs). Studies have shown that BGAs with Pb-free balls are more difficult to install reliably than those with Sn/Pb balls, especially when using Sn/Pb solder. The Pb-free balls do not fuse with the solder as readily unless a high process temperature is used [25].

JEDEC JC13.1 has a task group developing a MIL-STD-750 (discrete semiconductors) test method to measure Pb content using X-Ray Fluorescence (XRF). At the most recent meeting, the G12 committee was urged to put the emphasis on creating a single, perhaps GEIA test method to be used for all electronic part types. The concern is that separate MIL-STD-202 (passives), MIL-STD-750 and MIL-STD-883 (microcircuits) methods would be difficult to maintain current and equivalent. There are obviously common requirements, whether the part being analyzed is a hermetically-sealed, tubular passive EMI filter or a plastic encapsulated quad flat pack and those should be captured in a single, over-arching standard. There are also likely to be differences in technique that need to be captured in separate detail test methods in 202, 750 or 883. It is also hoped that this single standard will be expanded to include a test method for Energy-Dispersive X-ray Spectroscopy (EDS or EDX).

6.5. Center for Advanced Life Cycle Engineering (CALCE), University of Maryland [26]

NASA is a member of CALCE's Electronics Products and System Consortium (EPSC), along with over 100 other organizations, both government and industry. The EPSC reviews progress on existing projects and provides guidance for future work. Projects are led by professors and executed by graduate and under graduate students. Current projects include research into whisker growth, the evaluation of Pb-free solders and the cost impacts of various Pb-free strategies. The EPSC members can access the results of the projects via a restricted access, secure website. The results of CALCE's research are one source of the information used by LEAP in developing its standards.

Table 1. Current Status of GEIA 0005 Series Standards and Handbooks

Document	Title	Published Date
GEIA-HB-0005-1	Program Management/Systems Engineering Guidelines for Managing the Transition to Lead-free Electronics	June 1, 2006
GEIA-HB-0005-2	Technical Guidelines for Aerospace Electronic Systems Containing Lead-free Solder and Finishes	Nov. 21, 2007
GEIA-STD-0005-1	Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-free Solder	June 1, 2006
GEIA-STD-0005-2	Standard for Mitigating the Effects of Tin Whiskers In Aerospace and High Performance Electronic Systems	June 1, 2006
GEIA-STD-0005-3	Performance Testing for Aerospace and High Performance Electronics Containing Lead-free Solder and Finishes	In Ballot
GEIA-HB-0005-3	Rework and repair Handbook for Aerospace and High Performance Electronic Systems Containing Heritage SnPb and Lead-free Solder and Finishes	TBD
GEIA-HB-0005-4	Impact of Lead-free Solder on Aerospace Electronic System Reliability and Safety Analysis	TBD

research are one source of the information used by LEAP in developing its standards.

6.6. Center for Advances Vehicle Electronics (CAVE), Auburn University, Alabama [27]

The CAVE has 21 current members from government and industry providing guidance in the selection and execution of projects related to electronics. NASA has been a member of CAVE for several years. CAVE is also studying Pb-free solder characteristics and tin whisker growth. The CAVE work is generally complementary and not duplicative of the CALCE work.

6.7. International Electronics Manufacturing Initiative (iNEMI) [28]

iNEMI is another international government/ industry consortium that is heavily involved in Pb-free electronics research. In 2003, iNEMI published what is still the most extensive evaluation of Pb-free solder alloys. iNEMI has also performed evaluations of environmental tests intended to accelerate tin whisker growth, primarily based on thermal cycling and temperature/humidity exposure. The results of this work were compiled into JEDEC Standards JESD201, Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes and JESD22A121.01, Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes. While the procedures developed by iNEMI and documented in these standard can cause whiskers to grow, it has not been established that the whiskers are representative of those that grow naturally and no acceleration factors have been developed that can predict the relationship between test results and application risk. NASA does not support the use of the these JEDEC standards as a way of qualifying "whisker proof" or "whisker resistant" pure tin plating processes or of predicting the risk of whiskering in applications. The results produced by iNEMI have been used by LEAP and others in the development of Pb-free standards and test methods.

7. THE NASA LEAD-FREE POLICY – AGENCY COORDINATION

As shown in Appendix A, the NASA Pb-free policy will be integrated into the general parts policy. This draft had been coordinated with subject matter experts in all NASA Centers with an involvement in Pb-free. However, when the draft was re-distributed, following incorporation of the minor inputs from the previous coordination, a completely new issue was raised: precautions against the tin pest risk. This is a valid issue but more work is needed to accommodate it in this high level policy document without getting into too much technical detail. The effort continues. The policy is only the start of the effort to implement a controlled approach to Pb-free electronics at NASA. Processes need to be implemented to comply with the requirements of the policy. This is where unexpected challenges have been encountered. Some of these lessons learned will now be discussed.

As shown by Appendix A, NASA's policy is based on the GEIA 0005 documents. For any spaceflight applications, the concern about tin whiskers means NASA needs to know if tin is being used. This means tin must be controlled to one of the Level 2 options per GEIA-STD-0005-2. Tab 2 summarizes the levels.

Table 2. Summary of GEIA-STD-0005-1 Tin Control Level Requirements.

LEVEL	DOCUMENTATION OF TIN USAGE	DETECTION AND CONTROL	MITIGATION	RISK ANALYSIS
1 Don't Care	Supplier: General information on finishes used	None	None	None
2A	Supplier: General information on finishes used Customer: List any applications where tin prohibited	None	None except report any instances where used in analysis	Show meets performance even with whiskers or because of mitigation
2B	Supplier: List families, general applications Customer: List any applications where tin prohibited	Sampling plan for materials check recommended	At least two mitigation methods recommended	Application tolerance or mitigation success at family level
2C	Supplier: Detailed listing of all uses Customer: List any applications where tin prohibited	Sampling plan agreed between supplier and customer	At least two mitigation methods required	Application tolerance or mitigation success at instance level
3 NO TIN	Supplier: Results of lot screening for tin	$\leq$1 sample/lot must be tested for tin	None, N/A	None, N/A

8. LESSONS LEARNED

The NASA policy has two principle elements: avoidance of Pb-free solders and control of pure tin finishes. Unfortunately, there are complications with both.

8.1 Electronic Parts That Have Always Contained Lead-Free Solders

It has been realized that there are parts which have been made for years using Pb-free solders, including internal solder joints and many of these parts have been MIL qualified and successfully used by NASA for decades but are now non compliant to the tin prohibition boilerplate quoted earlier. A good example is passive EMI filters. These parts are constructed using successive solder joints making connections between inductor coils, capacitors and the terminations of the device. In order to not reflow solder joints that have already been made, with the heat used to make successive joints, a hierarchy of solders with progressively lower melt points is used. In this scenario, the higher melt point solders used first are often tin silver and tin antimony, both are Pb-free. Tin-antimony solders are often used for their high melting point in applications that can be heated significantly by installation processes such as hermetic seals around termination leads. The tin whisker potential for these Pb-free solders is poorly understood, due to their relatively low usage. Whiskers have been observed growing from thermally sprayed tin-antimony alloys used to terminate plastic film capacitors [29] but not from tin-antimony solder to date. Tin whiskers have been observed growing, at least occasionally, from a long list of Pb-free alloys [30,31,32,33,34], so the dilemma is between granting waivers to the requirement for a minimum of 3% Pb and setting precedents for the use of alloys that present an unknown risk if they are used widely. In general, these non compliant constructions are being "grandfathered" into the MIL system opening up the risk that there will be demands for more widespread use based on the precedent.

8.2. What is Pure Tin? How Can We Tell?

Commercial tin finishes are very unlikely to be truly "pure", there will always be contaminants if only at the trace level. Therefore the term "pure tin" has to be defined. To combat whiskers, a limit of 3% minimum Pb by weight in tin was established for the MIL specifications in the mid 1990's; it is well established and is the de facto definition of "pure tin". For the purposes of Pb-free policy, pure tin is any tin based material containing less than 3% by weight of Pb. Obviously, this definition requires the ability to accurately determine if unknown surface finishes contain less than 3% of Pb. For RoHS compliance this requirement extends down to the ability to detect 0.1% Unfortunately, there is currently no standardized process to make these determinations. There are no calibration standards for Pb content in tin, there are no standardized test methods, there isn't even agreement on the test equipment that should be used/allowed. The equipment that is being used does not have the capability of accurately resolving Pb content at these levels. There have been US government/industry meetings to discuss the issues but resolutions are clearly not imminent. The RoHS measurement issue is also the focus of intense research by EU members.

8.3. Calibration Standards

The US National Institute for Standards and Technology (NIST) has been approached to develop appropriate calibration standards. Challenges include: determination of which alloy ratio's are needed, what thicknesses and substrates are appropriate and of course, a business case that justifies the investment. Obviously, for the US a standard of 97/3 Sn/Pb is needed but should there also be a 99/1 and 90/10 for instance, or maybe four standards? The answer may depend on the test method/equipment used; the response may be non linear. The construction of the standard could also take different forms. To calibrate for plated finishes which are thin, it is logical to have a standard with a thin coating on an appropriate substrate so that any distortion of results by detecting materials in the substrate would be obvious. The problem of shooting through the plating into the substrate is a particular challenge with X-ray Fluorescence (XRF). A standard for use in measurements of solder joints and bulk solder would probably need to be a rod or slab without a substrate. The Pb in Sn/Pb is not smoothly distributed, instead the elements exist in Sn-rich and Pb-rich regions of variable sizes. Misleading results can be obtained if the test method uses a narrow beam that illuminates just a Sn or Pb rich region. The standard needs to have a morphology that represents real world platings and solders. Unfortunately the morphology of Sn/Pb can vary with rate of cooling from the molten state or the plating conditions and can vary over time once solidified [35]. Solutions to all of these issues will be found but there is a lot of work to do.

8.4 Test Methods for Lead Content

There are a number of potential test methods to determine Pb content but currently two are dominant in the market because of cost and practicality, XRF and EDS. There are no standardized test methods for the use of XRF or EDS and there is also a wide range of equipment at different costs and with different performances. Hand-held XRF units are being used for convenience but studies have shown they are less accurate than desktop models and should only be used for rough screening; they also require direct contact with the specimen [36,37]. For the most accurate analysis EDS is superior to even the best XRF but XRF machines are more convenient as they can be used in a normal work space. EDS requires a Scanning Electron Microscope (SEM) which limits throughput and specimen size. Whichever method is used, issues such as calibration, sample size, sampling area location, number of sampled areas, tolerances and format of results need to be addressed in the standardized methods. For XRF curved surfaces can deflect the beam creating the risk of errors. Should the results be displayed as a single value (the average, median etc. of the sample readings) or as a mean and standard deviation? There is a JEDEC team working on a standard XRF test method but has run into a long list of technical issues to be resolved. The author knows of no current efforts to tackle EDS. There is general agreement that operator training is key to the use of any equipment used to determine Pb content in Sn. The operator needs to understand the operating principles, the limitations, the error signatures and the basic physics involved.

9. CONCLUSIONS

1. NASA and other aerospace organizations not covered by RoHS or other Pb-free legislation still need a Pb-free policy to ensure the future reliability of their electronic systems.
2. The major threats to the reliability of electronic equipment posed by going Pb-free are: solder joints of unknown long-term reliability in harsh environments, tin whiskers and tin pest.
3. A framework for controlling Pb-free electronics exposure is provided by documents in the GEIA 0005 series of standards and handbooks.
4. At this time, there are technical challenges with implementing any Pb-free policy, except one with no restrictions at all.
5. NASA's draft policy is almost ready for release. Once released it will begin to control NASA's exposure to Pb-free by requiring relevant information to be supplied by NASA's contractors.
6. Currently, any policy which tries to control Pb content in tin, either at the RoHS limit or the MIL specified 3% faces the challenge that there are no practical, recognized test methods or calibration standards.
7. Without standardized test methods or calibration standards, measurements are subject to unrecognized errors.

10. REFERENCES

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Appendix A

NPD 8730.2B DRAFT

Effective Date: June 08, 1998
Expiration Date: June 08, 2008
COMPLIANCE IS MANDATORY

Subject: NASA Parts Policy (Revalidated TBD)
Responsible Office: Office of Safety and Mission Assurance

1. POLICY

It is NASA policy to control risk and enhance reliability in NASA spaceflight and critical ground support systems, in part, by managing the selection, acquisition, traceability, testing, handling, packaging, storage, and application of Electrical, Electronic, and Electromechanical (EEE) parts; advanced packaging and interconnect systems; associated materials (including solders), and mechanical parts (including fasteners, bearings, studs, pins, rings, shims, valves, springs, brackets, clamps, and spacers).

To carry out this policy, NASA shall accomplish the following:

a. Select parts, packaging technology and materials for electronics assembly based on their intended use considering, but not limited to, performance, environmental, criticality, and lifetime requirements. In particular, the following requirements apply to surface finishes for electronic and mechanical parts, the solders used in making electronic parts and electronic assemblies that utilize soldered connections:

(1) Tin-Lead (Sn-Pb) based solders and Sn-Pb part surface finishes (minimum 3% Pb by weight) are preferred and shall be used whenever possible for the assembly of electronics hardware intended for NASA spaceflight and critical ground support applications. The use of lead-free (Pb-free) solders or Pb-free Sn-based part surface finishes may be allowed when justified by technical need, but only by exception and with the approval of the parts, materials and processes control board for the NASA Project or an equivalent authority.

(2) All Programs and Projects shall require a Lead-Free Control Plan (LFCP) that meets the requirements set forth in GEIA-STD-0005-1. The LFCP shall include any special design considerations, manufacturing process controls, test and qualification requirements, quality inspection and screening, marking and identification, maintenance, and repair processes, and other steps taken to mitigate risks and to ensure the reliability of hardware for the intended application.

(3) All Programs and Projects shall require a control plan to reduce the harmful effects of tin whiskers that meets the Level "2C" requirements set forth in GEIA-STD-0005-2. Less stringent control plans meeting Levels "2A" or "2B" may be allowed in exceptional cases with the approval of the parts, materials and processes control board or an equivalent authority.

To assist Program Offices in understanding the unique problems lead-free electronics represents, consult GEIA-HB-0005-1 and the NASA Tin and Other Metal Whisker website: http://nepp.nasa.gov/whisker

b. Document the derating criteria for parts.

c. Utilize the results of surveys/audits as a means to determine capability and qualification of sources. NASA Centers may utilize the results of surveys/audits performed by other Centers or third-party auditors. The process used by third-party auditors/surveyors (including those performed by other Government agencies or commercial third-party auditors) must be reviewed prior to use to determine that the process meets minimum NASA requirements.

d. Coordinate procurement of parts among programs/Centers whenever feasible.

e. Maintain a NASA Parts Selection List (NPSL) to provide candidate selections for program use.

f. Participate in the Defense Standardization Program and appropriate voluntary consensus standards programs for the EEE and Mechanical Parts commodities.