Implications of Pb-Free Microelectronics Assembly in Aerospace Applications

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Abstract

The commercial microelectronics industry is rapidly moving to completely Pb-free assembly strategies within the next decade. This trend is being driven by existing and proposed legislation in Europe and in Japan. The microelectronics industry has become truly global, as indicated by major U.S. firms who already adopted Pb-free implementation programs. Among these forward-looking firms are AT&T, IBM, Motorola, HP and Intel to name a few.

Following Moore's law, advances in microelectronics are happening very rapidly. 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 attempt to 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 also look at different strategies for implementation. We consider 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? Finally, should companies try to comply with ISO14000 and 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 collected on a recent NASA project to focus on finding suitable alternatives to eutectic tin-lead solders and solder pastes. The first phase of this project dealt with determining the most feasible candidates to replace tin-lead and to determine 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 with Pb free assembly, either by availability or legislation. This paper provides some insight into some of the tradeoffs that should be considered.

I. Background

It is now widely recognized that lead (Pb) is a highly toxic substance. 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 [1]. 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 [2]. 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 [3; 4]. 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. [5]. Similarly, regulatory strategies for recycling leaded batteries vary across State and national boundaries [6], which has caused a number of developing countries to be 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 for voluntary environmental initiatives by corporations.

In this paper, we focus on the continuing 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 televisions, VCRs, refrigerators and dishwashers all contain lead-tin 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 [7]. This solder is metallic and typically has a composition of 38.1 wt% Pb – 61.9 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, which is expected to increase by 3% to 5% annually, could thus double in the next 12 to 15 years [8]. This implies that the amount of lead contained in municipal waste will also increase. Exposure to lead is known to have several adverse health effects, such as neurological, reproductive, renal, and hematological disorders [9]. Children are especially at risk, as early blood levels of lead can adversely affect their development.

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 US States. In Section III, we analyze current industry trends. Section IV considers various strategies for implementing lead-free electronics and their implications for aerospace applications. Section V gives an overview of a current JPL/NASA example of implementation. Section VI concludes.

II. Current Policy Status

Several countries have enacted legislation designed to minimize the environmental risks resulting from the disposal of e-waste, especially risks that result 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 European Union (EU) adopted three proposed directives to deal with WEEE and foster environmentally friendly manufacturing.

Japan has also been progressive about enacting waste management and recycling legislation, with five key pieces of legislation [10,11,12]. 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 seen the lead-free initiative as a marketing opportunity and have already made major strides toward achieving lead-free products. A new initiative that would phase out the use of lead from electronic products by 2005 is under consideration.

As of May 2002, eleven countries already have take-back laws for electronics, each a little different. Within five years, we expect 28 countries to have such laws.

In the U.S., electronics manufacturers are trying to agree on a national take-back plan that will include federal legislation if it succeeds. If this industry-sponsored plan does not succeed, there will be a need for more action at the State or Federal levels. Currently, twenty-four electronics bills are being considered in 10 States. In addition, there are 38 pending toxic metal-related restriction bills, 10 of which affect electronics [13].

Situation in the European Union (EU)

A number of different member countries of the European Union have already enacted their own legislation and adopted economic measures to deal with WEEE. 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 Landers. It is not possible to review here these different programs; we thus concentrate on what was done at the level of the EU. Currently, each European produces approximately 14 kg per year of e-wastes. Currently, 90% of these wastes are landfilled or incinerated without any pre-treatment [14]. It is estimated that around 40% of all lead in landfills and 50% of lead in incinerators comes from WEEE.

To address this growing problem, three directives have been proposed at the European level. These directives have been in the making for some time: the European Parliament, in its Resolution of 14 November 1996 (A4-0364/96), asked the European Commission to present proposals for directives on WEEE. 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) sets a collection target of 4 kilograms per person per year (approximately 8.8 pounds). Distributors have to accept old equipment when consumers are buying new products; they cannot charge consumers. Producers are responsible for the costs of processing used equipment, as well as recycling and disposal. Producers can, however, choose to either managing the waste on an individual basis or to participate in collective schemes. Existing producers are made responsible for the costs of dealing with the current stock of WEEE. This directive is supposed to become effective on January 1st, 2008.

The second directive restricts the use of hazardous substances in EEE (hence its acronym RoHS for Reduction of Hazardous Substances). Like the WEEE directive, it concerns all EEE equipment. It proposes to ban the use of lead, mercury, cadmium, hexavalent chromium, PBB, and PBDEs in EEE by July 1, 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 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.

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 WEE legislation abroad have been the main driving forces behind the adoption of a new legislation in Japan to deal with WEEE.
This new law took effect in April of 2001. It targets four types of home appliances (television sets, refrigerators, washing machines, and air conditioners); it does not include personal computers. Design guidelines will be addressed in another law.

Manufacturers and importers are responsible for recycling EEE; to this effect, they have built a number of recycling plants. 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.

End users pay a fee when they want to get rid of one the four products. Recycling fees for TVs, refrigerators/freezers, washing machines, and air conditioning units are respectively $22, $37, $22, and $28; collection fees range from $3 to $24 [15].[2] It appears that these fees will not be sufficient to cover actual recycling and disposal costs, but more experience is needed.

As users did not have to pay to get rid of their used appliances before this new law, 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, as predicted by economic theory. In addition, a small increase in illegal dumping has also been observed, although precise figures are obviously difficult to obtain.

The direct involvement of manufacturers in recycling in Japan and the prospect of the adoption of tough new laws in the EU seem to have had positive feedbacks on the designers who are progressively taking into account recycling and end of life considerations at the design stage [15].

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 [16]. Collection and recycling programs for e-waste have been organized in a number of states. We review here the situation in Western states. More information about the rest of the country can be found on the web page of the National Recycling Coalition at http://www.nrc-recycle.org/resources/electronics/policy.htm

[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" (NEMA Publications, http://www.nema.org/publications/ei/jun00/weee.htm.)

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

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. These are taken to a recycling facility (after refrigerants are removed, if necessary). During the first 10 months of the program (July 2001 to May 2002) approximately 350 tons of appliances have been collected.

Colorado

In Colorado, different cities (e.g., Boulder or 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 pounds of obsolete computer equipment during these events. A small fee ($5 for individuals and $15 for businesses) was charged for large items; small items (e.g., mice) were accepted for free.

California

California has recently realized the magnitude of the e-waste problem. According to San Francisco Supervisor Sophie 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 [17]. Because of concern for lead in CRTs, California has banned their disposal in landfills. For recycling, the state relies currently on industry initiatives. The list of manufacturers involved includes (but is not limited to) Best Buy, Dell, Hewlett Packard, Gateway, and Sony. Gateway offers qualified buyers a rebate of up to $50 when they purchase a new PC and donate or recycle their old one [18].
However, two bills on electronic waste, SB 1523 by Senator Sher and SB 1619 by Senator Romero have been passed and are currently on the Governor's desk. SB 1523 would require manufacturers to pay the net cost of recycling or proper disposal of electronic devices, especially CRTs. SB 1619 establishes recycling and recovery goals for CRTs. In addition, Congressman Mike Thompson (D-CA) has proposed Federal Legislation (HR 5158) on July 18, 2002; if passed, it will require the US EPA to develop a grant program for computer recycling programs.

Oregon

The Oregon Department of Environmental Quality (DEQ) is teaming up with local governments, the electronics industry, non-profit organizations, the U.S. Environmental Agency, 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 (a sharing of responsibility for the reuse and recycling of products by producers, sellers and users) 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) [19]. Developing a comprehensive and efficient system to deal with e-waste will be 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.

III. Commercial Industry Trends

Materials selection

Because of the international legislative pressure, alternative alloys 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 [20-24]. A complete life cycle analysis of lead-based and lead-free solders is presently underway at University of Tennessee in conjunction with 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 IR, convection or vapor phase reflow.

The attributes for an alternative alloy, ideally, should 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, non-toxic and having low dross formation.

Alloy alternatives

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

Table I. Current Pb-Free Alloy Alternatives.

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 [26]. These are the SnBiAg alloys and the SnAgCu alloys. For a number of reasons discussed below, the SnAgCu alloys appear to be the clear winners for most applications.

Alloy costs and availability do also play a role in the selection of alternative alloys. Metals like In or Ag are significantly (two orders of magnitude) higher than the other alternative metals in the table above [23]. 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 a reasonably good melting point (210°C) as well as having very good wetting characteristics. The difficulties with Bi are, that it forms a low melting (96°C) SnPbBi eutectic [23] if Pb is present and that it creates undesirable stresses during its phase transformation on particular types of solder joint configuration that will fail almost instantly. The ternary eutectic formation is a problem because most available components from many different suppliers still have thin layers of SnPb compounds to make them more easily assembled in existing manufacturing processes. Since the component market is global, there are very large inventories, and that there are thousands of suppliers involved, it will take some time before all remnants of Pb are gone from the system. Until that time, there is a significant danger, with Bi compounds, of forming alloys that will melt under normal use. In addition, nearly all Bi is found with Pb, so it is an equal problem to Pb during extraction and there is little or no data on the toxicity of Bi metal, which could turn out to be a problem.

SnAgCu Alloys

A number of turnery SnAgCu compounds, very near the eutectic at about 95%Sn, 3.5%Ag and 1.5%Cu are commercially available. 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 not much 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 with the SnAgCu system is that its melting point is somewhat higher at 217°C, which is enough higher to make processing difficult.

Pb- Free Paste Attributes and Development

Solder pastes consist of four constituents. The predominant constituent is the alloy itself, generally small spheres of metal, 85-90% of the composition by weight. The other constituents are the flux, used for oxide scavenging and surface energy reduction (wetting), a rehology 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 [26]. These processes have been resolved to differing degrees by different vendors and SnAgCu pastes are currently used in commercial production.

Assembly methods

The primary impact of the alternative alloys selected is on the assembly processes. The primary alternative alloys being considered all require higher processing temperatures. Typical processes 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 Tg. The industry can address this by using slightly more expensive components. The impact on the equipment used for assembly will probably be minimal as most of the equipment used can be run 20-35°C higher. Most assembly methods should not be all that different than for standard eutectic solders. The processes do have an impact on the diffusion of the substrate and component metallizations into the solder alloy, which will have an impact on the properties. Characterization of processes and new process controls ill need to be established to limit the formation of generally unfavorable intermetallic structures.

Reliability

The impact on reliability will probably be the most significant for the aerospace industry. There are a number of implications with both the selection of a new alloy as well as 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. The physical characteristics of the material, particularly fatigue properties, will be different from standard eutectic. Some of the implications follow.

The interaction of the new alloy with the substrate and component metallizations plays a significant role. All combinations of interface materials need to be tested for their reliability. 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 being processed at the higher temperature ranges. The current lifetime data does not take into account the additional stress that the components see for this higher temperature processing. 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 finish of their processing. The components may have internal characteristics that are not designed to withstand the higher processing temperatures as well.

An additional reliability risk is 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 after seeing the higher processing temperature.

Finally, in addition to the reliability risks mentioned above, as well as those not mentioned, 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 BGA may be acceptable individually, but the combined characteristic of the new alloy with the underfill epoxy may have a reliability problem. All of these things 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 the following categories: 1. initial development costs, 2. production operating costs, 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 in the reliability testing and qualification for several reasons. First, the number of parts that the testing will be amortized over will be substantially smaller (tens as opposed to tens of millions of parts). Second, the cost of space qualification of a product and process is typically very high due to the rigor of the testing as well as the significant documentation involved.

Supply chain

The supply chain is also critical in the effort. If the supply chain members are shared with commercial industry, which is usually the case, they may already have gone to Pb-free materials and processes. In this case, the standard materials and coatings used for Pb 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, some companies, such as HP have comprehensive supplier management programs. HP' s approach involves expectations for their supply chain partners including: planning, cost impact notification, reliability impact information, labeling, and design rules for manufacturability and test. HP is currently on schedule to have Pb free components shipping 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 [27].

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 exported electronic devices. 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 [AeA 2001]. 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 [23,24,29].

To date, the most comprehensive investigation of lead-free solders has been conducted by the National Center for Manufacturing Science (NCMS) [30]. 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 the study was to evaluate a set of more than 70 candidate alloys that are potential substitutes for tin/lead solder for safety, reliability, non-toxicity, and cost-effectiveness. Other institutional coalitions that have investigated the potential of lead-free solders in the electronics industry include the National Electronics Manufacturing Initiative, the Center for Advanced Vehicle Electronics, and the C.A.S.H. Project (ChipPac, Alpha Metals, Sanmina, and Hewlett-Packard) [31-33]. These corporate research coalitions have been sustained by the common product design goal of finding alternatives to lead-free solder in response to external legislative and market driving forces abroad.

IV. Strategies for Implementation and Implications

Policy Options

In fact, 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 can adopt a number of policies to help tackle the e-waste problem [16]. These policies include:

- 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 EEE.
- Charging a fee at the point of sale and investigate the feasibility of deposit-refund systems. This type of measures 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 that 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. The EPR seeks to promote environmental improvements by extending the responsibility of the manufacturers of a product to various parts of its life-cycle, especially its take-back, as well as its potential recycling and final disposal. It is typically non prescriptive; it can be implemented through a variety of instruments (such as economic or administrative). By internalizing the potential external costs linked to the end-of-life of a product, it typically leads to a reduction of the production of wastes and thus of social costs associated with the consumption of a product. Pushing manufacturers to look at the entire life cycle of a product is likely to foster a better overall design because it incorporates environmental considerations, at possibly a lower cost to the manufacturer. A number of different factors should be considered. They include: scope of the application of the principle, the range of producer responsibilities, the implementation of the proposed policies (infrastructure and funding mechanism), 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%.

Implementation

Companies can take a variety of strategies for implementation including an immediate implementation, a phase – in approach or no implementation at all (wait and see). If larger companies like HP or IBM do initiate implementation and their supplier chains follow, the impact on the above strategies could be significant. The do-nothing approach may be a higher risk path if the supplier chain starts to phase in a Pb-free system. The U.S. can no longer be considered an isolated system. With all of the Pb-free activity around the globe, it is likely that some form of policy will eventually be put in place. 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 Pb in its electronic assemblies in anticipation of legal and regulatory developments. HP has taken an industry standardization approach involving their supply chain, contract manufacturers, original equipment manufacturers, and consortia. Their goal is to develop and demonstrate reliable environmentally responsible alternatives. They are considering cost, availability, regulation and credible scientific evidence that the alternative is environmentally better than Pb. They are working with industry and the scientific community to determine if the alternatives are beneficial or harmful to the environment [27].

Many companies are using a phased-in approach. Some Japanese companies are using the environmentally friendly aspect as a product differentiator. As a result of this strategy, a number of Japanese companies have already implemented their own programs to move their products to Pb-free. By the end of 2001, Hitachi was Pb free, Matsushita had all of their consumer products converted to Pb-free, and Sony had Pb eliminated from all but their high-density products. By the end of 2002, Toshiba is planning to have Pb free mobile phones, NEC is planning Pb-free motherboards, and Fujitsu is trying to phase out all Pb [26]. 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 Pb bearing systems and will eventually be forced to go along.

V. An Aerospace Implementation Example

About one year ago, NASA funded a project to begin searching for suitable candidates under the aegis of the NASA Electronic Parts and Packaging (NEPP).

Table II: Lead-free Solder Alloys for Test

Composition	T_m (°C)	Advantages	Potential Issues
1) Sn96.5Ag3.5 (eutectic)	221	Good wetting characteristics and superior joint strength compared to Sn/Pb solder 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 $Cu6Sn_5$ and Ag_3Sn 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	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

Four lead-free solder pastes were selected based on an extensive search of the literature. These are given above in Table II. Two printed wiring boards (PWBs) per solder type were assembled using the four different solder pastes resulting in total of eight assemblies.

Objectives and Methodology
The objective of the task is to ensure that the new lead-free pastes can be successfully assembled. It is still an open issue whether PWBs and components can be successfully processed at the higher process temperatures (30°-35°C greater than for eutectic tin-lead).

Based on the results of the initial tests, a down select from the initial four pastes to two will take place. Assembly of four PWBs per paste (2 pastes) will take place and they will be thermal cycled. The exact thermal cycle conditions are still to be determined. Assembly of four PWBs with eutectic tin-lead paste as a control lot will also take place. There are several types of thermal cycles being used depending upon the product and the industry. These are described in IPC-9701. A vapor phase reflow used was a bench-top model for use in this project. Eight PWBs using the four different solder pastes per Table II were assembled.

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

Rosin-based fluxes and pastes are 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 is applied using a semi-automated screen printer ensuring that the paste is deposited in a uniform and consistent manner. Only stainless steel stencils are used in conjunction with a stainless steel squeegee. All boards are visually inspected for proper paste deposition after the stencil operation.

A laser-based solder paste height and width measurement system is used with a resolution of 0.0001 inch (2.5 µm). This system provides real time information on the uniformity of solder paste deposition. All boards are subjected to this measurement prior to the reflow operation. A batch vapor phase reflow operation was used to create the solder joints of the SMT PWAs. The SMT PWAs are thermally profiled. A thermocouple was attached to the PWB and to a microprocessor-based data logger attached to a computer. Thermal profiling was done to eliminate thermal shock during preheat and reflow. This operation consisted of a vapor phase reflow machine using a constant boiling perfluorocarbon material (under proprietary name Galden® from Ausimont Corp., boiling point 240°C) for soldering the lead-free SMT PWAs.

The PWAs were preheated to remove paste volatiles and to initiate the activation stage of the paste. The reflow liquid, since it 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 tin-lead and Indalloy 227, 3M Perfluorocompound FC-5312® with a boiling point of 216°C was used.

Assembly Process
Double-sided test PWBs with footprints for various chip components and IC packages, including BGAs, were assembled. The BGAs were daisy-chained. Various mechanical packages were selected for the test and were 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)

The assembly conditions were as follows:

Pre-assembly Inspection and Test
Prior to assembly, all the BGA pads on the PWBs were checked to ensure the daisy-chain integrity and in addition 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 were cleaned in an Accel centrifugal cleaner using Vigon® A200 chemistry available from Zestron Corp. Viagon chemistry consists of a 20% solution of a proprietary blend of alcoxypropanols and amine compounds in DI water with 1% corrosion inhibitor and 0.1% defoamer. The cleaning cycle and its parameters were as follows.

Purge the wash chamber with nitrogen gas for one minute
Wash cycle of 5 minutes duration using Vigon A200 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

Screen printing
PWBs were screen printed with four different pastes per following 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

Printing parameters were as follows:

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 was measured using 3-D laser based measurement system.

Component Placement
Components were 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 used to reflow the solder pastes. Both consisted 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 Galden perfluorocarbon material with a boiling point of 240°C. Paste 4 was reflowed using a stand-alone system containing 3M perfluorocarbon material with boiling point of 216°C.

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

Post Reflow Cleaning
All PWAs were 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 as follows.
Table 3: Ionic Contamination Levels

PWA S/N	Solder Paste Type	Ionics- mg/in2
S/N 001	Sn95.5Ag3.8Cu0.7	0.32
S/N 002	Sn95.5Ag3.8Cu0.7	0.33
S/N 003	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.05
S/N 004	Sn96.2Ag2.5Cu0.8Sb0.5 (Castin®)	0.05
S/N 005	Sn96.5Ag3.5 (eutectic)	0.26
S/N 006	Sn96.5Ag3.5 (eutectic)	0.19
S/N 007	Sn77.2In20.0Ag2.8 (Indalloy 227®)	1.68
S/N 008	Sn77.2In20.0Ag2.8 (Indalloy 227®)	1.28

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

Visual Inspection and X-Ray
All PWAs were inspected under a microscope at 12 X magnification. The observations made are listed below.

The solder flow generally appeared 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. There was one solder bridge at the corner on S/N and 008.

Conclusions for the JPL/NASA assembly

- No problems were encountered during the printing process with lead 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.

Additional work and reliability testing of these assemblies is currently underway.

VI. 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 alloy selection has been performed by commercial industry, but reliability testing and space qualification still need to be performed. There are a number of strategies that 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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References

[1] Sigman, H.A., "A comparison of public policies for lead recycling," RAND Journal of Economics, Vol. 26, No. 3. 452-478, 1995 pp.

[2] DTSC (Department of Toxic Substances Control, California). "Managing Waste Cathode Ray Tubes," Fact Sheet, 2001. http://www.dtsc.ca.gov/docs/hwmp/docs/HWM_FS_CRT-EmergencyRegs.pdf

[3] Nriagu, J., "Bucking the Trend: Increased Lead Content of Gasoline in Sub-Saharan African Counties," Seminar at the University of California, Irvine, 2002.

[4] Thomas, V.M., "The elimination of lead in gasoline. Annual Review of Energy and the Environment," 20:301-324, 1995.

[5] Thomas, V.M., Socolow, R.H., Fanelli, J.J., and Spiro, T.G. "Effects of reducing lead in gasoline: An analysis of the international experience," Environmental Science & Technology 33 (22): 3942-3948, 1999.

[6] Thomas, V.M., and A.O. Orlova. "Soviet and Post-Soviet Environmental Management: Lessons from a Case Study of Lead Pollution." Ambio 30(2): 104-111, 2001

[7] Smith, G.R., "Lead." U.S. Geological Survey, Minerals Yearbook, Metals and Minerals, 1: 44.1-44.24, 1998.

[8] Commission of the European Communities (CEC), "Amended proposal for a Directive of the European Parliament and of the council on the restriction on the use of certain hazardous substances in electrical and electronic equipment." 2000/0159, Brussels, 2001.

[9] Juberg, D. R., "Lead and Human Health: An Update." 2nd edition. Prepared for the American Council on Science and Health (ACSH), 2000 > (09/05/01) http://www.acsh.org/publications/booklets/lead_update.html

[10] Schoenung, J.M., "Lead Free Electronics: Current and Pending Legislation," Proceedings of the 104th Annual Meeting of the American Ceramic Society, accepted for publication, 2002.

[11] Tojo, N. "Analysis of EPR Policies and Legislation through Comparative Study of Selected EPR Programmes for EEE," M.S. Thesis, Lund University, Sweden, 1999.

[12] Le Fevre, P., "Environmental Issues in Power Electronics (Lead Free)," APEC 2002. http://www.ericsson.com/sustainability/pdf/Apec_2002(Final).pdf

[13] Raymond Communications, Incorporated, "Electronics Recycling: What to Expect from Global Mandates." Raymond Communications, Inc., College Park, MD., 2002.

[14] European Union Institutions Press Release (EU) 2002. "Commission welcomes European Parliament Vote on Waste Electrical Equipment and the Restriction of Hazardous Substances," Brussels, April 10, 2002, >09/27/02. http://europa.eu.int/rapid/start/cgi/guesten.ksh?reslist

[15] Tojo, N., T. Lindhqvist, and G. Davis, "EPR Programme Implementation: Institutional and Structural Factors," OECD Seminar on Extended Producer Responsibility, EPR: Programme Implementation and Assessment, 13-14 December, OECD, Paris, France, 2001.

[16] Environmental Protection Agency (EPA), 2000. WasteWise Update, Solid Waste and Emergency Response, EPA530-N-00-007, October, 2000.

[17] Silicon Valley Toxics Coalition (SVTC), "Solutions to E-waste Crisis Pending in State Legislature," 2002. >09/27/02. http://www.svtc.org/media/releases/ccc_81502.htm

[18] California Integrated Waste Management Board (CIWMB), Industry-Sponsored Electronic Equipment Recovery Resources Web Page, 2002. >09/27/02. http://www.ciwmb.ca.gov/Electronics/Recovery/

[19] State of Oregon Department of Environmental Quality (SODEQ), "Local groups organize to help deal with computer and electronic product waste," News Release July 3, 2001 >09/27/02. http://www.deq.state.or.us/news/releases/256.htm

[20] Ku, A. "Life Cycle Assessment of Alternatives to Lead Solders," Seminar at the University of California, Irvine, 2002.

[21] Griese, H. "Sustainable development of information and communication technology and lead-free interconnection system," Seminar at the University of California, Irvine, 2002.

[22] Allenby, B.R. "Design for the Environment: Implementing Industrial Ecology," Dissertation. Rutgers University, New Jersey, 1992.

[23] Lee, N.C. "Lead-free Soldering – Where the World is Going," Advancing Microelectronics, (Sept-Oct): 29-34, 1999.

[24] Smith III, E.B. and L.K. Swanger, "Are Lead-free Solders Really Environmentally Friendly?" Surface Mount Technology (March): 64-66, 1999.

[25] Geibig, J. Private communication, 2002.

[26] Dowds, S. "Pb-Free Solder Paste," Seminar at the University of California, Irvine, 2002.

[27] Bergman, D. "It's Not Easy Being Green," Seminar at the University of California, Irvine, 2002.

[28] American Electronics Association (AeA), "Cyberstates 2001: A State-by-State Overview of the High Technology Industry", 2001 > (08/24/01) http://www.aeanet.org/aeanet/aeacommon/display.asp?file=/aeanet/PressRoom/statmk0015_cs2001_caba_press.htm

[29] Charles, Jr., H.K. and N. Sinnadurai, "Microelectronics: Rising to the Environmental Challenge?," 2001. >(9/20/01) http://www.nemi.org/PbFreePublic/index.html

[30] National Center for Manufacturing Sciences (NCMS), "Lead Free Solder Project," 2001. > (10/11/01)

http://lead-free.ncms.org/

[31] Bradley, E. "Overview of No Lead Solder Issue," NEMI meeting, Anaheim, Feb. 23, 1999.

[32] Center for Advanced Vehicle Electronics (CAVE), "A National Science Foundation/Industry/University Cooperative Research Center,"2001. >(10/12/01) http://www.eng.auburn.edu/department/ee/cave/home.htm

[33] Alpha-Fry Technologies, "Partnering with the Global Electronics Industry in the Transition to Lead-Free Joining Solutions," 2001. >(10/12/01) http://www.alphametals.com/lead_free/