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Implications of 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 led a number of firms (including AT&T, IBM, Motorola, Hewlett-Packard, 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 parts for military and space applications. We can thus anticipate that the U.S. aerospace industry, which is not subject to foreign legislation, 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 alternative materials selection. In addition, we look at different strategies for implementation. The questions we address include the following: 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 U.S. Environmental Protection Agency, through some university programs, is exam-

ining 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.

Index Terms—Aerospace industry, assembly, environmental testing, lead alloys, pollution, soldering, tin alloys.

I. 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, 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 many 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 contain loopholes that defeat the purpose of regulation or erode corporations' incentives to participate in voluntary environmental initiatives.

In this paper, we focus on the potential discontinued use of lead as a solder material in electronics. Electronic devices such as computers, printers, cell phones, PDAs, and fax machines, as well as large electrical appliances such as televisions, VCRs,

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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 likely increase.

The rest of this paper is organized as follows. In the next section, we review the status of proposed and existing lead legislation in various countries, with a particular focus on the European Union (EU), Japan, and various U.S. states. In Section III, we analyze current industry trends and consider various strategies for implementing Pb-free electronics and their implications for aerospace applications. Section IV gives an overview of a current Jet Propulsion Laboratory (JPL)/NASA example of a reliability study. Section V concludes.

II. CURRENT POLICY STATUS

Several countries have enacted legislation designed to minimize the environmental risks linked to the disposal of e-waste, especially risks resulting from the toxic heavy metals contained in this waste. In Europe, Denmark was the first country to eliminate lead entirely from industrial activities. The Netherlands and Sweden followed suit with their own respective legislations. In an effort to harmonize these efforts, the EU has adopted two directives to deal with e-waste and to foster environmentally friendly manufacturing [10]; a third directive is under consideration.

Japan has also been progressive about enacting waste management and recycling legislation [11]–[13]. The combined effect of their laws is to encourage reuse and recycling of waste and to control the amount of lead released into the environment. Japanese manufacturers, who have a history of being environmentally conscious even without legislation, have converted the Pb-free initiative into a marketing opportunity, and they have already made major strides toward achieving Pb-free products. A new initiative that would phase out lead from electronic products by 2005 is under consideration [14].

As of May 2002, 11 countries already have take-back laws for electronics, requiring manufacturers to take-back their products. Within five years, we expect 28 countries to have such laws.

In the United States, electronics manufacturers are discussing a national take-back plan that includes federal legislation. If this industry-sponsored plan is not adopted, more action will be needed at the state or federal levels. Currently, 24 electronics bills are under consideration in ten states. In addition, there are 38 pending toxic metal-related restriction bills, ten of which affect electronics [15].

A. Situation in the EU

A number of different member countries of the EU have already enacted their own legislation and adopted economic measures to deal with e-waste, typically with a focus on recycling. For example, Norway has had a recycling law since 1999, and the Netherlands' law came into force in 2000. Recycling programs also exist in different German regions. For lack of space, we focus here on what was done at the EU level. Currently, each European produces on average approximately 14 kg per year of e-wastes. Currently, 90% of these wastes are landfilled or incinerated without any pretreatment [10]. It is estimated that around 40% of all lead in landfills and 50% of lead in incinerators come from e-waste.

To address the growing e-waste problem, two European directives have been ratified and a third has been proposed. These directives have been in the making at least since 1996 (see the European Parliament Resolution of Nov. 14, 1996 [A4-0364/96]). The objective of these directives is to improve the environmental performance of this sector of the economy by applying three principles: prevention, recovery, and safe disposal of waste. Moreover, producers are held responsible for any pollution resulting from their activities. Unlike the Japanese legislation, the scope of these directives covers all electronic and electrical equipment.

The first directive (the WEEE directive) focuses on recycling and on allocating responsibilities for managing e-waste. It sets a collection target of 4 kg per person per year (approximately 8.8 lb). Distributors have to accept old equipment back from consumers who are buying new products; they cannot charge consumers. Producers are responsible for the costs of processing used equipment, for recycling, and for disposal. In addition, existing producers are made responsible for the costs of dealing with the current stock of e-waste. This directive is supposed to become effective on 1 July 2006, although beginning 13 August 2005, consumers are allowed to return their WEEE to collection facilities free of charge. Member states of the EU had until 13 August 2004 to implement this directive [16].

The second directive, named “Reduction of Hazardous Substances” (RoHS), focuses on prevention and explicitly restricts the use of several hazardous substances in e-waste. It proposes to ban the use of Pb, Hg, Cd, hexavalent Cr, polybrominated biphenyls (PBBs), and polybrominated diphenol ethers (PBDEs) in EEE by 1 January 2006, but some exemptions have been granted.¹ This legislation has caught the attention of manufacturers throughout the world, as they do not wish to lose their market share in Europe.

Finally, the third directive, which is still under consideration, deals with design. Its goal is to prevent the use of materials problematic for the environment during the end-of-life phase of a product. It also addresses issues of maintenance, repair, reuse, and upgrade. To minimize environmental impacts, it tries to minimize energy use and the emission of pollutants during the useful life of a product.

¹“Medical equipment systems and monitoring and control devices, including thermostats and smoke detectors, are exempt from provisions dealing with product restrictions, including the substance bans, and collection from and education of private households” [17].

B. Situation in Japan

An increase in waste volume and the decreasing capacity of existing final disposal sites, combined with a lack of new sites, and the emergence of e-waste legislation abroad have been the main driving forces behind the adoption in Japan of new e-waste legislation. It is important to note that current Japanese legislation focuses on waste reuse and recycling and not directly with toxic substances in electronic products. The decision by Japanese manufacturers to eliminate lead from the solder they use is instead a consequence of European legislation [14].

Among the many recycling laws passed in Japan over the years, the most relevant one for e-waste is the 2001 revision of the Law for the Promotion and Effective Utilization of Resources to include PCs, copy machines, and small accessories such as mice. Manufacturers are now required to design products that promote the 3Rs—reduce, reuse, and recycle—and since October 2001, the cost of recycling must now be included in the purchase price of computers. By contrast, recycling costs range from \$25 to \$37 for computers purchased before October 2001. The Japan Post is the main collection agency for this program, so consumers can either drop off computers at post offices or arrange for pickup. In 2003, the collection of used data processing equipment (computers, printers, etc.) totaled 9280 tons (down 10% from 2002), and the recycling rate for data-collection and telecommunications equipment was 87% [18].

Another law, which took effect in April 2001, targets four types of home appliances (television sets, refrigerators, washing machines, and air conditioners), but it does not include PCs. Manufacturers and importers are responsible for recycling e-waste. Collection is done through manufacturers, but also through distributors (when a new product is purchased) and local government centers. The initial recycling target is approximately 50 to 60% by weight for the different products targeted, but this target is expected to increase over time. Recycling is not free for end users: they need to pay a recycling fee, which for TVs, refrigerators/freezers, washing machines, and air conditioning units is respectively \$22, \$37, \$22, and \$28; collection fees range from \$3 to \$24² [19]. It appears that these fees may not be sufficient to cover actual recycling and disposal costs, but more experience is needed. Because previously users did not have to pay recycling or collection fees, the number of products collected during 2001 is expected to actually decrease by 25% compared to the recycling rate before the implementation of this new law, a trend consistent with economic theory. In addition, a small increase in illegal dumping has been observed, although precise figures are not available.

The direct involvement of manufacturers in recycling in Japan and the adoption of tough new laws in the EU seem to have had positive feedbacks on designers who are progressively taking into account recycling and end of life considerations at the design stage [19].

C. Situation in the Western USA

According to the Institute for Local Self-Reliance, approximately 75% of obsolete electronics are currently being stored

until there is an agreement on how best to manage them [20]. Collection and recycling programs for e-waste have been organized in a number of states. We review here the situation in the western states. More information about the rest of the country can be found on the Web page of the National Recycling Coalition [21].

Arizona—The Arizona Department of Environmental Quality started funding the City of Phoenix Appliance/Electronics Collection and Recycling Program in 2001. Initial funding was used for purchasing two vehicles and some equipment for the collection of appliances, including computers and monitors but not televisions. It costs \$10 per visit to have a truck pick up old appliances, which are then taken to a recycling facility (after refrigerants are removed, if necessary). During the first ten months of the program (July 2001 to May 2002) approximately 350 tons of appliances were collected.

California—California has recently realized the magnitude of the e-waste problem. According to San Francisco Supervisor S. Maxwell, there are approximately 1.2 million computers and TVs stockpiled in people's homes in the nine Bay Area counties, and about three-quarters of a million more units are projected to become obsolete each year [22]. Because of concerns about lead in CRTs, California has banned their disposal in landfills. For recycling, the state recently passed the California Electronic Waste Recycling Act (CEWRA), also known as SB20. Prior to this state legislation, industry players such as Best Buy, Dell, Hewlett Packard, Gateway, and Sony had already implemented various recycling initiatives. For instance, Gateway offered qualified buyers a rebate of up to \$50 when they purchased a new PC and donated or recycled their old one [23].

Colorado—In Colorado, different cities (e.g., Boulder and Fort Collins) have created collection centers or organized the collection of used electronic equipment. At the state level, the Governor's Office of Energy Management and Conservation (OEMC) has organized recycling events at 15 different Colorado sites. The OEMC was aided by the Computer and Electronics Recycling Task Force, a public-private group formed by OEMC. Collection events were held April through September of 2002. OEMC and its partners hoped to collect 300 000 lb of obsolete computer equipment. A small fee (\$5 for individuals and \$15 for businesses) was charged for large items; small items (e.g., computer mice) were accepted for free.

Oregon—The Oregon Department of Environmental Quality (DEQ) is teaming up with local governments, the electronics industry, nonprofit organizations, the U.S. Environmental Protection Agency (EPA), as well as state and local governments from eight western states to form the Western Electronic Product Stewardship Initiative. This group seeks to develop a voluntary plan based on a product stewardship approach (an agreement between producers, sellers, and users for sharing the responsibility for reuse and recycling) to minimize the environmental impacts of electronic products and keep them out of the waste stream.

According to the DEQ, approximately 3.5 million computers have been sold in Oregon since 1982. It is estimated that about half are unused or in storage. As many as 700 000 new computers are now sold annually in Oregon, and about half a million are disposed of (approximately 10 000 tons) [24]. Developing a comprehensive and efficient system to deal with e-waste will be

²This corresponds to an exchange rate of ¥ 124.44 for \$1. Numbers are rounded to the nearest dollar.

a major challenge, as the collection, reuse, and recycling of electronics in the United States has not kept pace with this rapidly growing waste stream.

D. Policy Options

An outright ban on lead-based solders may not be the best policy to limit human exposure to lead. Recycling policies similar to those for lead batteries or for general e-waste, which rely on economic instruments and education campaigns, may provide similar health benefits at a lower cost for both industry and society. With no current legislation pending at the federal level regarding the use of lead-based solders in the electronics industry, an investigation of the implications of national and foreign lead control initiatives for the U.S. economy and public health policy is urgently needed.

Governments could adopt a number of policies to help tackle the e-waste problem [20]. Although these policies are more far-reaching than just the Pb-free issue, they are proactively designed to prevent the most severe forms of pollution resulting from e-waste, and they provide some alternatives to the imminent change to Pb-free metallurgy. This issue is already on the horizon with the second (RoHS) and the third EU directives dealing with e-waste. These policies include the following.

- Mandating the use of labels on all materials, especially hazardous materials. The goal of this measure is to facilitate the recycling and disposal of materials. Some states (e.g., Vermont) require manufacturers to label certain mercury-containing products. This type of measure should be universal.
- Changing the taxation of virgin products and (if necessary) providing financial incentives to promote the recycling of materials typically found in obsolete e-waste.
- Charging a fee at the point of sale and investigating the feasibility of deposit-refund systems. This type of measure presents several advantages. First, it guarantees a steady source of funds for recycling and/or disposal of e-waste if this money can be deposited in a separate trust fund. Second, a refund would reward good behavior on the part of consumers who are “doing the right thing,” i.e., bringing obsolete equipment to recycling centers. Third, we know from experience (e.g., see the Japanese experience above) that charging owners of obsolete equipment is a disincentive to recycling which can lead to illegal dumping.
- Setting up local collection sites. It is important, in order to avoid illegal dumping and the resulting social costs, to offer costumers easy and convenient access to collection centers for waste.
- Investigating the feasibility of an extended product responsibility (EPR) agreement with industry. EPRs seek to promote environmental improvements by extending the responsibility of manufacturers to various parts of its product life cycle, especially potential recycling and final disposal. EPRs are typically nonprescriptive, and they can be implemented through a variety of instruments. By internalizing the potential external costs linked to the end-of-life of a product, waste is typically reduced and so are the associated social costs. Motivating manufacturers

to look at the entire life cycle of a product is likely to foster better overall design because it incorporates environmental considerations, at a possibly lower cost to the manufacturer. A number of different factors should be considered. They include the scope of the application of the principle; the range of producer responsibilities; the implementation of the proposed policies (infrastructure and funding mechanisms), as well as products that are excluded; and finally, consideration of the existing backlog of products that need to be recycled. The implementation of an EPR is a necessary step to implement the design for the environment philosophy promoted by industrial ecology. For example, New York State has proposed take-back legislation that would require manufacturers of electronic equipment to establish collection and/or disassembly centers with a recovering rate target of at least 90%.

III. COMMERCIAL INDUSTRY TRENDS

A. 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 [25]–[29]. A complete life cycle analysis of lead-based and Pb-free solders is currently underway at University of Tennessee in conjunction with the U.S. EPA [30].

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 for hand soldering; 2) bulk molten solder used in wave soldering processes or solder pots; and 3) solder pastes for surface mount assemblies usually used with 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 [31]. Although desirable, it is not a necessity that the alternative alloy be compatible with all processes. Each assembly method can use its own alloy suited to its specific needs; however, the alternative alloys would need to be compatible with circuit board and component finishes which are often common to more than one process.

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

Of the candidates listed above, two alloy ranges appear to be preferred [31]: SnBiAg and SnAgCu. Ge alloys have fallen out of favor due to higher melting points and the brittleness of their intermetallic structures. For a number of reasons discussed below, the SnAgCu alloys appear to be the solder of choice for most applications.

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

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 [28]. As a result, these metals are unlikely candidates or must represent only a very small percentage of 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 [28] 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. Fig. 1 shows this region of the SnAgCu phase diagram [32]. The eutectic composition has been patented as well as several near-eutectic compositions [33]–[35]. Many companies are exploring additional alloys that are also 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 complicates processing.

B. 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

Fig. 1. The primary Pb-free alternative, SnAgCu, Sn-rich portion of the ternary phase diagram [28].

Pb-free pastes also include compatibility with screen-printing processes, shelf-life, working-life, and segregation [31]. These processes have been resolved to differing degrees by different vendors and SnAgCu pastes are currently being used in commercial production.

C. 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 °C–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). This issue can be addressed by switching to 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 °C–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.

D. Reliability

Reliability will probably be the most significant factor for the aerospace industry if it converts to Pb free. Since the military and aerospace companies have the option of a phase-in strategy, there is time for them to collect data in this area. If a Pb-free strategy is selected, a number of issues related both to the selection of a new alloy and to the higher processing temperatures involved will need to be examined. 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 [36]. It is one of the manifestations of metal movement, in the form of a growth of a whisker-like crystal, typically perpendicular to the metal surface, thought to form in the presence of a mechanical strain field. It is a mode of failure common to high-tin solder joints of various kinds. The SnAgCu alloy under consideration 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 [37]. Tin whisker growth relating to the surface finish of Pb-free components is one area of concern where substantial studies are currently underway at NASA [38]–[40].

Finally, in addition to the reliability risks mentioned above, the interactions between different types of risks also needs to be carefully considered. For example, the fatigue characteristics of the new alloy 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.

E. Cost Drivers

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

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.

F. 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 Hewlett-Packard (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 has been making progress along these lines and has supplier specifications that are RoHS compliant [41], although it is not known how many suppliers are currently granted exemptions. 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 [42].

G. 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 \$67.5 billion in high-tech goods in 1999, which represented over 56% of California's total exports [43]. 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 [28], [29], [44].

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) [45]. 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, nontoxicity, 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 HP). The conclusion of nearly all of these studies was to proceed with implementation of an alloy near the eutectic SnAgCu composition [46]–[48]. These corporate research coalitions have been sustained by the common product design goal of finding alternatives to Pb-free solder in response to foreign legislative and market forces.

H. 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.

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-free alternatives [41], [42].

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, as were all of Matsushita’s consumer products, and Sony had eliminated lead from all but its high-density products. In addition, Toshiba was working on Pb-free mobile phones, NEC was planning to make Pb-free motherboards, and Fujitsu was trying to phase out all lead from electronics [34]. European companies such as Nokia and Thompson, and American companies such as Motorola and Intel, were 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.

I. Differences Between the Aerospace and Commercial Industry

Commercial applications and aerospace applications have somewhat different driving forces. The commercial industry is mostly driven to Pb-free by market forces. Efforts by Japanese companies to implement Pb-free assembly processes, and the European ban of Pb in many applications, have put pressure on U.S. manufacturers to follow suit. In addition, most commercial assembly processes use epoxy–fiberglass-type

materials for printed circuit boards, which is less forgiving toward higher processing temperatures than polyimides. The aerospace industry would not migrate to Pb free unless there was a compelling reason to do so. A compelling reason would be that the manufacturers of solder products may cease offering Sn–Pb products. Because of this possible availability issue, the effects of converting to Pb-free solders need to be well understood.

IV. AEROSPACE RELIABILITY STUDY EXAMPLE

About three 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 BGA, flip chip, or chip scale packages for NASA applications. The surface finishes of the components tested are described in Section IV-B below. 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. This project is divided into two phases, an evaluation of four alloys and a further evaluation of two down-selected alloys.

A. 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 lead-free solder pastes were selected based on an extensive literature search (see Table II).

Two printed wire boards (PWBs) per solder type were assembled using the four different solder pastes, resulting in a total of eight assemblies. See Fig. 2, which shows a 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 semiautomated 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

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 b) Long history of use	a) May exhibit structural weakness at solder connection b) High T_m
2) Sn95.5Ag3.8Cu0.7	217-218	a) Recommended by NEMI b) Virtually no plastic range c) Rapid solidification avoiding formation of cracks d) Formation of intermetallics Cu ₆ Sn 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 b) Solder coating offers flatter pads and uniform coat c) Works well with Ni/Au Ag/Pd and OSP boards d) Sb slightly reduces melting temperature and refines grain structure	a) Sb trioxide may exhibit toxicity at higher temperatures b) High T_m
4) Sn77.2In20.0Ag2.8 (Indalloy 227®)	175 (T_s^*) – 187 (T_L^*)	a) Compatible T_m to Sn/Pb b) Good ductility, strength and creep resistance c) Low dross in wave solder	a) Supply and cost may be prohibitive factors in its use. b) 118°C eutectic point may deteriorate mechanical properties of solder joint c) Large plastic range

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

Fig. 2. Bottom and top view, respectively, of the test PWB.

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., Milan, Italy) 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.

B. Assembly Process

Double-sided test PWBs with footprints for various chip components and 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

- chip resistor, 0603 package (24 each per board); 100% Sn finish;
- chip resistor, 1206 package (18 each per board); 100% Sn finish;
- small outline transistor (SOT) 23 package (two each per board); 100% Sn finish;

- small outline IC (SOIC) 20 package, 50-mil pitch (two each per board); 98%Sn/2.0%Cu finish;
- plastic leaded chip carrier (PLCC) 68 package, 50-mil pitch (one each per board); 100% Sn finish;
- quad flat pack (QFP) 100 package, 25-mil pitch (one each per board); 100% Sn finish;
- quad flat pack 208 package, 20-mil pitch (one each per board); 100% Sn finish;
- BGA 225 full array package, 1.5-mm ball pitch (one each per board); 95.5%Sn/4.0%Ag/0.5%Cu finish;
- BGA 352 area array package, 1.27-mm ball pitch (one each per board); 95.5%Sn/4.0%Ag/0.5%Cu finish.

C. Assembly Conditions

PreAssembly 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 a 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 alcoxypyrpanols and amine compounds

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

in deionized (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 1 min;
- wash cycle of 5-min duration using the alcoxopropanols and amine compounds solution heated to 50 °C;
- rinse cycle of 10-min duration using DI water heated to 50 °C;
- dry cycle of 5-min duration using air heated to 180 °C;
- vacuum oven bake cycle for 8 h 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.

The printing parameters are

- stencil type—stainless steel with foil thickness of 7 mils;
- squeegee type—metal blade;
- squeegee pressure setting—5.6 kg;
- squeegee speed—15 mm/s.

Paste height is measured using three-dimensional laser-based measurement system.

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

Solder Paste Reflow—Two types of vapor phase 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/s followed by vapor phase reflow. The dwell time above liquidus is 62 s.

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.

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

Visual Inspection, SAM, and X-Ray—All PWAs were inspected under a microscope at 12× 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 grainier than the other three types of joints.

SAM 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 PWBs were assembled and thermal cycled. Four PWBs 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.

D. Evaluation of Pb-Free Alloys Phase II

During the second phase, 12 of the same test PWBs as used in Phase I (Fig. 2) were utilized. The second phase of this project down-selected to two of the pastes from Table II:

- Paste 1 Sn95.5Ag3.8Cu0.7 (near eutectic T_m 217–218 °C);
- Paste 2 Sn96.2Ag2.5Cu0.8Sb0.5 (near eutectic T_m 217–218 °C).

These two solder alloys were preferred to Pastes 3 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 very scarce.

Four PWAs per paste were assembled along with eutectic Sn/Pb (Sn63Pb37 – 183 °C T_m) as a control, giving a total of 12 PWAs. These assemblies were then subjected to thermal cycling between −55 °C and 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 30× magnification.

E. 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 $+125^{\circ}\text{C}$ with no signs of cracking.

V. CONCLUSION

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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