EUROPEAN POWER SUPPLY MANUFACTURERS ASSOCIATION
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The Status of Lead-Free Electronics and its Impact on Power Electronics

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The European Power Supply Manufacturers Association was established in 1995, to represent the European power supply industry.

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Introduction

The management committee of the EPSMA has requested a report from the technical committee that will have as its main deliverable a clearer understanding of upcoming WEEE & ROHS legislation & roadmap with respect to implementation. An overview of some of the main technical challenges which the power electronics industry will face is also included which will allow the membership assess and face the challenges which the proposed legislation will pose. This document was produced by John Flannery, Artesyn Technologies with assistance from Patrick Le Fèvre, Ericsson Power Converters.

Background

After many years of extensive research, involving thousands of researchers, the International Panel on Climate Change (IPCC) concluded that we are already living in an era of global warming. Many of the issues and concerns which this raised were adopted into the "The United Nation Framework Convention On Climate Change" in Rio de Janeiro in June 1992 and at the Conference of the Parties to the UNFCCC in Kyoto, December 1997 [1, 2]

These concerns have led to concerted actions within many member states to reduce the environmental impact of ongoing human activity. These problems/incidents usually fall into one of three categories.

1. The first category creates environmental impact on a **global** basis. For example, diminishment of the stratospheric ozone layer caused by the use of chlorinated or brominated, low molecular weight hydrocarbons; or global warming, the result of extensive use of fossil fuels.
2. The second category involves problems that have a **regional** impact on the environment. For example:
   - Acid rain in the southern parts of Scandinavia and in the North-Eastern parts of the US.
   - A high concentration of ground-level ozone-forming compounds that diminish crop yields, due to discharges of nitrogen oxides and hydrocarbons (mainly from the transportation industry).
3. The third category includes problems that have a **local** impact on the environment. Very often, these relate to the unwanted presence of "dirty" industries or landfill areas which, being perceived as polluters of air, water or land with negative impact upon the environment.

This third category is directly addressed by the European Community directive on waste electrical and electronic equipment (WEEE) proposal in June 2000 [3] with subsequent amendments. [4, 5]

Waste electronic equipment

The rapid growth of waste electrical and electronic equipment is of concern. In 1998, six million tonnes of waste electrical and electronic equipment were generated (4% of the municipal waste stream). The growth of this waste is about three times higher than the growth of the average municipal waste. Because of the hazardous content, electrical and electronic equipment can cause major environmental problems during the waste management phase if not properly pre-treated. As more than 90% of WEEE is deposited in landfill, incinerated or recovered without any pre-treatment, a large proportion of various pollutants found in the municipal waste stream comes from this electronic waste. The WEEE and its associated Reduction of Hazardous Substances (ROHS) directive aim to promote recycling of, as well as eliminate a number of hazardous substances (including lead) from electronic equipment.

Lead as a hazardous substance

Lead is recognised as one of the most significant environmental health threats to humans, especially to pregnant women, infants, and children up to six years of age [6]. Children and developing foetuses are known to absorb lead more readily than adults, and, once in the body, lead is distributed into blood, soft tissue, and bone. Children exposed to lead can suffer from brain damage, central nervous system damage, slow growth, hyperactivity, and behaviour and learning problems. Adults exposed to lead can suffer difficulties during pregnancy, high blood pressure, nervous disorders, and memory and concentration problems [7].

At issue is not the lead in electronic products, but the accumulative effects of lead in the waste stream.[8]
The lead used in electronics accounts for less than 2% of total world consumption with batteries accounting for 90%. Only 40% of the amount of lead in landfill is from WEEE, but of that, only 4% is from lead in PCBs while 36% is due to the use of leaded glass in monitors and televisions. (The CRT in a TV could contain 2 kg of lead)

The lead contained within the power electronics industry is an insignificant factor with respect to what the United Nations Convention on Climate Change aims to achieve. However, despite the weight of arguments against the decision to ban lead from passive and active components, the electronics industry has started to move towards reducing the use of hazardous substances and to implement global recycling policies, before local or global regulations come in force.

Drivers for lead free
EU

Legislation
Driving the interest in lead and its effects are regulations and legislation changes. The only direct legislation pending anywhere in the world are the impending WEEE and ROHS directives in the EU.

In 1998, the European Commission introduced two draft proposals called the "Waste Electrical and Electronic Equipment" (WEEE) directive and the "Reduction of Hazardous Substances" (ROHS) directive. The primary objective of these complementary proposals is to minimise the risks and impacts that the production, use, treatment, and disposal of waste electrical and electronic equipment have on the human health and the environment. Additionally, the directives intend to prevent uncontrolled disposal of electrical and electronic equipment and to foster the development of reuse and recycling methods in order to reduce the amount of waste for disposal. The Commission, which revised the original draft in 2000, included the implementation date for the lead ban as January 1, 2008. In further revision by the European Parliament, in May 2001, and the Council of Ministers in June, proposed that the ban on lead take effect January 1, 2006 and January 1, 2007, respectively. On October 11th, 2002 a Conciliation Committee reached agreement on these conflicting proposals and the most recent version of the directive adopted on Jan. 27th 2003 [9] proposes a date of July 1st, 2006 as the ROHS implementation date. The present situation is therefore that no new products introduced for sale in the EU after that date can contain any of the banned substances including lead. (For a list of certain exceptions refer to the relevant section on page 5. Some of these exceptions are very important to aspects of the power electronics industry serving communications and computing infrastructure.)

The key issues in both of the directives are as follows

WEEE (Waste of Electrical & Electronic Equipment)

The WEEE directive is primarily concerned with the implementation of take-back facilities for WEEE.

- Collection systems are to be set up 30 months after the entry into force of the proposed Directive, allowing final holders and distributors of equipment to return WEEE free of charge.
- When supplying a new product, distributors shall be responsible for ensuring that such waste can be returned to the distributor at least free of charge on a one to one basis as long as the equipment is of equivalent type and has fulfilled the same functions as the supplied equipment.
- Member States may, for a period not exceeding 5 years after the entry into force of the Directive, set up or facilitate alternative free take-back systems.
- Member States may allow producers to set up and operate individual and/or collective take-back systems.
- The collection target for private households should be set at a minimum rate of four kilograms on average per inhabitant per year and is to be reached within 36 months from the entry into force of the Directive.
- Recovery and recycling targets are to be reached within 46 months of the entry into force of the Directive.
- For large household appliances, the rate of recovery shall be increased to 80%, the rate for re-use and recycling to 75%. For IT, telecommunication and consumer equipment, the rate of recovery is 75% and the rate for re-use and recycling 65%. (*For the other categories the rate of recovery shall be 70% and the rate of re-use and recycling 50%).*
- Producers will pay for the collection, treatment, recovery, and environmentally sound disposal of WEEE from private households. The financing shall be provided by means of collective and/or individual systems.
- The responsibility for the financing of the costs of "historical waste" shall be provided by one or more systems to which all producers present in the market when the respective costs occur contribute proportionately.
- The setting up of the financing systems should be reached within 30 months from the entry into force of the Directive. (*An exemption from the financing requirements was granted to small independent manufacturers with fewer than 10 employees and a turnover of less than 2 MEUROS for a transitional period of 5 years after the entry into force of the Directive).*

ROHS (Reduction of hazardous substances)
The purpose of the ROHS directive is to restrict or eliminate the use of certain hazardous substances in electrical and electronic equipment which cause significant environmental problems during the waste management phase and to substitute them by a certain date.

The Council has agreed [9] that by 1 July, 2006 at the latest, Member States shall ensure that new electrical and electronic equipment put on the market does not contain the following,

- lead,
- mercury,
- cadmium,
- hexavalent chromium,
- polybrominated biphenyls (PBB) and/or
- polybrominated diphenyl ether (PBDE).

The annex to the directive contains exceptions for

- Mercury in CFLs and standard fluorescent lamps and other lamps
- Lead in CRTs and fluorescent tubes
- Lead as an alloying element in steel (max. 0.35%), aluminium (max. 0.4%), and copper (max. 4%),
- Lead in the following solders
  - Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead),
  - Lead in solders for servers, storage and storage array systems (exemption granted until 2010),
  - Lead in solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunication,
- Lead in electronic ceramic parts (e.g. piezoelectric devices).
- Cadmium plating except for applications banned under Directive 91/338/EEC amending Directive 76/769/EEC relating to restrictions on the marketing and use of certain dangerous substances and preparations
- Hexavalent chromium as an anti-corrosion of the carbon steel cooling system in absorption refrigerators.

These exemptions and further amendments are under evaluation. The amendments suggest that exemptions should be granted if scientific evidence demonstrates that a materials use poses no significant risk to human health or the environment.

Other European initiatives:

In 1994 the EU sponsored a research program entitled “Improved Design Life and Environmentally aware Manufacturing of Electronics Assemblies” (IDEALS) which began investigation of lead free alternatives.

On July 16th, 2001, in a move aimed at accelerating the use of lead-free packages and stimulating the further development of lead-free technologies, three major European semiconductors manufacturers Philips Semiconductors, Infineon Technologies AG and STMicroelectronics unveiled their proposal for the world's first standards for defining and evaluating lead-free semiconductor devices[10]. Their joint document defines the requirements for “green packages”, lead-free solderability tests, moisture sensitivity levels and whisker-free terminations. The agreed definitions are presented here.

1 A **green package** for semiconductor devices is to be lead free, halogen free and antimony free with the following acceptable levels

Definition	**Substance**	**Upper limit**
Lead-free	Pb	1000 ppm
Halogen-free	Cl + Br	$\Sigma < 900$ ppm
Antimony-free	Sb_2O_3	900 ppm

2 **Solderability tests**: The lead-free solderability tests will be based on IEC60068-2-58 and IEC60068-2-69. The solder alloy will be Sn/Ag(3.3-4.3%)/Cu(0.4-1.1%). The details are given in the following table.

Dip & Look test

Solder bath	SnPb40		SnAgCu
Dipping time	3 s	2 s	3 s
Bath temperature	215ºC	235ºC	245ºC
Flux	25% Colophony 75% Isopropanol		25% Colophony 75% Isopropanol
Comment	As IEC 60068-2-58		As IEC 60068-2-58 using SnAgCu at 245ºC

Wetting balance test

– According to IEC 60068—69 using SnAgCu at 245ºC
– Both bath and globule test method can be used
– Pass/fail criteria must be fixed for each package individually

3 **Moisture sensitivity level** (MSL). The three companies have agreed on a common specification with the following criteria

– Preconditioning levels are the same as existing J-STD-020A, with the same MSL
– Delamination criteria are more severe. Any crack or die-top delamination is enough to downgrade the MSL to the next level
– Two possible peak temperatures, 245ºC and 260ºC are defined. Reflow parameters are as follows

Profile	**"260ºC"**	**"245ºC"**
Ramp rate	Not specified	Not specified
Preheat	125ºC to 220ºC 150 s to 210 s 0.4 K/s to 1.0 K/s	125ºC to 220ºC 150 s to 210 s 0.4 K/s to 1.0 K/s
Time at T>220ºC	60 s to 90 s	60 s to 90 s
Peak temp	260ºC –5/+0ºC	245ºC –5/+0ºC
Peaktime	10 s to 30 s ≥ 250ºC	10 s to 30 s ≥ 235ºC
Cooling rate	≤ 6 K/s	≤ 6 K/s
Time from 25ºC to peak	240 s to 360 s	240 s to 360 s

It should be noted that since these announcements were made a joint industry association (IPC/JEDEC) has addressed the lack of MSL standards by issuing a revision of J-STD-020A. The revised standard J-STD-020B[11] proposes peak temperatures of 245°C and 250°C +0/-5°C for large and small components respectively. These peak temperatures are still lower than the commonly perceived lead-free requirement of 260°C.

4 **Whisker free**. One of the main concerns with a lead-free termination is growth of tin whiskers. The companies have agreed that all components must remain whisker free for a period of two years stored at ambient, but an acceptable level of whisker growth has not been agreed.

US

Legislation

In early 1990, the US Senate discussed a piece of proposed legislation known as the "Reid Bill" after Senator Reid. This bill which proposed the prohibition of materials containing a certain lead content was not passed and Senator Reid was not re-elected.

In September 2001, The United States Environmental Protection Agency took a major step by issuing [12] "Emergency Planning and Community Right-to-Know Act-Section 313: Draft Guidance for Reporting Releases and Other Waste Management Activities of Toxic Chemicals: Lead and Lead Compounds."
This document is intended to provide guidance on the specific details of this new regulation, which facilities must file release reports for lead and lead compounds, and methods to estimate releases of lead, and lead

compounds into the environment following manufacture, processing, use, or waste management activities of lead and lead compounds.

In January 2001 the EPA lowered the reporting threshold for lead under the Toxic Release Inventory (TRI) rule to 100 lbs. (approx. 285 lbs., eutectic solder). The new rule is effective immediately and the requirements for lead and lead compound emissions applied to all lead use and waste management in 2001 [13]

Other initiatives:

In the late 1990s, non-governmental associations started to develop lead-free initiatives to investigate different scenarios as lead-free regulations are put into place in different parts of the world.

One of those, The National Electronics Manufacturing Initiative (NEMI) leads a task group, working in close co-operation with major manufacturers, to support lead-free manufacturing initiatives. In conjunction with major CEMs, NEMI adopted a pro-active approach by initiating a lead-free committee [14]

Others American NGOs are also working on lead-free initiatives, e.g. The Institute for Printed Circuits (IPC) [15], the National Centre for Manufacturing Studies (NCMS)[24] and the High Density Packaging Users Group (HDPUG) [16].

In 2002 an alliance of senior executives from leading EMS providers (Celestica, Flextronics, Jabil Circuits, and Sanmina-SCI) mounted a campaign to pressure electronic component manufacturers to convert their production lines to the use of lead-free solder in keeping with new environmental regulations aimed at reducing industry reliance on the toxic metal. The group are drafting a global industry standard for the use of lead-free components in an effort to comply with legislation passed within the last year in Europe and Japan[17].

At of today, there are no specific regulations in the U.S.A. banning lead in electronic components but, as previously mentioned, several initiatives are underway to get products and processes ready to meet European, Japanese and future US market requirements.

Japan

The level of environmental awareness in the Japanese electronics industry is shown by the fact that of the 700 organisations which were certified to ISO 14001 in 1997, two-thirds were related to electronics companies. Lead-free initiatives started long before any industry regulation was introduced.

Legislation

In the early 1990s the Japanese community started to implement control of the lead released out of landfills and waste disposal.
In 1994, “The Water Pollution Prevention Law” lowered the permitted lead content of rivers from 0.1 mg/L to 0.01 mg/L.
In 2001, “The Consumer Electronics Recycling Law” required manufacturers to recovers harmful material. Japan has begun its version of take-back legislation effective in 2001 for a variety of its domestic products. This law passed the obligation for collection and recycling of waste appliances to the producers of those appliances. Colour televisions are included in the first wave of products that fall under the legislation.

There is no legislation requiring the elimination of lead from electronics.

Other initiatives

The Japan Electronics and Information Technology Industries Association (JEITA)[18] supports lead-free investigations and consolidates independent test results. Their lead-free initiative fixed three milestones to gradually remove lead from all components and sub-assemblies.

1. From2003, lead-free solder should be used preferentially.
2. From 2005 to 2010 solder containing Pb should only be used by exception.
3. By 2015 the use of Pb in solder should be eliminated.

Strong manufacturing initiatives and an objective to use Pb free solder in mass production, starting in 2001, combined with strong NGO support, gives significant leadership to Japanese manufacturers. Several of them have already released lead-free components and end-user products made without the introduction of lead during manufacturing (lead-free solder, low lead components…).

During 2001, most CEMs and in-house manufacturing plants migrated from SnPb to lead-free solders (e.g. SnAg or SnAgCu). The 2001 implementation of lead-free processes in manufacturing by the Japanese electronics industry is the first step before the next milestone of 2003.

Performance demands

It is reasonably well substantiated that thermal fatigue failures of solder interconnect are linked to the Pb rich phase. Under thermomechanical fatigue conditions the Pb rich phase tends to coarsen and eventually leads to solder joint cracks. Therefore the absence of the lead phase in lead free (Sn based) solder may impart improved mechanical behaviour in some circumstances[19]. However the lack of long term experience and reliability data to support the use the proposed lead-free solder alloys and processes is a concern. This has been tackled by the various industrial consortia and information on reliability trials is available to members.

Market requirement

The change to lead-free technologies is imminent, if not for environmental or regulatory reasons, then possibly for market differentiation. Many Japanese consumer product manufacturers are ahead of the proposed regulated ban on lead. One of the early lead free consumer electronics products was the Matsushita MJ30 mini-disc player that was launched in 1998. This product, differentiated only by being lead-free, immediately secured an estimated 11% of the available market.

The industrial market for power electronics has been slow to request lead free products. It appears that the exceptions are the large telecomms[22] and computing OEMs.

Drivers against lead free

The case for a positive environmental impact of the elimination of lead from electronic products is far from proven. At a minimum there is the materials processing cost needed to refine and run lead-free soldering operations at higher temperatures with narrower process windows. This energy cost has been estimated at more than twice the equivalent cost of SnPb processing[20]. Many of the main lead-free alloying elements, incl. silver and bismuth, have their own associated toxicity concerns and are listed as elements of concern.[21]

The long term reliability of products assembled at these increased reflow temperatures and subsequently used in harsh environments such as automotive is also of concern[22]. The concerns are mainly in the following three areas

1. Failing solder joints due to thick intermetallic layers,
2. Damage (cracks, delaminations) in plastic IC packages occurring during field use,
3. Electromigration due to PCB cleanliness issues.

All of these concerns need to be addressed during the lead-free implementation phase.

Implementation issues

Definitions

One of the major barriers against eliminating the use of lead in the industry has been a lack of internationally agreed standards and methodologies for evaluating the quality and reliability of 'lead-free' technologies. In contrast, single lead-tin alloy has been used for many decades and standard procedures are used worldwide to evaluate its quality and long-term reliability.

To accelerate the transition to lead-free technology, the electronics industry needs a common approach to quantifying solderability, heat resistance and other issues that affect reliability. At present, there is not even an internationally agreed definition of the maximum amount of lead that can be allowed in a 'lead-free' component or process[23]. This is being addressed in Europe by the previously mentioned initiative led by the big three semiconductor manufacturers[10]. Details of the proposals have already been presented on page 5.

Lead free solders

There is no internationally agreed lead-free solder to replace the current alloy. However, both a fundamental materials science perspective as well as a practical perspective indicate that a tin (Sn) based solder (min. 60% Sn) is the only practical alternative. This limits the practical choice of solders alloys to those based on SnAg, SnAgCu, SnAgCuSb, SnCu, or SnAgBi. Many industry associations such as “National Electronics Manufacturing Initiative (NEMI)[14], the National Centre for Manufacturing Studies (NCMS)[24] and HDPUG[16] have carried out studies on variants of these alloys. The details of these studies are only available to the members of the consortia.

Table 1: Melting point of solder alloys

Alloy	**Melting temperature**
Sn/Pb37	183ºC
Sn/Ag3.5	221ºC
Sn/Ag4/Cu0.5	218ºC
Sn/Ag3.4/Cu0.7	217ºC
Sn/Ag2.5/Cu0.7/Sb0.5	217ºC
Sn/Ag/Cu/Bi	205-214ºC
Sn/Cu	227ºC

A common feature of all of the lead-free alloys is that they have a much higher melting temperature than Sn/Pb37 thus requiring a higher processing temperature. Most of the industry talk of a peak reflow temperature of 260ºC.

The SnAg3.5 alloy has a long history in the hybrid circuit and electronics industry but has several associated issues, high melting temperature, high cost and a reliability issue due to a silver phase change problem.

The addition of a small amount of other alloying elements such as copper, bismuth, antimony (Cu, Bi, Sb) can depresses the melting point by a small amount, aid wetting and increase strength to varying degrees. The addition of bismuth (Bi) while offering better mechanical properties has the drawback of being very intolerant of contamination with lead, producing a secondary eutectic with a melting point of 96ºC which would lead to negative effects on reliability of any assembly exposed to thermal stress [25].

Some of the alloys are covered by patents (e.g. US5527626). Although the position of the patents are unclear. Even if the composition of an alloy is outside the patented range, if during manufacturing the alloy picks up a base metal such as copper and forms an intermetallic that contains the elements covered under a patent, the manufacturer has violated that patent and may be subject to legal action [26].

To combat the expense of silver alloy in bulk form such as associated with wave soldering it has been suggested that a Sn/Cu0.7 alloy be used. However this alloy has a higher melting temperature (ref. Table 1), and has poorer wetting compared to other lead-free solders which may mandate the use nitrogen atmosphere and more aggressive fluxes. Furthermore it has lower capillary action to draw it into PTHs and lacks the fatigue resistance needed for SMT.

There have been many studies carried out on the most appropriate alloy and the overwhelming recommendation from EU and US based research (e.g.NEMI) is for a Sn3.5Ag0.7Cu alloy which has a eutectic temperature of 217°C.

Lead free solders are available from most of the major solder materials manufacturers.

There is some reliability information in the public domain[27] but most is only available through membership of initiatives such as NEMI, NCMS, HDPUG. etc.

The lead free soldering process

The main implications in the implementation of a lead free process are as follows

- Higher temperature process
- New solder material requiring new inspection criteria due to different grain structure, reflectivity and surface tension
- Component compatibility criteria

High temperature

There is considerable debate about the temperatures needed for lead free soldering. The common response is to use a reflow temperature which is 40°C higher than the melting temperature, as has been the practice with conventional solder. This is the source of the 260°C peak profile. There is a growing amount of evidence that adequate solder joints can be formed at lower than 245°C [27, 28, 29]. The high temperatures will have many implications on solder joint reliability such as the growth of thicker intermetallic layers. Also the higher reflow temperature can have a remarkable impact on device reliability. Preliminary data published by international committees[30] have shown that while soldering in the range of 240 - 245°C has limited impact on the package integrity. But soldering in the range 255 - 260°C can cause severe delamination and cracks in a large number of devices, with down stepping of their MSL level by one or two levels [10].

Materials behaviour

Molten lead free solders have higher surface tension than SnPb so wetting angles and fillet heights will be significantly different from the target and acceptable conditions specified in IPC-A-610 rev. C. The resulting joints are less shiny and have a more grainy finish. For this reason, inspection standards will have to change. Tests have shown that adequate wetting can be achieved with suitable flux chemistry, but nitrogen inert atmospheres may be desirable. Increased time above liquidus encourages better wetting, but also increases the chances of component damage. These conflicting constraints will have to be balanced during optimisation of reflow and wave solder profiles. The bottom line is that process windows will narrow significantly, and improved process control will be vital.

New flux chemistries and altered cleaning processes will also be required and the high temperatures are expected to make the formation of voids more likely. The residues of the new fluxes and new cleaning methods will need to be analysed to ensure they do not impact SIR etc.

Process equipment

The higher temperature process has implications on equipment, components, handling, etc. It is likely that peak reflow temperatures of up to 260°C will be required although there is an emerging view that 245 – 250°C may be adequate as mentioned previously.
Figure 1 shows what is likely to be a worst case reflow profile.

Peak temperatures	260°C
Time at peak	20 seconds
Time above 220°C	60 seconds

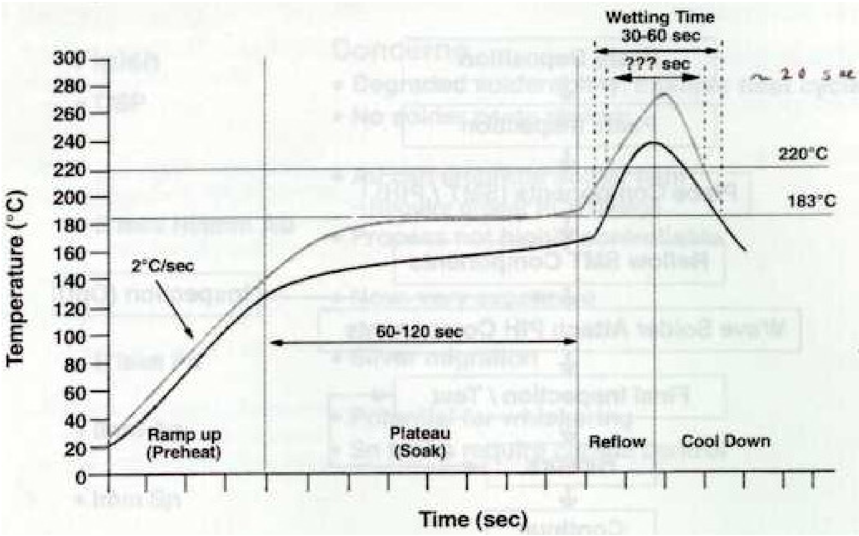

Figure 1: Typical lead-free solder reflow profile

These higher peak temperatures will entail a higher energy requirement and more frequent equipment maintenance. It is also possible that nitrogen inerting may be required. Most modern convection reflow ovens are capable of the required peak temperatures but the tight process windows may require up to 11 zones.

Lead free wave soldering equipment should have a non-stainless steel alloy with a protective high-temperature coating. This is because stainless steel has a high nickel content. In solder pots lined with stainless steel, nickel reacts with the no-lead solder and leaches into the solder bath, thereby contaminating it. As the nickel leaches out of the solder pot walls, the walls become thinner and over time the solder pot will develop pinhole leaks[31]. Single sided wave soldering of PTH components is a relatively benign one on the components as the substrate will effectively shield the components from the heat.

Solderability standards

There are no standard solderability tests for lead-free materials. The common standards J-STD-002A, IEC60068-2-58, IEC 60068-2-69 applies only to SnPb so will need to be adopted or amended. This has been addressed by the definitions proposed by the three big European semiconductor manufacturers referenced above.

Component management

Lead-free component substitutions must be identified for all active part numbers. In addition to lead-free terminations, components will need vendor certification for heat resistance to the recommended reflow profile. The metallurgical composition of the alternate finishes will need to be known, so that compatibility issues can be researched.
In an interim period when both lead free and conventional processes and components are available it may be necessary to allocate more part numbers to segregate lead containing and lead-free components.

Reliability implications

Many parts in the existing supply chain have ratings that will be exceeded by the high reflow temperatures. The higher processing temperatures will stress constituent parts more than before and the consequent effects of the reliability changes to the products are not yet known. Some of the concerns are documented in more detail in reference 22. These include

- Failing solder joints due to thick intermetallic layers
- Damage (cracks, delaminations) in plastic IC packages occurring during field use
- Electromigration due to PCB cleanliness issues.

Solder joint reliability test data for both Sn3.9Ag.6Cu and Sn3.5Ag systems shows improved tensile strength, fatigue and plasticity, compared to SnPb [32]. Each user will have to ensure compatibility with all relevant termination, board finishes and soldering metallurgies.

Compatibility with substrates, components, and finishes

FR4

One of the most common substrates in use in the power industry is PCB based on FR4 grade material.
The limitations of FR4 material for lead free compatibility include the T_g (glass transition temperature) which for normal material is 130-140°C and general thermally induced degradation . Above the T_g temperature the Z-axis expansion greatly increases leading to a greater degree of substrate bowing as well as a reliability implication for plated through holes (PTH). It is likely that materials with higher T_g of 170°C or greater will be needed. However the 170°C Tg systems are more susceptible than lower Tg systems to thermal degradation because some thermal stability was sacrificed in order to make these materials process like the lower Tg systems they replaced[33]. In order to increase the thermal performance of the resin system while maintaining processability and cost requirements, new resin systems will be required. Isola have developed a number of resin formulations which give good performance to the "T_{260} test" (time to delamination at 260°C). e.g. IS410 is an FR4 system with a Tg of 180°C and a T_{260} of > 60 seconds which is designed to support higher levels of reliability and the trend to lead-free solder.

In reflow temperatures of 250-260°C there are consequences for the cleanliness during manufacture of PCBs. In these higher than normal reflow temperatures more contaminants which are embedded in the inner layers diffuse to the surface through the solder mask[34] and can cause shorting due to electromigration during biased humidity test. Thus PCB manufacturers should clean the boards at intermediate manufacturing steps and measure cleanliness before application of solder mask. In lead-free soldering this is more important than ever.

Conventional FR4 finishes include HASL (hot air solder level), OSP (organic solderability preservative), Immersion silver, nickel gold. Of these, conventional HASL whereby the PCB is dipped into a bath of molten solder is obviously not compatible with lead-free and HASL with a lead free solder is unlikely to be viable because of the excess temperatures causing too much damage to the PCB as well as poor planarirty. OSP is a low cost alternative but there are concerns about the thermal degradation of the OSP thus limiting the processability of the second side in two-sided assembly. Immersion silver (Alpha Level™) with its very thin co-deposited organic layer may have a similar setback. Immersion tin which is an organo-metallic tin with a fine grained structure that eliminates whisker growth. The tin deposit maintains excellent solderability even after multiple heat excursions and harsh environmental storage conditions. Deposits are fully compatible with no-clean soldering materials and compliant pin technologies.
Nickel/gold is regarded as the best finish but suffers from its own process issues such as e.g. black-pad.
There are some indications that the processability of finishes such as OSP would be greatly improved by soldering in an inert environment using nitrogen.
Bismuth is also being considered but could be deemed unsuitable due to the incompatibility with lead contamination.

Active components and terminations

The solder terminations on many semiconductor packages are plated tin/lead usually in the range 60/40 to 90/10. Plated tin would be a very attractive and cost effective alternative. There are concerns over the potential for tin whisker growth from a pure tin finish but with effective control of plating additives potential for tin whisker growth can be eliminated[35]. Matte tin is under evaluation at many of the major semiconductor manufacturers such as Philips, On Semiconductor, IBM, Maxim, Vishay-Siliconix, Carsem and Amkor [35]. Matte tin has been used on passives such as MLCCs for a number of years.

Some semiconductor vendors (notably TI) advocate the use of a palladium nickel finish or Pd/Ni or Pd/Ni with a gold flash (Pd/Ni/Au). However palladium is an inherently high cost material and also has a much lower dissolution rate than tin during reflow soldering so may necessitate longer soldering times.

Other leadframe and termination finishes include tin-bismuth and tin-copper.

Passive components and terminations

Passives such as ceramic capacitors have been available in a variety of termination finishes for a few years. Thick film silver was a very common MLCC termination but owing to silver leach and solderability problems many manufacturers have changed to electroplated tin (Sn) on a nickel barrier layer.

AVX have announced a 100% Sn lead free termination for their common tantalum capacitors.

There are many chip resistor manufacturers which provide Sn termination as standard.

Component technologies which are not lead free compatible

Some common components are not compatible with the lead free process due to the high temperatures. These include

- MLP capacitors. The release agents used in the polymer will not withstand the high temperatures
- Electrolytic capacitors. There is a concern about the stability of the electrolyte
- High temperature solders. Some electronics assembly operations require a hierarchy of soldering operations at successfully lower reflow temperatures. Typically the solder used in a high temperature die attach process might be Sn10/Pb90 which has liquidus at approximately 302ºC and solidus at 268ºC. There is no lead-free substitute for this type of application

Implementation examples

The lack of either universally accepted or legislation backed definitions for lead-free has led to some vagueness over a product's claim to be "lead-free" or "lead-free compliant". Some interpretations include,

- Max. lead concentration of 0.1%,
- No intentionally added lead,
- Lead free solder process used,
- Compatible with a 260ºC reflow profile
- Components with lead free terminations used,
- Components with lead free terminations used wherever possible,
- Process and all components will be lead-free by July 1st, 2006,

There are a number of products on the market which are claimed to be lead free but it is not clear what definition of lead-free is. One of the first consumer products was the Panasonic Minidisc player, released in Japan in 1998. There are also reports of a lead-free cellphone from Motorola. There are a wide variety of Japanese manufactured consumer electronic goods including digital cameras, video camcorders available in the EU at present 2002-2003. The solder alloy commonly used in Japan is based on SnAgBi

In the power electronics arena the first lead-free dc-dc converter (Ericsson's PKD) was launched at APEC in March 2002. At Electronica 2002 at least two further power converter manufacturers claimed to have lead free or lead-free compatible product.

Other issues

Readiness of the European industry

Despite European legislation being a driver for lead free technology there has been very little effort expended to co-ordinate and summarise activity in Europe as a whole (as has been the case with IPC in the US and JEITA in Japan who have both produced roadmaps). This is due to the fact that there is no Europe wide industry organisation to assume responsibility for this type of activity. Soldertec, (the soldering technology centre associated with Tin Technology[36]) have completed a survey[37] of European companies on the lead free issue. The schedule shown in Figure 2 summarises the state of the industry as perceived by those who replied to the survey.

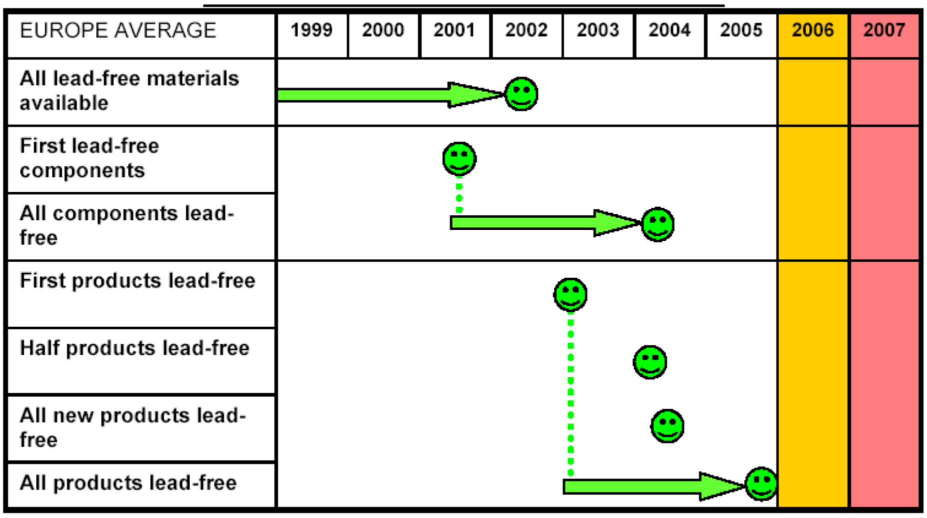

Figure 2: Average targets for lead free implementation (from EU Roadmap Version 1 -Soldertec)

Other impacts of the legislation on the power electronics industry

The WEEE directive effectively enforces recycling while the substance ban is in the ROHS directive.

WEEE

It is likely that the proposed WEEE legislation will enforce OEMs to take back equipment for subsequent recycling or disposal. In operating this policy it is possible that the OEMs will in-turn return subsystems to their manufacturers. This could have a serious effect on the original power electronics manufacturers.

ROHS

The banned substances under the ROHS directive are

1. Lead
2. Cadmium
3. Mercury
4. Hexavalent chromium
5. Polybrominated biphenyls (PBB)
6. Polybrominated diphenyl ethers (PBDE)

Lead. The primary use for lead in power electronics is in solder and component terminations. However lead in glass is a very important contributor to lead in the environment but glass is likely to be exempt from ROHS. The situation with lead is well explored in this document.

Cadmium. Cadmium is often used as an electroplated coating to provide corrosion resistance to metals such as steel, primarily in aerospace, marine and military applications. Cadmium is also found in switch contacts, CdTe solar cells and some plastics

Mercury. Used in certain lamps and tilt switches.

Hexavalent Chromium (Cr VI). Chromium occurs in three stable forms, as a metal, as trivalent Cr (Cr III) which is non toxic and as hexavalent chromium (Cr VI) which is carcinogenic. Electroplated chromium coatings are made by electroplating from a solution containing Cr VI. Plated chromium from other solutions results in a coating with different appearance and inferior wear properties so are not widely used. Conversion coatings for use on aluminium, steel and galvanised products are also produced from Cr VI. The NCMS is running a project on alternative chromate-free coatings, and to identify potential replacement technologies for their applications[38].
Many metalised plastics are produced with a process step involving a chromic acid etch (contains Cr VI).

PBB and **PBDE**. These materials are both flame retardants. Although manufacture of PBB ceased in 2000 some older components such as tantalum caps may still contain PBB. There is no evidence that Octa-BDE and Deca-BDE have any harmful effects but at present they are part of the proposed blanket ban.
Components where PBDEs could occur are ABS moulded parts, epoxy and phenolic PCB, acrylic connectors, polyproplyene, TV cabinets and computer covers, polyethylene and PVC wire insulation[39]

The industry will need to be mindful of the possible implication of all of these issues on their component streams, products and operations.

Conclusion

There are two key triggers that will accelerate activity on lead-free electronics among EMSPA members. These will be either be legislation or market driven

It is clear that the move towards lead-free will occur in some form so it is prudent for all members to remain aware of the situation and take at least some immediate steps in the interim period. During all new product designs they should endeavour to choose component sets which comprise as many lead-free components as possible. They should stay in regular contact with their major and critical vendors to understand their lead-free implementation plan. Questions which should be asked of the vendors could include some of the following,

- Is the component lead free?
- Is there a lead-free alternative part?
- Is the component qualified for reflow at 260°C without impact on datasheet parameters?
- Will lead-free parts be available prior to July 2006?
- Will you have separate part numbers for lead-free parts?

For those manufacturers wishing to investigate a lead-free soldering process they could consider joining one of the industry initiatives such as run by NEMI, HDPUG or others at a national level. These actions will allow manufacturers to be in a reasonable position to initiate action ahead of a legislative demand.

The listed exceptions in the ROHS directive effectively offer a technical exemption on lead content for any products targeted at servers and storage systems (up to 2010) as well as switching and signalling network infrastructure equipment. These exceptions are however under evaluation in order to establish whether they are to be amended.

The lack of definitions in the ROHS directive will continue to be a source of confusion on what can be claimed as "lead-free". It is likely that the industrial customers will provide the requirements.

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References

[1] Report of the conference of the parties on its third session, held at Kyoto From 1 to 11 December 1997 and Addendum Part Two (FCCC/CP/1997/7/Add.1)

[2] Patrick Le Fèvre, "Environmental Issues in Power Electronics (Lead Free)". Proceedings of the Applied Power Electronics Conference (APEC) 2002.

[3] Proposal for a European Parliament and Council directive on Waste Electrical and Electronic Equipment

[4] Proposal for a European Parliament and Council directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (COM(2000) 347 -C5-0415/2000 - 2000/0159(COD))

[5] DIRECTIVE 2002/96/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 January 2003 on waste electrical and electronic equipment (WEEE)

[6] "Recommendations," in *Guidelines for Drinking Water Quality*, 2nd ed. Geneva, Switzerland: World Health Organization, 1993, vol. 1, pp. 49–50.

[7] The United States Environmental Protection Agency (EPA) CASNR 7439-92-1. http://www.epa.gov/iris/subst/0277.htm

[8] R. C. Ciocci,. "Handling the migration to lead free" IEEE transactions on components and packaging technologies, Vol 25, No. 3, September 2001, pp 536—538.

[9] DIRECTIVE 2002/95/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment

[10] "Top Three European Semiconductor Manufacturers Announce Initiative to Eliminate Lead from Semiconductor Products". July 16th, 2001 (http://www.semiconductors.philips.com/news/content/file_728.html)

[11] IPC/JEDEC J-STD-020B. "Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices

[12] EPA, Draft guidance for reporting release and other waste management activities of toxic chemical: lead and lead compound. http://www.epa.gov/tri/lead_doc.pdf

[13] 40 CFR Part 372 http://www.epa.gov/tri/tri1045.pdf

[14] National Electronics Manufacturing Initiative (NEMI) – lead-free group http://www.nemi.org/PbFreePUBLIC

[15] The Institute for Printed Circuit Board (IPC) http://www.ipc.org/ and http://www.leadfree.org/

[16] High Density Packaging Users Group, (www.hdpug.org)

[17] Claire Serant, "EMS group urges component makers to go lead free" EBN (06/07/02, 04:33:16 PM EST)

[18] The Japan Electronics and Information Technology Industries Association (JEITA) http://www.jeita.or.jp/english/index.htm

[19] Jennie Hwang , "Soldering materials", SMT, March 2002. Pages 56-64,

[20] IKP University of Stuttgart, Department of Life Cycle Engineering.

[21] Comprehensive Environmental Response, Compensation, and Liability Act. http://www.atsdr.cdc.gov/99list.html

[22] Hans Danielsson, "Lead-free soldering causes reliability risks for systems with harsh environments", "Advancing Microelectronics" Vol. 29, No. 3, May/June, 2002.

[23] Bill Schweber, "Lead free mandate plumbs new design challenges" EDN, April 18, 2002, pp 55-59.

[24] National Centre for Manufacturing Studies, Final Report of NCMS Project No. 170502 (August 1997) www.ncms.org.

[25] Karl Seelig and David Suraski "Lead Contamination in Lead-Free Electronics Assembly", AIM

[26] Karl Seelig, David Suraski, "Materials and process considerations for lead-free electronics assembly" AIM

[27] Ahmer Syed, "Reliability of lead-free solder connections for area-array packages", APEX 2001

[28] Kenichiro Suetsugu, Matsushita "Development and Application of lead-free solder bonding technology", 20/12/2000, www.smtinfocus.com

[29] "Eliminating lead in electronic assemblies", 2001 IEEE/EIA Technical Seminar, 51st Electronic Components & Technology Conference (ECTC).

[30] NEMI report – Jan 17 2001.

[31] Julie Fields and Ron Berri "Cost-Effective Practices for Lead-Free Wave Soldering" SMT Magazine, August 2002.

[32] Jennie Hwang, "Environment-friendly Electronics: Lead-free Technology", Electrochemical Publications Ltd, 2001.

[33] Eric Holman, Terry Smith, Isola Laminate Systems "Laminate Materials for No-Lead Solder Applications" IPC Expo 2002,

[34] Hans Danielsson "Lead-free soldering causes reliability risks for systems with harsh environments", Advancing Microelectronics, May/June 2002, pages 6-11

[35] Sandra Winkler, Bance Hom, "A look at the past reveals a leadfree drop in replacement" High Density Interconnect" 13/03/01. (www.hdi-online.com/story/OEG20010313S0094)

[36] SOLDERTEC is an organisation focusing on research into soldering technology, including lead-free issues. It is part of the Materials Division of Tin Technology, a company supported by major tin producers and tin consuming industries worldwide. Tin Technology is one of the world's foremost authority on tin with access to more than 60 years experience through its association with ITRI Ltd (formerly the International Tin Research Institute). www.tintechnology.com

[37] European Lead-free Technology Roadmap, Version 1: February 2002. Soldertec

[38] NCMS Chromate conversion program. http://chromate.ncms.org

[39] P.D.Goodman "The EU directive on the restriction of hazardous substances (ROHS)", Advancing Microelectronics, May/June 2002

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