# Pb-Free Microelectronics Assembly in Aerospace Applications

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*Abstract*—The commercial microelectronics industry is rapidly implementing Pb-free assembly strategies and it should be mostly Pb-Free within the next decade. This trend is driven by existing and proposed legislation in Europe and in Japan, which has already lead a number of firms (including AT&T, IBM, Motorola, HP and Intel) to adopt Pb-free implementation programs. This is another sign that the microelectronics industry has become truly global.

Following Moore's law, progress in microelectronics is brisk but not uniform: in many cases, commercial industry is ahead of the aerospace sector in technology. Progress by commercial industry, along with cost, drives the use of Commercial Off-The-Shelf (COTS) parts for military and space applications. We can thus anticipate that the aerospace industry will, at some point, be forced to use Pb-free components and subsystems as part of their standard business practices.

In this paper we provide a snapshot of the commercial industry trends and how they may impact electronics in the aerospace environment. Impacts will be felt in the areas of: reliability, assembly methods, cost drivers, supply chain selection and alternate materials selection.

In addition, we look at different strategies for implementation. We address a number of questions: Should companies immediately embark on a program to convert all of their electronics to Pb-free? Should they phase it in instead and if so, over what time frame? Should companies try to comply with industry Pb-free standards? What requirements should flow down to subcontractors and component suppliers? Legislation is pending in a number of states that may affect these decisions and their timing. The EPA, through some university programs, is examining the implementation of Pb-free as well.

Finally we present data from a portion of a recent NASA project that focuses on finding suitable alternatives to eutectic Sn-Pb solders and solder pastes and on determining suitable processing operations in assembling printed wiring boards.

The world is moving toward implementation of environmentally friendly manufacturing techniques. The aerospace industry will be forced to deal with issues related to Pb-free assembly, either because of the progressive scarcity of eutectic Sn-Pb solder or because of legislation. This paper provides insights into some of the key tradeoffs that should be considered.

# 1. Background

It is now widely recognized that lead is a highly toxic substance. Exposure to lead is known to cause neurological, reproductive, renal, and hematological disorders [1]. Children are especially at risk, as early high blood lead levels can adversely affect their development. Therefore, lead is no longer used as an additive in gasoline or in paint sold in the United States. In addition, an effort was made to implement comprehensive lead battery recycling programs [2]. Most recently, cathode ray tubes (CRTs) have been categorized as universal waste because of their lead content, and they can no longer be disposed of in California landfills [3]. These changes were brought about by government regulations, which have allowed a progressive phase out or a thorough recycling of lead in various sectors.

However, international endorsement of these regulations is spotty at best [4, 5]. For instance, leaded gasoline is still used in a considerable number of countries despite the well-documented adverse effects of lead. There is a clear correlation between the continued use of lead in gasoline and the internalized concentration of lead in humans at levels that have been shown to produce cognitive impairment and other symptoms of ill health in many countries [6]. Similarly, regulatory strategies for recycling lead batteries vary across state and national boundaries [7]. This has caused a number of developing countries to become the recipients of hazardous wastes in general and lead-containing wastes in particular. With increasing globalization and free trade agreements, poorly conceived environmental protection initiatives tend to leave loopholes that defeat the purpose of regulation or to erode the incentives to corporations for participation in voluntary environmental initiatives.

In this paper, we focus on the potential discontinued use of lead as a solder material used in electronic devices. Electronic devices such as computers, printers, cell phones, PDAs, and fax machines, as well as large electrical appliances such as televisions, VCRs, refrigerators and dishwashers all contain Sn-Pb solders that are used primarily for interconnecting and packaging electronic components and assemblies, such as on printed circuit (or wiring) boards. In the United States alone, approximately 10,900 tons of refined lead was used for soldering in 1998 [8]. This solder is metallic and typically has a composition of 37 wt% Pb – 63 wt% Sn, and a melting point of 183 °C.

With the decreasing lifespan and increased use of both consumer electronics and large appliances, there has been a substantial growth in lead containing waste electrical and electronic equipment ("WEEE" or "e-waste"). In 1998, e-waste represented over 6 million tons of waste or approximately 4% of the municipal waste stream. This volume is expected to increase by 3% to 5% annually, so it could thus double in the next 12 to 15 years [9]. This implies that the amount of lead contained in municipal waste will increase.

The rest of this paper is organized as follows. In the next section, we analyze current industry trends. Section 3 considers various strategies for implementing Pb-free electronics and their implications for aerospace applications. Section 4 gives an overview of a current JPL/NASA example of implementation. Section 5 concludes.

## 2. Commercial Industry Trends

*Materials Selection*

Because of international legislative pressure, alternative alloys to tin-lead are being considered. Favorite alloy systems contain tin (Sn), silver (Ag), bismuth (Bi), copper (Cu), indium (In), antimony (Sb), zinc (Zn), gold (Au) and/or germanium (Ge). Various studies have shown that some of these alternatives also pose environmental and/or public health concerns, especially if the entire life cycle is considered [10-14]. A complete life cycle analysis of lead-based and Pb-free solders is presently underway at University of Tennessee in conjunction with the U.S. EPA [25].

*Desired Attributes* — The specific attributes for manufacturing with alternative alloys to the standard eutectic Sn63-Pb37 most commonly found in industry can be defined in light of several specific soldering processes. The three primary forms of solder found in standard industrial processes are: 1) wire solder, used for hand soldering, 2) bulk molten solder used in wave soldering processes or solder pots; and 3) solder pastes used for surface mount assemblies usually used with infra-red (IR), convection or vapor phase reflow.

The attributes for an alternative alloy should ideally be amenable to all three assembly processes. These attributes include: a melting point close to 183°C, a narrow plastic range, adequate wetting, adequate mechanical and physical characteristics, compatibility with existing fluxes, no toxicity and low dross formation [16].

*Alloy Alternatives* —Current Pb-free alloys being considered by the industry are shown in Table I below.

Table I. Current Pb-Free Alloy Alternatives.

| Alloy | Melting Point |
|---|---|
| SnZn | 199°C |
| SnBiAg | 210°C |
| SnBiAgCu | 210°C |
| SnAgCu | 217°C |
| SnInBiAg | 179-210°C |
| SnAgCuSb | 210-217°C |
| SnInAg | 175-227°C |
| SnAg | 221°C |
| SnCu | 229°C |

Of the candidates listed above, two alloy ranges appear to be preferred to the rest [16]: SnBiAg and SnAgCu. For a number of reasons discussed below, the SnAgCu alloys appear to be the solder of choice for most applications.

Alloy costs and availability also play a role in the selection of alternative alloys. Costs for metals like In or Ag are significantly (two orders of magnitude) higher than the other alternative metals in Table I [13]. As a result, these metals are unlikely candidates or must be used in a very small percentage in the alloy.

*Bi Alloys* — SnAgBi alloys have the distinct advantage of having both a reasonably good melting point (210°C) and very good wetting characteristics. Two difficulties associated with bismuth are that it forms a low melting (96°C) SnPbBi eutectic if lead is present [13] and it creates undesirable stresses during its phase transformation on particular types of solder joint configuration which can fail almost instantly. The ternary eutectic formation is problematic because most available components still have thin layers of SnPb compounds to facilitate assembly in existing manufacturing processes. Because the component market is global, there are very large inventories. Moreover, as there are thousands of suppliers involved, it will take some time before all remnants of lead are gone from the system. Until then, there is a significant danger, with bismuth compounds, of forming alloys that will melt under normal use. In addition, nearly all bismuth is found with lead, so problems linked to its extraction are similar to those of Pb. Finally, there is little data on the toxicity of bismuth metal, which could turn out to be problematic.

*SnAgCu Alloys* — A number of ternary SnAgCu compounds, very near the eutectic at about 95%Sn, 3.5%Ag and 1.5%Cu, are commercially available. Figure 1 shows this region of the SnAgCu phase diagram [17]. The precise eutectic composition has been patented, so many companies are using alloys that are near the eutectic composition. This off-eutectic approach is of little consequence because diffusion of the metals used on the boards or components during processing will tend to make the alloy off-eutectic anyhow. The primary difficulty of the SnAgCu system is its high melting point at 217°C, which makes processing difficult.

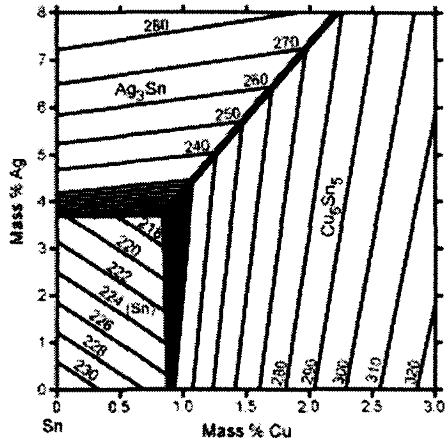


Figure 1. The primary Pb-free alternative, SnAgCu, Sn-rich portion of the ternary phase diagram [17].

*Pb- Free Paste Attributes and Development*

Solder pastes consist of four constituents. The predominant constituent is the alloy itself, generally small spheres of metal, which represent 85-90% of the composition by weight. The other constituents are the flux, used for oxide scavenging and surface energy reduction (wetting), a rheology agent, used for making the paste flow during the screen-printing process, and a solvent. The main attributes determining the success of paste formulation are flux compatibility and wetting to a variety of metallizations. Issues encountered during the development of Pb-free pastes also include compatibility with screen-printing processes, shelf-life, working-life, and segregation [16]. These processes have been resolved to differing degrees by different vendors and SnAgCu pastes are currently being used in commercial production.

*Assembly Methods*

The most noticeable impact of the alternative alloys selected is on the assembly processes. The main alternative alloys being considered all require higher processing temperatures. Typical process temperatures are about 20-35°C higher than the melting point of the alloy and some of the polymeric materials used for components, staking, and boards can sustain damage by going above their $T_g$ (glass transition temperature). The issue can be addressed by using slightly more expensive components and materials. The impact on the equipment used for assembly will probably be minimal as most of it can be run 20-35°C higher. Most assembly methods should not differ much from those for standard SnPb eutectic solders. The processes do affect the diffusion of the substrate and component metallizations into the solder alloy, which will have an impact on its properties. Characterization of processes and new process controls will need to be established to limit the formation of generally unfavorable intermetallic structures.

*Reliability*

Reliability will probably be the most significant factor for the aerospace industry. There are a number of implications with both the selection of a new alloy and the higher processing temperatures involved. The new alloys have not been thoroughly characterized, particularly for military and space environments. Substantial work has been performed by companies for commercial environments, but little has been done for the extreme conditions encountered in military and space applications. Very little long-term reliability data exist for military and space environments. The physical characteristics of the material, particularly fatigue properties, will be different from standard SnPb eutectic. Some of the implications follow.

The interaction of the new alloy with the substrate and component metallizations plays a significant role. This is particularly important because of the intermetallic structures formed by solders and Au, Ni and Cu bonding interfaces. The differing amounts of interface metallizations will diffuse differently forming different intermetallics, all of which will need reliability testing.

The components used in assemblies have not been reliability tested for processing at the higher temperature ranges. The current lifetime data does not take into account the resulting additional stress. Residual stresses on the components themselves could be a problem, as well as the additional stresses related to the cooling of the components at the end of their processing. The components may also have internal characteristics that are not designed to withstand higher processing temperatures.

An additional reliability risk is the residual degradation of materials, such as polymers or magnetic materials used in the circuit assembly. The reliability of these materials again has not been characterized at higher processing temperatures.

The formation of tin-whiskers is another concern that has been around for quite some time [18]. It is one of the manifestation of metal migration in the presence of an electrical or mechanical strain field, which is a mode of failure common to solder joints of various kinds. The SnAgCu alloy being considered is primarily tin, and to some extent it behaves like tin with some impurities. The mechanisms of tin whisker growth have been examined in detail [19]. Tin whisker growth relating to the surface finish of Pb-free components is one area of concern where substantial studies are presently underway at NASA [20-22].

Finally, in addition to the reliability risks mentioned above, there is another risk due to the interaction of the effects of the new risks. For example, the fatigue characteristics of the new alloy may be acceptable and the underfill epoxy characteristics for a ball grid array (BGA) may be acceptable individually, but the combined characteristic of the new alloy with the underfill epoxy may not be sufficiently reliable. All of these factors need to be considered and tested before implementation into the military and space environment.

*Cost Drivers*

The cost drivers for military/space and commercial applications are likely to be substantially different because of the volume of parts manufactured. The cost drivers fall into three categories: 1) initial development costs, 2) production operating costs, and 3) reliability and qualification costs.

The initial development costs should be similar for military/space and commercial applications. The drivers for commercial operations will be in the increased energy consumption during the production phase. Commercial entities are concerned with costs of a fraction of a cent per device. The more important cost to the military/space side will be reliability testing and qualification for several reasons. First, the number of parts over which the cost of testing is amortized will be substantially smaller (tens as opposed to tens of millions). Second, the cost of space qualification of a product and process is typically very high because of the additional rigor of tests and the significant documentation involved.

*Supply Chain*

The supply chain is also critical. If the supply chain members are shared with commercial industry, which may happen in the future, they may already have gone to Pb-free materials and processes. In this case, the standard materials and coatings used for lead based assembly may no longer be available. Also, if the assembly operation is going Pb-free, the supply chain must have its materials and processes developed and qualified to be compatible with the ultimate Pb-free assembly operation.

In order to address this particular issue, several companies, such as HP, have comprehensive supplier management programs. HP's approach involves expectations for their supply chain partners regarding planning, cost impact notification, reliability impact information, labeling, and design rules for manufacturability and testing. HP is currently on schedule to ship Pb-free components in volume by June 2004. Schedule elements include collection of supplier plans, integration of plans with current and expected legislation, a schedule rollout and supplier requirements, and Pb-free qualification [23].

*Industry Activity*

The U.S. electronics industry has a great deal at stake if it does not comply with the need to eliminate lead-based solder from its exports. California, with a high technology job base of over 900,000 people, hosts the largest proportion of industries responsible for manufacturing lead-containing electronics products in the United States. California alone exported $67.5B in high tech goods in 1999, which represented over 56% of California's total exports [24]. Thus, from the perspective of trade and economic strength, it is imperative that alternatives to lead-based solder be identified and used. However, from the perspective of disposal and occupational health, it is not clear that currently available alternatives are better for the environment, because they also rely on heavy metals that can impact human health [13,14,25].

The industry has put significant work into the implementation of Pb-free solder. To date, the most comprehensive investigation of Pb-free solders has been conducted by the National Center for Manufacturing Science (NCMS) [26]. The $10.5 million NCMS project was a collaborative effort of 11 public and private institutions including AT&T/Lucent Technologies, the U.S. Navy, GM-Delco Electronics, Ford Motor Company, GM-Hughes Aircraft, the National Institute of Standards and Technology, Rensselaer Polytechnic Institute, Rockwell International, Raytheon, Hamilton Standard Division of United Technologies Corp., and the U.S. Department of Defense. The focus of this study was to evaluate a set of more than 70 candidate alloys that are potential substitutes for Sn-Pb solder for safety, reliability, non-toxicity, and cost-effectiveness. Other institutional coalitions that have investigated the potential of Pb-free solders in the electronics industry include the National Electronics Manufacturing Initiative (NEMI), the Center for Advanced Vehicle Electronics, and the C.A.S.H. Project (ChipPac, Alpha Metals, Sanmina, and Hewlett-Packard). The conclusion of nearly all of these studies was to proceed with implementation of an ally near the eutectic SnAgCu composition [27-29]. These corporate research coalitions have been sustained by the common product design goal of finding alternatives to Pb-free solder in response to external legislative and market forces from abroad.

*Industry Implementation Strategies*

Companies can adopt a variety of strategies including (1) immediate implementation, (2) a phase–in approach or (3) no implementation at all (wait and see). If larger companies like HP or IBM do initiate implementation and if their supplier chains follow, the impact on the above strategies could be significant. The do-nothing approach may present a higher risk if the supplier chain starts to phase in a Pb-free system. The U.S. can no longer ignore all of the Pb-free activity around the globe. The companies that are prepared and already have programs in place will suffer the least and are likely to end up with a competitive advantage.

Hewlett-Packard (HP), for example, adopted the phase-in approach. HP has an active program looking at alternatives to lead in its electronic assemblies in anticipation of legal and regulatory developments. HP has taken an industry standardization approach involving its supply chain, contract manufacturers, original equipment manufacturers, and consortia. HP's goal is to develop and demonstrate reliable environmentally responsible alternatives. HP is considering cost, availability, regulation and credible scientific evidence of improved environmental performance compared to tin-lead. HP is working with industry and the scientific community to investigate the environmental characteristics of Pb-alternatives [23].

Many other companies have also adopted a phase-in approach. A number of Japanese companies have already implemented Pb-free programs and turned the environmental friendliness of their products into a marketing advantage. By the end of 2001, Hitachi was Pb-free, Matsushita had all of their consumer products converted to Pb-free, and Sony had lead eliminated from all but their high-density products. By the end of 2002, Toshiba was planning to have Pb-free mobile phones, NEC was planning to make Pb-free motherboards, and Fujitsu was trying to phase out all lead [16]. European companies such as Nokia and Thompson, and American companies such as Motorola and Intel are following suit.

If this trend continues, military and space companies will have difficulty procuring devices that are suitable for lead bearing systems and will eventually be forced to go along.

## 3. An Aerospace Implementation Example

About two years ago, NASA funded a project to begin searching for suitable Pb-free solder candidates under the aegis of the NASA Electronic Parts and Packaging (NEPP) program.

The objective of this NEPP task is to investigate the reliability of lead-free solder alloys in space applications. One goal is to study the compatibility of lead-free solder alloys with the comparable surface finishes of surface mount components including chip capacitors, chip resistors, and advanced packages such as ball grid array (BGA), flip chip or chip scale packages for the NASA applications. A reliability database is being developed. Another goal is to obtain the mechanical material properties of lead-free solder alloys to understand the behavior of solder joints and the role of composition on reliability. The project is divided into two phases, an evaluation of four alloys and a further evaluation of two down-selected alloys.

*Evaluation of Pb-Free Alloys Phase I*

The first phase of this JPL project deals with determining the most feasible candidates to replace eutectic tin-lead and suitable processing operations in assembling printed wiring boards. Four (4) lead-free solder pastes were selected based on an extensive search of the literature (see Table II ) .

Two printed wire boards (PWBs) per solder type were assembled using the four different solder pastes resulting in total of eight assemblies. See Figure 2, which shows a bottom and top view respectively of the test PWB.

Table II: Pb-free Solder Alloys for Test.

| Composition | $T_m^*$ (°C) | Advantages | Potential Issues |
|---|---|---|---|
| 1) Sn96.5Ag3.5 (eutectic) | 221 | a) Good wetting characteristics and superior joint strength compared to Sn/Pb solder<br>b)Long history of use | a) May exhibit structural weakness at solder connection<br>b) High $T_m$ |
| 2) Sn95.5Ag3.8Cu0.7 | 217-218 | a) Recommended by NEMI<br>b) Virtually no plastic range<br>c) Rapid solidification avoiding formation of cracks<br>d) Formation of intermetallics $Cu6Sn_5$ and $Ag_3$ Sn provide greater strength and fatigue resistance than Sn/Pb solder | a) High $T_m$ |
| 3) Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | 217-218 | a) Addition of Sb improves thermal fatigue<br>b) Solder coating offers flatter pads and uniform coat<br>c) Works well with Ni/Au Ag/Pd and OSP boards<br>d) Sb slightly reduces melting temperature and refines grain structure | a) Sb trioxide may exhibit toxicity at higher temperatures<br>b) High $T_m$ |
| 4) Sn77.2In20.0Ag2.8 (Indalloy 227®) | 175 ($T_S^*$) –187 ($T_L^*$) | a) Compatible $T_m$ to Sn/Pb<br>b) Good ductility, strength and creep resistance<br>c) Low dross in wave solder | a) Supply and cost may be prohibitive factors in its use.<br>b) 118°C eutectic point may deteriorate mechanical properties of solder joint<br>c) Large plastic range |

* Note that $T_m$ ,$T_S$ and $T_L$ are the melting point, the solidus and the liquidus temperatures respectively

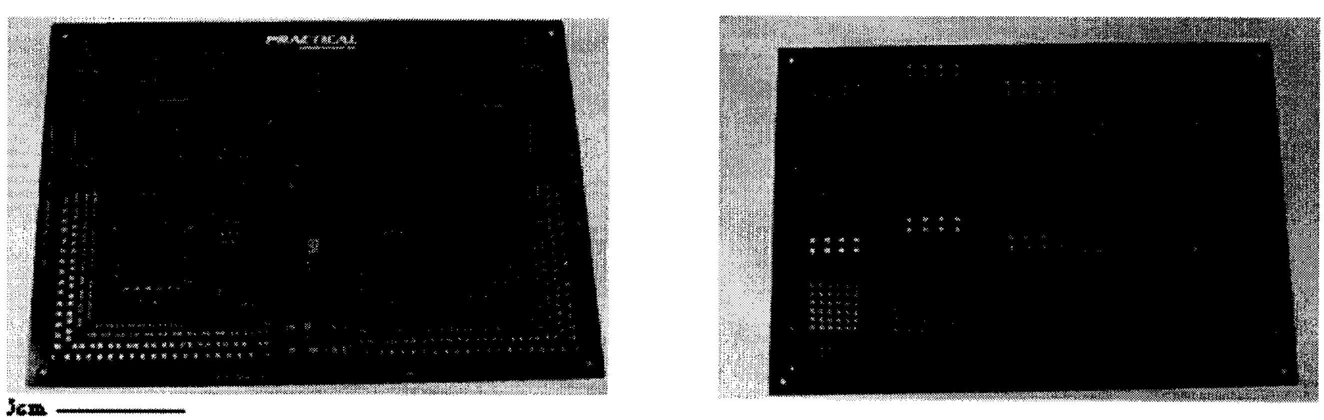


Figure 2. Bottom and top view respectively of the test PWB

*Pertinent Process Information* —The following JPL process information is pertinent to the discussion:

Rosin-based fluxes and pastes were used to produce all electronic hardware. Using the terminology of Mil-F-14256, the classification of these products is rosin mildly activated (RMA).

The solder paste was applied using a semi-automated screen printer ensuring that the paste was deposited in a uniform and consistent manner. Only stainless steel stencils were used in conjunction with a stainless steel squeegee. All boards were visually inspected for proper paste deposition after the stencil operation.

A laser-based solder paste height and width measurement system was used with a resolution of 2.5 µm (0.0001 inch). This system provides real time information on the uniformity of solder paste deposition. All boards were subjected to this measurement prior to the reflow operation. A batch vapor phase reflow operation was employed to create the solder joints of the surface mount technology printed wire assemblies (SMT PWAs). The SMT PWAs were thermally profiled. A thermocouple was then attached to the PWB and to a microprocessor-based data logger connected to a computer. Thermal profiling is done to eliminate thermal shock during preheat and reflow. The reflow operation consisted of a vapor phase reflow machine using a constant boiling perfluorocarbon material (Galden® from Ausimont Corp. or 3M perfluorocompound FC-5312®) PWAs.

The PWAs were preheated to remove paste volatiles and to initiate the activation stage of the paste. The reflow liquid, which boils at a constant temperature, minimizes the possibility of overheating the PWAs during reflow and ensures that the vapor blanket performs a uniform and consistent soldering operation. For eutectic Sn-Pb and Sn77.2In20.0Ag2.8 , a perfluorocompound with a boiling point of 216°C was used.

*Assembly Process*

Double-sided test PWBs with footprints for various chip components and integrated circuit (IC) packages, including BGAs, were assembled. The BGAs were then daisy-chained. Various mechanical packages were subsequently selected for the test and acquired. Component package types used were as follows.

Chip resistor, 0603 package (24 each per board)
Chip resistor, 1206 package (18 each per board)
SOT 23 package (2 each per board)
SOIC20 package, 50 mil pitch part (2 each per board)
PLCC68 package, 50 mil pitch part (1 each per board)
QFP100, 25 mil pitch part (1 each per board)
QFP208 package, 20 mil pitch part (1 each per board)

BGA225 full array package, 1.5 mm ball pitch (1 each per board)
BGA352 area array package, 1.27 mm ball pitch (1 each per board)

*Assembly Conditions*

*Pre-assembly Inspection and Test* — Prior to assembly, all the BGA pads on the PWBs and all BGA components were checked to ensure the daisy-chain integrity. All eight PWBs and one sample of each component were tested with scanning acoustic microscope (SAM) to obtain a signature prior to assembly.

*PWB and Component Preparation* — All PWBs are cleaned in an Accel centrifugal cleaner using Vigon® A200 chemistry available from Zestron Corp. Viagon chemistry consists of a 20% solution of a blend of alcoxypropanols and amine compounds in d- ionized (DI) water with 1% corrosion inhibitor and 0.1% defoamer. The cleaning cycle and its parameters were

- Purge the wash chamber with nitrogen gas for one minute
- Wash cycle of 5 minutes duration using the alcoxypropanols and amine compounds solution heated to 50°C
- Rinse cycle of 10 minutes duration using DI water heated to 50°C
- Dry cycle of 5 minutes duration using air heated to 180°C
- Vacuum oven bake cycle for 8 hours at 100°C

Except for the BGAs, the leads of the components used were tinned with Sn/Ag bar solder.

*Screen printing* — PWBs were screen printed with four different pastes, as shown in Table III.

Table III: Four Pb-free Solder Pastes Used.

| Item | Paste Type | PWB Serial Number |
|---|---|---|
| 1 | Sn95.5Ag3.8Cu0.7 | PWB S/N 001 and 002 |
| 2 | Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | PWB S/N 003 and 004 |
| 3 | Sn96.5Ag3.5 (eutectic) | PWB S/N 005 and 006 |
| 4 | Sn77.2In20.0Ag2.8 (Indalloy 227®) | PWB S/N 007 and 008 |

Here are also the printing parameters:
Stencil Type— Stainless steel with foil thickness of 7 mils;
Squeegee Type —Metal Blade;
Squeegee pressure setting — 5.6 kg;
Squeegee speed — 15 mm per second.

Paste height is measured using 3-D laser based measurement system.

*Component Placement* — Components were then placed on side 1 using automated placement machine. A split vision rework system was used for component placement on side 2.

*Solder Paste Reflow* — Two types of vapor phase reflow systems were employed to reflow the solder pastes. Both consist of an infrared preheating zone followed by a constant temperature boiling vapor zone.

Pastes 1, 2 and 3 (listed in Table II) were reflowed using a bench top vapor phase system containing the perfluorocarbon material with a boiling point of 240°C. Paste 4 was reflowed using a stand-alone system containing the perfluorocarbon material with boiling point of 216°C.

A thermal profile was generated for each system. The assembly is preheated to approximately 158°C at the rate of 0.88°C/second followed by vapor phase reflow. The dwell time above liquidus is 62 seconds.

*Post Reflow Cleaning* — All PWAs are cleaned in the centrifugal cleaning system using the cleaning cycle.

*Cleanliness Test* — All PWAs were tested for ionic level using an Ionograph 500® tester. The cleanliness levels recorded by the Ionograph were summarized in Table IV.

Table IV: Ionic Contamination Levels.

| **PWA S/N** | **Solder Paste Type** | **Ionics- mg/cm$^2$** |
|---|---|---|
| S/N 001 | Sn95.5Ag3.8Cu0.7 | 0.050 |
| S/N 002 | Sn95.5Ag3.8Cu0.7 | 0.051 |
| S/N 003 | Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | 0.0077 |
| S/N 004 | Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | 0.0077 |
| S/N 005 | Sn96.5Ag3.5 (eutectic) | 0.093 |
| S/N 006 | Sn96.5Ag3.5 (eutectic) | 0.029 |
| S/N 007 | Sn77.2In20.0Ag2.8 (Indalloy 227®) | 0.26 |
| S/N 008 | Sn77.2In20.0Ag2.8 (Indalloy 227®) | 0.20 |

All PWAs were baked in a vacuum oven at 70°C for 30 minutes.

*Visual Inspection, Scanning Acoustic Microscopy and X-Ray* — All PWAs were inspected under a microscope at 12 X magnification. The solder flow generally appeared to be good except that the solder appeared grainier compared to Sn/Pb solder joints. The solder joints containing indium were even more grainy than the other three types of joints.

Scanning acoustic microscopy analysis performed on test boards and components was used for ascertaining if damage occurs to boards during processing. The boards themselves processed satisfactorily at the higher temperatures. However, some of the plastic BGAs had experienced delamination, indicating the necessity of baking them prior to reflow.

*Environmental Testing* — Twelve additional PWB's were assembled and thermal cycled. Four PWB's were assembled with Sn95.5Ag3.8Cu0.7 and four with Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®). An additional four were made from SnPb eutectic. The assemblies were thermal cycled from -55°C to +125°C for 100 cycles. All assemblies passed continuity testing.

*Evaluation of Pb-Free Alloys Phase II*

During the second phase, twelve of the same test PWB as used in Phase I (Figure 2) were utilized. The second phase of this project down-selected to two (2) of the pastes from the list above:

(2) Sn95.5Ag3.8Cu0.7 (near eutectic $T_m$ 217-218°C);
(3) Sn96.2Ag2.5Cu0.8Sb0.5 (near eutectic $T_m$ 217-218°C).

These two solder alloys were preferred to (1) and (4) because they are more suitable for reflow operations. The indium containing paste was considered undesirable for two reasons. First, it has a wide pasty region, which is not particularly good during reflow. Second, indium is a very scarce element

Four (4) PWAs per paste were assembled along with using eutectic Sn/Pb (Sn63Pb37—183°C $T_m$) as a control, giving a total of twelve PWAs. These assemblies were then subjected to thermal cycling between –55°C to 125°C for 100 cycles. The set of lead-free PWAs described above were subjected to the aforementioned thermal cycling. After 100 cycles, the PWAs were taken out of the thermal chamber and observed both visually and under 30x magnification.

*Conclusions for the JPL/NASA Assembly*

- No problem was encountered during the printing process with Pb-free paste. The printing was uniform for all PWBs.
- A longer delay was required for the first three pastes during the reflow process. This was due to the higher melting temperature of the solders.
- Although the solder fillets appeared to be generally good, the solder joint appeared grainier than those formed by Sn63/Pb37 solder.
- Sn95.5Ag3.8Cu0.7 and Sn96.2Ag2.5Cu0.8Sb0.5 passed 100 cycles from-55°C to +125°C with no signs of cracking observed.

## 4. CONCLUSIONS

Legislation and policy decisions are currently driving the global commercial electronics industry to Pb-free processes. Many commercial companies are already implementing Pb-free strategies for their products. With pressure for military and space programs to use commercial-off-the-shelf parts, there will be strong motivation for them to also go Pb-free.

The replacement alloy has been selected by commercial industry and preliminary testing looks promising but complete reliability testing and space qualification still need to be performed. A number of strategies can be used, including immediate implementation, phase-in and no implementation. Commercial industry has a large number of examples to follow.

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Tables and Figures

Tables Table I. Current Pb-Free Alloy Alternatives.

| Alloy | Melting Point |
|---|---|
| SnZn | 199°C |
| SnBiAg | 210°C |
| SnBiAgCu | 210°C |
| SnAgCu | 217°C |
| SnInBiAg | 179-210°C |
| SnAgCuSb | 210-217°C |
| SnInAg | 175-227°C |
| SnAg | 221°C |
| SnCu | 229°C |

Table II: Pb-free Solder Alloys for Test.

| Composition | $T_m^*$ (°C) | Advantages | Potential Issues |
|---|---|---|---|
| 1) Sn96.5Ag3.5 (eutectic) | 221 | a) Good wetting characteristics and superior joint strength compared to Sn/Pb solder<br>b)Long history of use | a) May exhibit structural weakness at solder connection<br>b) High $T_m$ |
| 2) Sn95.5Ag3.8Cu0.7 | 217-218 | a) Recommended by NEMI | a) High $T_m$ |

| | | | |
|---|---|---|---|
| | | b) Virtually no plastic range<br>c) Rapid solidification avoiding formation of cracks<br>d) Formation of intermetallics $Cu6Sn_5$ and $Ag_3$ Sn provide greater strength and fatigue resistance than Sn/Pb solder | |
| 3) Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | 217-218 | a) Addition of Sb improves thermal fatigue<br>b) Solder coating offers flatter pads and uniform coat<br>c) Works well with Ni/Au Ag/Pd and OSP boards<br>d) Sb slightly reduces melting temperature and refines grain structure | a) Sb trioxide may exhibit toxicity at higher temperatures<br>b) High $T_m$ |
| 4) Sn77.2In20.0Ag2.8 (Indalloy 227®) | 175 ($T_S^*$) –187 ($T_L^*$) | a) Compatible $T_m$ to Sn/Pb<br>b) Good ductility, strength and creep resistance<br>c) Low dross in wave solder | a) Supply and cost may be prohibitive factors in its use.<br>b) 118°C eutectic point may deteriorate mechanical properties of solder joint<br>c) Large plastic range |

* Note that $T_m$ ,$T_S$ and $T_L$ are the melting point, the solidus and the liquidus temperatures respectively

Table III: Four Pb-free Solder Pastes Used.

| Item | Paste Type | PWB Serial Number |
|---|---|---|
| 1 | Sn95.5Ag3.8Cu0.7 | PWB S/N 001 and 002 |
| 2 | Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | PWB S/N 003 and 004 |
| 3 | Sn96.5Ag3.5 (eutectic) | PWB S/N 005 and 006 |
| 4 | Sn77.2In20.0Ag2.8 (Indalloy 227®) | PWB S/N 007 and 008 |

Table IV: Ionic Contamination Levels.

| PWA S/N | Solder Paste Type | Ionics- $mg/cm^2$ |
|---|---|---|
| S/N 001 | Sn95.5Ag3.8Cu0.7 | 0.050 |
| S/N 002 | Sn95.5Ag3.8Cu0.7 | 0.051 |

| | | |
|---|---|---|
| S/N 003 | Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | 0.0077 |
| S/N 004 | Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®) | 0.0077 |
| S/N 005 | Sn96.5Ag3.5 (eutectic) | 0.093 |
| S/N 006 | Sn96.5Ag3.5 (eutectic) | 0.029 |
| S/N 007 | Sn77.2In20.0Ag2.8 (Indalloy 227®) | 0.26 |
| S/N 008 | Sn77.2In20.0Ag2.8 (Indalloy 227®) | 0.20 |

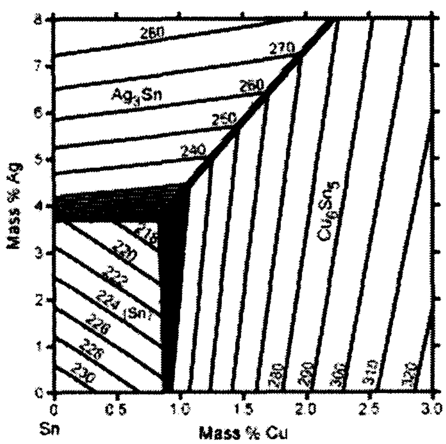


Figure 3. The primary Pb-free alternative, SnAgCu, Sn-rich portion of the ternary phase diagram [30].

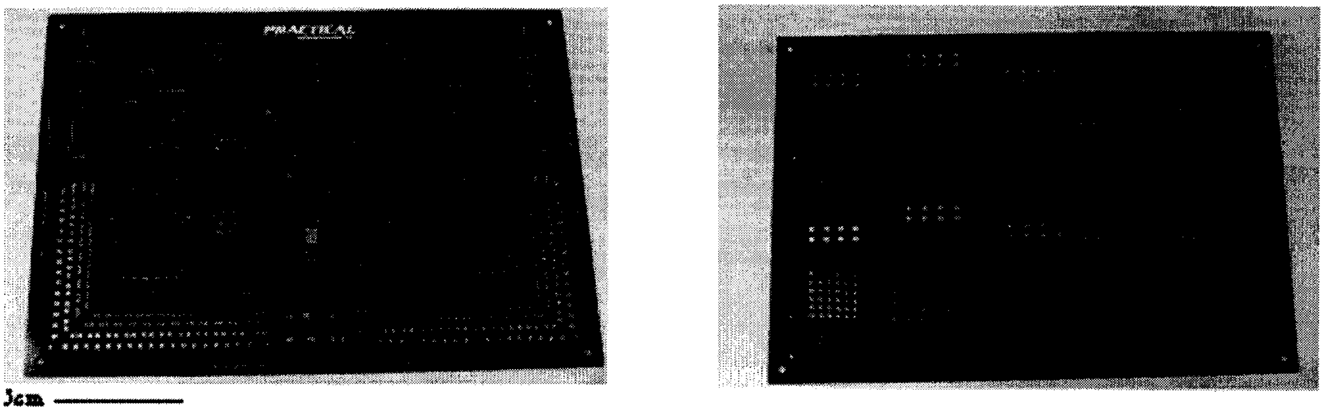


Figure 4. Bottom and top view respectively of the test PWB