NEPP TRO
Lead-Free Soldering for Space Applications
Lead-Free Solder Body of Knowledge

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The following document presents the state of lead-free soldering technology as of April 2005 and evaluates its readiness for insertion into space flight systems.

1.0 *INTRODUCTION*

The commercial sector is driving component and board suppliers to provide lead-free part finishes, surface finishes and solder alloys for use in electronic assemblies. Ever increasing legislature against lead in electronics, coupled with the consumer trend that electronics customers prefer environmentally friendly lead-free products is forcing this trend. The United States Environmental Protection Agency (USEPA) has lowered the Toxic Chemical Release reporting threshold for lead to 100 pounds. Overseas, the Waste Electrical and Electronic Equipment (WEEE) [1] and the Restriction on Hazardous Substances (RoHS) [2] Directives in Europe and similar mandates in Japan are being implemented.

NASA programs require high reliability electronic parts and assemblies, but are increasingly dependent on commercial off the shelf (COTS) electronic parts and assemblies due to the ever diminishing market share that the aerospace electronics sector holds. Exemptions written into the legislature for high reliability electronics assemblies required for aerospace applications will not protect these assemblies from the introduction of lead-free. Some part suppliers will switch to lead-free and not change part identification numbers or serial numbers. A few high reliability electronics users, and a high profile testing program, received lead-free parts with pure tin part finishes even though there procurement contracts prohibited lead-free.

The objectives of this task were to:

- Perform a technology readiness overview of lead-free solder
- Summarize assembly and material characterization testing data
- Identify experts within government, NASA, industry and academia
- Identify technical gaps in the understanding of lead-free solder, with emphasis on reliability testing relevant to space hardware
- Identify risks to NASA of both the commercial lead-free transition and the possibility of converting to lead-free solder alloys
- Recommend mitigation strategies for each risk

It is the intent that this report be used to guide future NASA lead-free policy and strategy, and to inform project managers of potential lead-free solder impacts.

2.0 *DESCRIPTION OF LEAD-FREE SOLDERING TECHNOLOGY*

For electronic assembly processes involving the reflow of lead-free solder alloys, the tin-silver-copper (SAC) family of solder alloys has become the predominant choice for reflow soldering and as a possible general purpose lead-free solder (See Table 1). Solder alloys of the type Sn-(3.0-4.1)Ag-(0.45-0.9)Cu generally exhibit the following characteristics:

Positive:

- Supply of the materials required for the alloy are sufficient
- Lower melting temperature than some other popular lead-free alloys, such as tin-silver (SnAg)
- Good mechanical properties
- Better wetting than SnAg

Negative:

- Concern about supply of Ag for wave soldering
- Potential component thermal damage
- Higher cost than SnPb and other alloys with less Ag
- Unknown reliability for military/aerospace applications

Table 1 Recommended Tin-Silver-Copper Solder Alloys for Reflow

JEITA	Sn-3Ag-0.5Cu
iNEMI formally NEMI	Sn-3.9Ag-0.6Cu
SOLDERTEC	Sn-(3.4-4.1)Ag-(0.45-0.9)Cu
BRITE-EURAM	Sn-3.8Ag0.7Cu
Ames	Sn-3.6Ag-0.7Cu
IDEALS	Sn-3.6Ag-0.7Cu

As SAC alloys emerge as the dominant lead-free solder of choice, the exact composition of the alloys vary by manufacturer. The current popular SAC alloys have variances in silver content from 3 percent to 4 percent, while copper content varies from 0.4 to 0.8 percent. The SAC alloys have a relatively low melting point (217°C) and studies indicate that SAC alloys have reliability similar to Sn-Pb under moderate thermal cycling conditions.

Other popular lead-free alloys include tin-copper (SnCu) (promising for wave soldering), tin-silver (SnAg), and tin-silver-copper-bismuth (SACB), among many others.

3.0 *STATE OF LEAD-FREE SOLDERING TECHNOLOGY*

3.1.1 Maturity

Technology maturity is defined relative to the performance requirements. Lead-free alloys presently perform within the specifications needed for many commercial electronics applications, as noted by the fact that a wealth of lead-free solder alloys are available commercially and are being used by commercial electronics manufacturers. However, for military and space applications, the necessary testing has not been done to determine if current lead-free solders can meet the high-reliability and low risk requirements. In terms of Technology Readiness Level (TRL) [3], Level 4 (Component and/or breadboard validation in laboratory environment) has been demonstrated for high-reliability applications. Making the jump to TRL 5 (Component and/or breadboard validation in relevant environment) for high-reliability applications are currently being addressed by programs such as CALCE [4], CAVE [5], and JCAA [6]/JG-PP[7], all of which NASA is an active participant. Support for programs like CALCE, CAVE and JCAA/JG-PP is crucial for lead-free technology insertion in spacecraft systems.

The overall maturity level of lead-free soldering technology is low. The fundamentals of assembling circuit cards with lead-free solder has largely been worked out, but the jump necessary to proceed to implementing lead-free soldering on high-reliability products product hasn't materialized. Further financial investments are needed to identify and characterize failure mechanisms and identify the best lead-free alloys based on reliability test data. Although the commercial sector has been the prime (if not sole) investor in lead-free for commercial applications, NASA and military agencies are the only entities examining lead-free in high-reliability applications, but only for limited studies, not for a large-scale technology insertion. Because the high-reliability aerospace industry represents only 1% of the total electronics market (the rest being commercial), there is little incentive for the commercial industry to step in and prove lead-free viability for high-reliability applications. In the meantime, it is advisable that the aerospace community continue to test promising lead-free solder alloys—and all the various combinations of board finish and component type and lead finish—under space mission environments. This testing will not be done by the commercial sector and is necessary for evaluating technology readiness and providing developers with the necessary feedback to ensure robust, space-flight quality devices.

3.1.2 Current Commercial Implementation

Japanese manufacturers have been using lead-free solder technology in consumer products since 1998. Examples of lead-free consumer products include mobile phones, televisions, video cassette recorders, personal computers, notebook computers, printed circuit boards and motherboards. Motorola assembled i85 mobile phone handsets with the Sn 3.9 Ag 0.6 Cu solder alloy and reported no issues with reliability following several years of consumer use. Several other Japanese companies have been using the Sn3.0Ag0.5Cu solder alloy for consumer applications with no reports of solder joint reliability issues.

Increasing consensus from the consumer electronics industry, including the telecommunications industry, indicates that lead-free solder alloys from the SnAgCu family are preferred. Field data on the performance of SnAgCu solder alloys, used in consumer electronics, is limited but does indicate that SnAgCu solder alloys are at least as reliability as eutectic tin-lead solder alloys. With the introduction of the European Union End-of-Life Vehicles (ELV) Directive, the automotive industry has been dealing with the issue of lead-free since 2000. Several companies, including Visteon, Delphi Delco and Motorola, involved with automotive electronics have implemented lead-free into their automotive products.

One company in particular, Tyco Electronics, has indicated that it will maintain two specific product lines to accommodate lead and lead-free electronics assemblies. Tyco Electronics supplies the commercial aerospace sector with lead-free products and processes and is planning to continue to support legacy commercial aerospace products. Tyco Electronics developed part number tracking procedures to keep the new lead-free parts distinguished from the legacy leaded parts.

Another company, Fairchild Semiconductor, issued a Process Change Notification (PCN) stating that it was converting all packages to lead-free terminal plating. They will not be changing parts numbers because they determined through their testing that form, fit and function are the same, but will contain different marking. Fairchild intends to ship lead-free devices intermixed with SnPb products (for non-lead-free orders only) during the transition period.

Hamilton-Sundstrand (H-S) has also announced the decision that the company will be lead-free on all new H-S systems by 2007 and lead-free on all H-S legacy systems by 2012. This includes all H-S products for NASA, DoD and commercial customers. H-S currently is a main contributor to Space Suits. While working on the design for new battery and charger for suit, they found that leaded parts were unavailable. They are currently performing a survey of suppliers to determine best course of action.

4.0 *PRODUCTION AND MANUFACTURING ISSUES*

4.1.1 Voiding

One issue that exists for all lead-free solder alloys is voiding. Lead-free solder alloys have a higher surface tension than tin-lead alloys which creates a trapping effect of the flux residues creating voids within the solder. Data suggests that voiding is not a reliability issue until part pitch equals 0.5mm or above. The Sn-3Ag-0.5Cu alloy has been shown to provide the lowest voiding among lead-free solder alloys. To further reduce voiding, special attention should be paid to flux design and process conditions. It has been suggested that performing lead-free reflow processes in a nitrogen atmosphere will reduce the formation of voids in SAC alloys. Nitrogen inerting has been attributed to decreased void size and a reduction in irregularly shaped solder balls following reflow processing.

4.1.2 Plated Through Holes

Data on plated through-hole reliably is limited. It is know that the higher process temperatures required for lead-free solders causes stress on the plated through holes. Concerns created by the higher processing temperatures of lead-free solder alloys includes delamination, blistering, and cracking of the copper plating in the barrel of the plated through hole. The exact effect of this stress on the reliability of plated through holes is not fully understood. What little data exists on reliability of lead-free plated-through-holes after lead-free processing is mixed.

4.1.3 Temperature Profile

Much work has been done with regards to optimizing reflow temperatures and profiles. Opinions vary greatly with regards to process zones, peak temperatures, the amount of time above liquidus and cooling rates. The aforementioned conditions must be specifically tailored to the manufactures equipment, solder paste selection, board finish, flux and end product. Each manufacturer will have to establish their own process details and guidelines in order to optimize lead-free processing at their facility.

Since higher temperatures are present during lead-free processing, care needs to be taken when selecting board materials and parts for lead-free assembly. Typical lead-free assembly processes require an increase in operating temperature between 20^{o}C to 35°C. Some parts may pose a reliability risk when exposed to the higher operating temperatures associated with lead-free assembly. Composition limits and moisture sensitivity levels are two factors that could reduce reliability in lead-free manufacturing processes.

Part suppliers are addressing composition issues by making parts available that can withstand the elevated temperatures associated with lead-free processing. Some parts suppliers are working to re-qualify or modify parts to ensure that they can withstand at least 260°C to 265°C. The focus is on material development for new packaging materials. New component molding compounds, which can withstand temperatures in excess of 260°C, are being incorporated into lead-free part design. To date, newly developed high temperature resistant components are not readily available. Some in the electronics industry are concerned that they will have part failure issues during lead-free assembly caused by elevated lead-free processing temperatures and non-compliant components. It is also expected that cost will be higher for the high temperature resistant components.

4.1.4 Rework

Rework procedures for solder joints assembled with lead-free solder alloys can introduce negative impacts to part and board reliability. Higher temperatures required to process lead-free solder alloys place increased stress on parts and boards during rework procedures. Risks associated with rework include board layer delamination, board warping, via damage and part damage. Damage associated with lead-free rework is not limited to the specific part being reworked, but other parts in close proximity will also be exposed to increased operation temperatures. Rework techniques which will reduce damage during rework are being evaluated. These techniques will need to be refined and adjusted for each individual rework scenario. Close attention to detail is required when selecting materials that will see rework processing. Increased temperature gradients, rework time and preheat times can destroy part and board materials not suited to handle higher temperatures.

4.1.5 Solder Compatibility

Solder compatibility between lead-free and tin-lead solder alloys could create major issues with solder joint reliability. Early in the lead-free transition process, suppliers and manufactures may chose to maintain leaded and lead-free product lines. Maintaining two separate lines will increase the risk of mixing leaded and lead-free solder alloys creating two types of solder compatibility issues, backward compatibility and forward compatibility. Backward compatibility is categorized as lead-free parts/packages being soldered onto printed circuits boards using eutectic tin-lead solder. Forward compatibility is categorized as leaded parts/packages being soldered onto printed circuit boards using lead-free solder.

How lead-free solder joints are affected by the presence of lead appears to be directed linked to the amount of lead present. Lead amounts up to 0. 5% have been shown to have little or no effect on the reliability of lead-free solder joints, and may even increase reliability for some part types. Once lead content in lead-free solder joints exceeds 0.5%, lead-free solder joint mechanical strength and reliability are reduced. Reduced reliability and mechanical strength has been shown to be part and package dependent as well as lead-free alloy dependent.

5.0 *RELIABILITY CONCERNS*

Because lead-free solders are at such a low maturity level, there are reliability concerns at all levels – design, fabrication, post-production/packaging, and system insertion/harsh environments.

5.1.1 Tin-Silver-Copper (SAC) Alloy

A tremendous amount of commercial work is ongoing which focuses on the reliability of the tin-silver-copper alloys. The predominant method used for evaluating solder alloy reliability is thermal cycling. Solder joint failures under thermal cycle testing are created by coefficient of thermal expansion (CTE) mismatch. Under thermal cycle stresses, CTE mismatches occur between the part substrate, circuit board and solder joint. In areas of the solder joint where CTE mismatch is greatest, solder joint failure is observed.

In review of the data available on lead-free solder joint reliability, numerous thermal cycles were identified with regards to testing methodology; 0°C to 100°C, -40°C to 125°C, -40°C to 150°C , –50°C to 150°C, -55°C to 125°C and -55°C to 150°C. In review of published studies, lead-free solder joints have been shown to double the fatigue life of tin-lead solders under lower temperature and strain ranges, while eutectic tin-lead solder joints performed better than lead-free when subjected to high temperature and strain ranges. Data results from thermal cycle testing where the peak thermal cycle range is 125°C or less, suggest that tin-silver-copper solder alloys have similar, and in some cases improved, reliability when compared to eutectic tin-lead solder alloy. However, in studies where the peak thermal cycle range is 150°C the eutectic tin-lead solder outperformed the tin-silver-copper solder alloys. Much work is still required to fully understand the creep/strain relationships of lead-free solder as compared to eutectic tin-lead solders.

The mechanical strength and associated reliability of the SAC alloys can be increased by optimizing processing conditions resulting in a homogeneous distribution of the Ag3Sn and Cu6Sn5 intermetallic layers. Studies have shown that increasing the wetting performance of lead-free solders can result in a larger area of interface between the part lead and solder resulting in improved joint strength. Part lead finishes may influence the wetting performance of lead-free solders. To date, the data is limited on the role that part finish plays on the wetting characteristics of lead-free solders. Initial data indicates that part finishes consisting of Ni/Pd/Au may improve wetting of lead-free solders. A full understanding of this issue, including intermetallic interactions, has yet to be obtained.

5.1.2 Other Lead-Free Alloys

Solder alloys which incorporate bismuth, such as tin-silver-bismuth, and tin-silver-copper-bismuth have been shown to poses good processability and solder joint reliably. Adding bismuth to tin-silver and tin-silver-copper solder alloys decreases the melting point of the alloys, improves wettability, and increases joint strength. Thermal cycle test results indicate that bismuth containing alloys perform at least as well as SAC alloys and may be a good candidate to replace reflowed eutectic tin/lead in high reliability electronics. However, the presence of bismuth does have drawbacks which will limit the use of bismuth containing lead-free solder alloys in production electronics. It has been shown that too much bismuth, greater than 5 percent, causes questionable results for joint reliability as temperatures approach 140^{o}C. There is also much concern over lead contamination and bismuth containing lead-free solder alloys. When lead, present in a board finish or part finish, comes in contact with the bismuth contained in the ternary or quaternary lead-free solder alloys a tin-lead-bismuth compound can form. The tin-lead-bismuth compound has a melting point of 96^{o}C, which leads to premature failure during thermal cycle evaluations. Bismuth containing lead-free solder alloys will not be a viable candidate until the risk of lead contamination is zero.

For wave solder applications, the tin-copper stabilized lead-free solder alloy is a popular choice. The tin-copper stabilized alloy is a binary tin-copper alloy with the addition of a small amount of nickel (about 0.05 percent by weight). It has been determined that the addition of nickel to the tin-copper alloy increases the alloys fluidity which in-turn decreases solder joint failures caused by bridging and icicle formations. The tin-copper stabilized alloy also has a low dross rate and does not erode equipment which reduces the costs associated with lead-free wave soldering operations. Solder fillets formed using the tin-copper stabilized alloy have been characterized as smooth and bright, which aid in the inspection process, when compared to other lead-free wave solder alloys. Reliability testing has shown that tin-copper stabilized alloy is as reliable as SAC and tin-lead solder alloys. The tin-copper stabilized alloy does have the disadvantage of having a high melting temperature, 227^{o}C. The higher melting temperature will result in the need to closely monitor the temperature thresholds for board materials and parts being processed through a tin-copper stabilized wave solder process. Survey results indicate that tin-copper stabilized is a popular choice for lead-free wave solder applications and this trend is expected to continue.

The tin-silver lead-free solder alloy has been used in automotive electronics applications for quite some time. The alloys exhibit good wettability, mechanical strength and creep resistance and is readily available in bar, wire and paste forms. Thermal fatigue data suggests that tin-silver solder joint reliability is comparable with eutectic tin-lead. One major drawback to tin-silver solder alloys is the formation of the brittle Cu6Sn5 intermetallic when soldered to copper base metal. Alternative surfaces finishes are being evaluated, such as immersion gold over nickel over copper. The nickel forms a barrier which limits the formation of the brittle Cu6Sn5 intermetallic. Other surface finish materials such as immersion silver do not have the nickel barrier and will require further investigation to fully understand the metallic interactions between the solder, board finish and copper pad. The tin-silver lead-free alloy does have a higher melting temperature, 222^{o}C. The increased melting temperature further complicates the managing of thermal thresholds for parts and boards which are already approaching maximum thermal limitations.

5.1.3 Other Reliability Issues

Further complicating the issue of solder joint reliability is the fact that reliability has been shown to be part dependent. Parts that have a high CTE mismatch with the board, ceramic parts on a FR-4 board, have shown decreased solder joint reliability when comparing lead-free to tin-lead solder joints. This trend is reversed when the part and board have a similar CTE. This can be attributed to a reduction in the stress applied to the solder joint. Issues with CTE mismatch and the effect on solder joint reliability is not confined to different part types. The same part, including solder ball pitch, had increased solder joint reliability when comparing lead-free to tin-lead solder for a smaller part size. When the part size was increased, tin-lead solder outperformed lead-free solder due to the increased thermal mass of the larger part which increased CTE mismatch.

Mechanical properties of lead-free solders are an area of study which still requires much investigation. Leading universities [8, 9, 10, 11] which examine the intermetallics of lead-free solder and the associated properties were queried for data gaps regarding lead-free mechanical properties. Work has been done with regards to thermal aging and how it affects the mechanical properties of lead-free solders. However, there are still many questions that need to be answered. The following table lists several mechanical properties of lead-free solders that still require investigation.

Data Gaps Remaining for Lead-Free Mechanical Properties[9]	
Creep and viscoplastic properties	Low-cycle fatigue properties and associated predictive equations
High-cycle fatigue properties	Shock and impact data on lead-free solder
Grain size and microstructure evolution in lead-free solder	Fracture strength of lead-free solder and particularly for intermetallic regions

Additional information on all aspects of lead-free is summarized in Appendix A, "*Lead-Free Document Summarization Table*".

5.2 Environmental Stresses

In general, one must address the environmental stresses imposed on a lead-free soldered device throughout the lifetime of the mission.

The following environmental effects are the major contributors to failure of solder joints in general:

5.2.1 Thermal Cycling

Operational thermal cycling affects all solder joints. Whether lead-free soldered joints perform better or worse than tin-lead joints under harsh environments (-55^{o}C to +125^{o}C) is only beginning to be understood and is part of the JCAA/JG-PP testing. Full thermal cycling characterization for PTH parts and some newer SMT components is required for insertion into spacecraft systems:

5.2.2 Vibration

The effect of random vibration on lead-free soldered joints is being evaluated by JCAA/JG-PP. Further details with regards to the JCAA/JGPP vibration testing can be found in the Joint Test Protocol (JTP) [13]. However, full vibration characterization for PTH parts and some newer SMT components should be investigated before insertion into spacecraft systems.

5.2.3 Mechanical Shock

Mechanical shock evaluation of lead-free soldered joints is being evaluated by JCAA/JG-PP. However, full mechanical shock characterization for PTH parts and some newer SMT components should be investigated before insertion into spacecraft systems.

5.2.4 Extreme High –or Low – T

While the effect of moderate temperature extremes on lead-free solder joints (-55^{o}C to +125^{o}C) is being evaluated under JCAA/JG-PP, the effect of extreme temperatures (-230^{o}C to +200^{o}C) typical of space hardware environments has not been explored.

5.2.5 Storage (Survival Conditions)

The effects of salt spray and humidity on lead-free soldered joints are being evaluated by JCAA/JG-PP. No effect is expected that would make lead-free joints perform any worse than SnPb, but the JCAA/JG-PP testing will verify.

5.2.6 Radiation Effects (SEU, TID, FLASH X-RAY)

The effect of radiation on lead-free solder joint performance has not been explored and is recommended to fully understand the effect of the radiation environment on lead-free technology.

5.2.7 Human Life Issues – Extremely Low Risk Restrictions

Lead-free soldering technology is too immature to be considered in situations where failure of the device could result in loss of human life. Only after *all* of the aforementioned issues have been addressed should they be considered appropriate for such low-risk applications.

(Only some of the high-stress environment testing mentioned above is beginning to be done because it is not necessary for most commercial applications, the automotive industry excepted.)

5.3 Mission Scenarios

Below each of the following mission categories is a flight readiness recommendation for use of lead-free soldering in that scenario and a supplemental table listing potential environmental stresses and their associated effects on joint performance.

5.3.1 LEO, ISS, Shuttle

It has not been shown that lead-free soldered joints meet the reliability requirements for this scenario.

Issues to be addressed: thermal cycle, vibration, and mechanical shock performance characterization; extremely low risk statistical testing; proton total dose radiation testing.

Environment/condition	Expected Effect on LF Joint Performance
Thermal Cycling	Possible electrical failure
Vibration (launch)	Possible electrical failure
Mechanical Shock	Possible electrical failure
Human Life issues	Very high reliability requirements
Radiation Effects (proton) – unshielded component	Unknown

5.3.2 Aeronautics

It has yet to be shown that lead-free soldered joints meet the reliability requirements for this scenario.

Issues to be addressed: vibration, mechanical shock, and high-temperature performance characterization; extremely low risk statistical testing.

Environment/condition	Expected Effect on LF Joint Performance
Vibration (launch)	Possible electrical failure
Mechanical Shock	Possible electrical failure
High temperature (inside nose cone)	Possible electrical failure
Human Life issues	Very high reliability requirements

5.3.3 MEO, GEO

It has not been shown that lead-free soldered joints meet the reliability requirements for this scenario.

Issues to be addressed: thermal cycle, vibration, and mechanical shock performance characterization; total dose/single event radiation effects testing; identify effects of plasma charging/discharging.

Environment/condition	Expected Effect on LF Joint Performance
Thermal Cycling	Possible electrical failure
Vibration (launch)	Possible electrical failure
Mechanical Shock	Possible electrical failure
GEO - Radiation Effects TID (electrons)	Unknown
MEO – Radiation Effects TID (protons and electrons)	Unknown
Plasma effects – spacecraft charging/discharging	Unknown

5.3.4 Mars Surface

It has not been shown that lead-free soldered joints meet the reliability requirements for this scenario.

Issues to be addressed: thermal cycle, vibration, mechanical shock, and low-temperature performance characterization; total dose/single event radiation effects testing.

Environment/condition	Expected Effect on LF Joint Performance
Thermal Cycling	Possible electrical failure
Vibration (launch)	Possible electrical failure
Mechanical Shock	Possible electrical failure
Low Temperatures	Possible electrical failure
Radiation Effects TID (electrons and protons)	Unknown

5.3.5 Jovian System, Outer Planets

It has not been shown that lead-free soldered joints meet the reliability requirements for this scenario.

Issues to be addressed: vibration, mechanical shock, and low-temperature performance characterization; plasma effects testing; accelerated life testing; total dose radiation testing

Environment/condition	Expected Effect on LF Joint Performance
Vibration (launch)	Possible electrical failure
Mechanical Shock	Possible electrical failure
Low Temperatures	Possible electrical failure
Plasma effects	Unknown
Long-life issues	Unknown, but believed to be on par with SnPb solder
Radiation effects – TID (high energy electrons)	Unknown

5.3.6 Outside Solar System, Very Long Life Missions

It has not been shown that lead-free soldered joints meet the reliability requirements for this scenario.

Issues to be addressed: vibration, mechanical shock, and low-temperature performance characterization; accelerated life testing; total dose radiation testing.

Environment/condition	Expected Effect on LF Joint Performance
Vibration (launch)	None
Mechanical Shock	Possible electrical failure
Low Temperatures	Possible electrical failure
Long storage issues	Unknown, but believed to be minimal
Long-life issues	Unknown, but believed to be on par with SnPb solder
Radiation effects – TID (interstellar radiation protons)	Unknown

6.0 *TECHNOLOGY EVOLUTION IN NEAR TERM*

The driving forces for lead-free solder—marketing and legislation—are likely to persist and therefore ensure wide insertion of lead-free technology through commercial applications. Assembly and rework using lead-free solders will be adjusted to optimize performance and increase reliability, but no drastic changes to lead-free alloys is anticipated, with SAC the likely front runner for reflow and manual soldering and SnCu for wave soldering.

Listings of current and future studies are identified in Appendix B, "*Current and Future Studies*"

7.0 *RISKS*

The commercial transition to lead-free electronic assemblies poses a risk to current and future NASA projects and programs. Continuing to use electronic assemblies which contain lead creates risks associated with compliance with current environmental legislation, compliance with developing and future environmental legislation, part obsolescence and solder contamination. Under current US and EU legislation, exemptions for lead solder have created a lack of understanding with regard to lead-free solders and the risks they may impose on aerospace applications.

Currently there is not enough high-reliability (IPC Class 3)[12] data to understand how lead-free materials will behave under the harsh environments of space applications. There are too many variations with lead-free materials including board finishes, part finishes and solder alloys. Process and performance reliability is tied the selection of lead-free materials for specific applications. Further complicating the issue is the fact that process and performance reliability can vary greatly for the same product supplied by different vendors.

Within all levels of NASA and the military, the overall view of lead-free solder is that unless specifications call for it, it will not be implemented and along those lines, there is no current push to perform much, if any, testing on lead-free solders to identify potential replacements to tin-lead solders. Contractors and subcontractors that are involved in procurement and assembly of electronic systems are aware that some vendors have already begun the switch to both lead and lead-free process lines.

8.0 *RISK MITIGATION STRATEGIES*

Within NASA itself, very little work has been done to mitigate the risks of receiving lead-free inadvertently or identify what suppliers' plans are in regards to lead-free. Some of the major contractors have started this process through identification of parts of most concern and surveys of suppliers.

The following risk mitigation strategies are proposed:

1. Ensure that everyone, from Procurement to Logistics to Technicians, understands the issue and concerns of lead-free solder and parts that may contain lead-free solder. Making it everyone's responsibility will reduce the risk of component or system failure from the use of lead-free solder.

2. Identify what part manufacturers and suppliers are doing; which are converting to lead-free, which are going to have two lines, and what controls will be in place to prevent mix-ups.

3. Modify logistics systems to capture all possible methods of identifying lead-free products by modifying inventory system to flag lead-free, RoHS compliant and “Green” products. Be prepared to conduct a physical inventory for products not changing part numbers

4. Implement internal procedures to deal with issues of lead-free product re-labeling and non-lead-free return processes. Clearly defined labeling and parts numbers need to be created for each product to differentiate it from its leaded counterparts. If the OEM refuses to make such a differentiation, then the local NASA Quality Assurance (QA) departments will have to work with technicians requesting the purchases to ensure that some sort of post-purchase/post-delivery identification system is set up to keep the leaded parts separate from the lead-free parts.

5. Develop a clause or clauses for the Federal Acquisition Regulation (FAR) and/or the NASA FAR Supplement defining the requirement for contractors who purchase parts/supplies/components to establish and maintain a purchasing, receiving, storage and usage system that differentiates leaded/lead-free items from each other. Existing clauses, especially those having to do with "buy-green," will need to be updated to reflect the new lead-free soldering material and any parts that are created using them. In addition to any clauses, all of the PONs, directives, etc., where it is appropriate to include this new lead-free way of doing business will need to be updated.

6. For those contracts where a supplier has been producing leaded parts/components/systems and where a non-leaded part/component would not work for technical reasons, new contracts directing the supplier to maintain an appropriate amount of leaded spares to cover the reasonable lifetime of the items in the field need to be prepared.

7. In order to reduce the risk of obsolescence, a one-time buy of leaded solders and/or parts could be initiated to maintain the program until a suitable replacement is found or a reliable supply chain is identified.

8. Define training requirements for the people who design, maintain, and repair those items where lead-free solder may be used or where there may be a mixture of leaded and lead-free parts. JPL teaches soldering classes and would most likely be where technicians would be trained in the use of lead-free solder.

9. Use of x-ray fluorescence (XRF), scanning electron microscopes (SEM), or other equipment to scan parts and assemblies for the presence of lead. Portable XRF is a viable option for screening components and in some cases assembled circuit cards for the presence of lead. These technologies are quite costly, time consuming, and have limitations, but may be necessary if NASA part and components suppliers maintain lead and lead-free products lines. At least one NASA contractor is using XRF and another is using SEM to screen parts for the presence of lead.

10. Continue participation in efforts such as CALCE, CAVE, and JCAA/JGPP Lead-Free Solder.

11. Coordinate a NASA Lead-Free presentation to be presented to NASA Headquarters to ensure they are fully aware of the issue and the technical challenges that may be present in the future.

9.0 *LEAD-FREE SOLDER SOURCES*

9.1.1 NASA Contacts

A listing of points of contact throughout NASA Centers that were contacted with regards to lead-free appears in Appendix C, “*NASA Centers’ Contact Lists.*”

9.1.2 Other U.S. Contacts

While we have focused much of our time on facilities within NASA, we have also made contacts within other government agencies, universities and industry that hold close ties with NASA. Among these organizations contacted, Northrop Grumman, Lockheed Martin, Boeing, Honeywell and United Space Alliance (USA) were able to identify areas of perceived risk concerning lead-free solder and were also able to establish that there is very little ongoing work within their organizations dealing with lead-free solders for aerospace electronics systems.

9.1.3 International Contacts

Contacts within the European Union have also been identified and some progress has been made identifying their knowledge of progress made in lead-free solder for Class 3 [12] electronics. Boeing's Madrid Research Facility has conducted some preliminary testing on a lead-free solder for their applications but no concrete data has been disseminated to date. Outside of these efforts, most of the research derived concerning lead-free solders outside of the US focuses on Class 1 [12] and Class 2 [12] electronics systems and may not directly relate to Class 3 [12] systems although it is certain that some useful information may be attained from these efforts.

A listing of individuals contacted for lead-free information appears in Appendix D, "*Subject Matter Experts*"

10.0 *RECOMMENDATIONS FOR FUTURE WORK*

The following are recommendations for follow-on tasks by NEPP:

1. Evaluation of lead-free electronics used in specific hardware configurations.
Data currently being generated from the JCAA/JGPP lead-free solder project indicates that component location contributes to reliability results. Before implementing lead-free solder in space applications, testing will need to be conducted on specific circuit board configurations and hardware to ensure that lead-free electronics in specific space hardware configurations meets reliability requirements.

2. Evaluation of lead-free electronics used in space exploration missions.
Hardware used in space exploration missions can experience temperature extremes, -230^{o}C to +200^{o}C. Evaluation of lead-free electronics currently being conducted focus on a standard set of temperature ranges, -20^{o}C to + 80^{o}C, -55^{o}C to +125^{o}C, -40^{o}C to +125^{o}C and -40^{o}C to + 150^{o}C, none of which approaches the expected operating temperatures of space exploration issues. The effects of cosmic radiation on the reliability of lead-free electronics will also need to be evaluated for space exploration hardware. Testing of lead-free electronics used in space exploration hardware will need to be conducted in a simulated deep space environment in order to truly understand the reliability of lead-free electronics.

3. Evaluation of material compatibility for lead-free assemblies.
There are many remaining data gaps concerning lead-free electronics with regards to compatibly of surface finish, component finish and solder alloy. To ensure optimum reliability of lead-free electronics used in space applications, reliability data must be collected and analyzed for all combinations of surface finish, component finish and solder alloy that could be configured on space hardware.

4. Evaluation of lead-free wave solder assembly.
Current reliability testing indicates that more information is required for lead-free through-hole component assembly and rework as well as affects of lead-free wave solder assembly processes on surface mount components. Further evaluation of test boards containing surface mount components and plated through-hole components is needed in-order to fully under the reliability of lead-free plated through-hole solder joints and the effects of lead-free wave solder processing on surface mount components.

5. Evaluation of the effects of lead-free solder processing on circuit board materials.
More information is required with regards to lead-free solder assembly on alternative board materials in high reliability electronics assemblies. Additional data in needed to understand the effects that lead-free surface mount and plated thru hole soldering processes have on printed wiring board material characteristics/properties and board fabrication structures such as trace size, plated thru holes, surface mount pads, conductive anodic filament (CAF) formation, high density structures blind vias and/or buried vias. Test boards containing various surface mount and plated through-hole components assembled on boards comprised of alternative materials is required.

11.0 *REFERENCES*

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12.0 *APPENDICIES*

Appendices for this document have been consolidated into a signal document "*NASA Lead-Free Solder BOK Appendices May 2005*". The following is the table of contents from the "*NASA Lead-Free Solder BOK Appendices May 2005*".