UDK621.3:(53+54+621+66), ISSN0352-9045 Informacije MIDEM 35(2005)4, Ljubljana

WEEE, RoHS, AND WHAT YOU MUST DO TO GET READY FOR LEAD-FREE ELECTRONICS

Valérie Eveloy, Sanka Ganesan, Yuki Fukuda, Ji Wu, and Michael G. Pecht

CALCE Electronic Products and Systems Center, University of Maryland, USA

INVITED PAPER
MIDEM 2005 CONFERENCE
14.09.2005 - 16.09.20045, Bled, Slovenia

Key words: Lead-free, implementation, manufacturing, reliability, compliance, WEEE, RoHS.

Abstract: The transition to lead-free electronics requires surmounting a host of technical, socio-political and economical issues. This paper discusses key concerns in lead-free product development, and provides guidelines to help equipment manufacturers efficiently implement a transition to lead-free electronics. The guidelines address key questions confronting the industry, including those related to lead-free compliance, lead-free part and supplier selection, lead-free manufacturing, and lead-free training and education.

WEEE, RoHS in kaj vse morate storiti, da se pripravite na elektroniko brez svinca

Kjučne besede: komponente brez svinca, tehnologija brez svinca, zanesljivost, WEEE, RoHS

Izvleček: Prehod na elektroniko brez svinca pomeni premagati kopico tehničnih, sociopolitičnih in ekonomskih ovir. V prispevku obravnavamo nekatere ključne zadeve pri razvoju izdelkov brez svinca ter predlagamo vodila, ki naj pomagajo proizvajalcem opreme pri prehodu na elektroniko brez svinca. Poudarek je predvsem na izobraževanju in šolanju za izdelavo elektronike brez svinca, proizvodnji brez svinca, izboru komponent brez svinca, izboru dobaviteljev in končno skladnosti z ustreznimi standardi.

Introduction

An expedient transition to lead-free electronics has become necessary for most electronics industry sectors, considering the European directives /1, 2/, other possible legislative requirements, and market forces /3, 4/. In fact, the consequences of not meeting the European July 2006 deadline for transition to lead-free electronics may translate into global market losses.

Considering that lead-based electronics have been in use for over 40 years, the adoption of lead-free technology represents a dramatic change. In less than ten years, the industry is being asked to adopt different electronic soldering materials, component termination metallurgies and printed circuit board finishes. This challenge is accompanied by the need to re-qualify component-board assembly and rework processes, as well as implement test, inspection and documentation procedures. In addition, lead-free technology is associated with increased materials, design and manufacturing costs[1]. The use of lead-free materials and processes has also prompted new reliability concerns /3/, as a result of different alloy metallurgies and higher assembly process temperatures relative to tin-lead soldering.

This paper discusses key concerns in lead-free product development, and provides guidance to efficiently implement a lead-free transition process that accounts for the company's market share, associated exemptions, technological feasibility, product reliability requirements, and cost. Lead-free compliance, part and supplier selection, manufacturing, and education and training are addressed.

The guidelines are presented in the form of answers to key questions, that are crucial to electronics manufacturers who are interested in migrating to lead-free products, to those companies that will purchase lead-free parts or sub-assemblies, and to those companies, which will support (maintain) traditional products.

1. What is the value for us to provide a lead-free product to our customer(s)?

Both legislative pressures resulting from the European Union (EU)'s proposed ban and the enacted Japanese take-back legislation, and marketing policies from electronics companies, are the driving forces behind lead-free solder adoption.

[1] *The cost of implementing the RoHS directive in the EU has been estimated to be US $ 20Bn /5/. Intel Corporation's efforts to remove lead from its chips have been estimated to cost the company over US$ 100 million so far /6/.*

An analysis of individual companies' strategies and consumer reaction within the electronics industry shows that to date, the main benefit of migrating to lead-free electronics has been increased market share through product differentiation, in terms of product environmental friendliness /4/. Consumers are thus holding corporations responsible for a quality of life that goes beyond the value of their product or service. As product, sub-assembly, component, and board manufacturers wish to be considered environmentally conscious, they are voluntarily migrating to lead-free technology prior to the implementation of legislation. However, once the European legislation becomes effective (July 1, 2006), migrating to lead-free electronics will become a requirement for equipment manufacturers who wish to maintain their market in that region.

As an increasing number of electronic suppliers transit to lead-free technology, the limited availability of lead-based items will become an additional driver to change to lead-free electronics, as manufacturers wish to ensure that their products remain reliable, repairable, and affordable. Considering that most of the electronics supply chain is migrating to lead-free technology, equipment manufacturers who are not prepared for this transition will be left behind technologically, and may ultimately incur substantial costs.

The difficulty for manufacturers to manage their design, manufacturing process, inventory, and logistics to a different set of regulations for each region and customer, may prompt them to extend lead-free product compliance to regions outside the EU. This strategy has been adopted by Hewlett Packard, who plans to extend lead-free compliance on a world-wide basis for non-exempted applications /7/.

A recent survey estimates that 68% of original equipment manufacturers (OEMs) are being requested to comply with the customer's corporate environmental policy /8/. Large OEMs and electronic manufacturing service (EMS) providers have responded more rapidly to the market's demand for lead-free products than mid- and small-sized ones /8/. Major OEMs who have successfully introduced lead-free products include Fujitsu, Hitachi, Matsushita, NEC, Philips, Sony and Toshiba in the consumer sector, which was the first industry to implement lead-free electronics; Dell, HP, IBM, NEC and Toshiba in the computer/server industry; and Ericsson, Infineon, and Motorola in the telecommunication sector.

A survey conducted on 53 component suppliers indicates that 44% of the component suppliers interviewed is already manufacturing compliant parts, and that 94% are designing RoHS-compliant parts /9/. It has been estimated that 69% of component manufacturers expect to be fully compliant by July 2006 /10/.

2. How do we certify lead-free compliance with the regulatory authorities?

An overview of current legislation pertaining to lead-free electronics is available in /4/. As the European Restriction of Use of Hazardous Substances (RoHS) directive /2/ is currently the only legislation that restricts the use of lead in electronic products, the guidelines provided in this section focus on compliance to this directive regarding the usage of lead[2]. However, manufacturers who plan to commercialize products in the EU after July 1, 2006, or in regions affected by other environmental regulations, will also need to ensure compliance with any other legislative or regulatory environmental constraints that may apply to their products[3].

As per the European Commission /11/, the concentration of lead in electrical and electronic products commercialized in Europe after July 1, 2006 should be less than 0.1% by weight in homogeneous materials[4]. The product categories and applications of lead currently exempted from the legislation are listed in the annex of the RoHS directive. The rationale behind the RoHS exemptions and their potential impact on the electronics industry are discussed in /4/. As of now, exemptions include: medical devices and monitoring and control instruments; oil and gas electronics if they are equipment for control and monitoring /12/; batteries used in electrical and electronic equipment, but these will be collected with the equipment once it becomes waste, on the basis of the WEEE directive; and

2 *In addition to lead, the RoHS directive /2/ also prohibits the use of cadmium, mercury, hexavalent chromium, and two halide-containing flame retardants, namely polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), in non-exempted electronic products.*

3 *Other environmental regulations applicable to electronic products are limited in scope to product take-back, reuse, and recycling. These regulations include The European Waste from Electrical and Electronic Equipment (WEEE) legislation /1/, the Japanese Household Electric Appliances Recycling Law /16/, and other laws enacted by China and certain states in the United States. China's Ministry of Information Industry's (MII) draft regulation, "Management Methods for the Prevention and Control of Pollution from Electronics Information Products," bans the use of lead, cadmium, mercury, hexavalent chromium, PBB and PBDE in electronic information products. This regulation is scheduled to take effect on July 1, 2006. Japan has had voluntary green initiatives in place for many years, and South Korea's electronic companies have adopted a voluntary program to comply with RoHS /17/.*

4 *A homogeneous material is defined as a material that cannot be mechanically disjointed into different materials. The terms 'homogeneous' and 'mechanically disjointed' can be explained as "of uniform composition throughout" and "separated by mechanical actions such as unscrewing, cutting, crushing, grinding, and abrasive processes", respectively /11/.*

applications of lead listed in the annex of the RoHS directive /2/. As avionics and automotive electronics have not been specifically mentioned among the categories of electronics covered by the WEEE and RoHS legislations /2, 13/, they can be considered to be outside their scope. However, automotive electronics are covered by the scope of the End-of-life Vehicle (ELV) legislation /14/, which establishes a framework to ensure that vehicles are designed and manufactured in a way that optimizes opportunities for reuse, recycling and recovery. There are also bans for certain substances, but lead used in solders for automotive electronics is specifically exempt /15/.

In December 2004 and March 2005, the Technical Adaptation Committee (TAC) of the RoHS directive voted in favor of a draft Commission decision to add new exemptions, and modify existing ones. The additional applications of lead proposed were: lead in solders to complete a viable electrical connection between semiconductor die and carrier with IC flip chip packages (i.e., flip chip solder joint interconnections), lead used in compliant pin connector systems, lead as a coating material for the thermal conduction module c-ring, lead in solders consisting of more than two elements for the connection between the pins and the package of microprocessors with a lead content of more than 80% and less than 85% by weight, and lead in optical and filter glass /18, 19/. However, the European Parliament raised concerns regarding the legitimacy of the proposed exemptions, and requested the Commission to re-examine its draft decision /20/. Other exemptions /21/ have been requested by various industry stakeholders, which are to be reviewed by the TAC.

In the following sections, guidelines are provided to help establish a company's strategy to comply with the lead-free RoHS regulation, and verify product compliance to this regulation[5].

2.1 Company's Compliance Strategy

The company's strategy (i.e., legal policies) to comply with the RoHS regulation /2/ should be established both at corporate and division level, and documented in the form of a position statement that can be distributed to customers and suppliers. An example of a corporate RoHS compliance position statement is given in /7/.

A company's position regarding the RoHS directive should define what product(s) are to become compliant, the date which these product(s) are commercialized, and regions in which they are introduced if compliance is extended to regions outside the EU. The manufacturer should identify whether any of its products and their applications are exempt from the RoHS legislation. If necessary, clarification should be obtained from the regulatory body on how exemptions may apply to the company's specific products and applications. If the company is planning to use any of the RoHS exemptions, these should be specified in the company's position statement.

Exemptions are likely to remain the only option as long as substitution of a lead-based material by a lead-free one is not technically feasible from a process, reliability or cost viewpoint. For example, the use of high melting temperature (greater than 300°C) lead-based solder, such as Pb-3Sn, in flip chip BGA (FCBGA) applications prevents remelting of the bumps during lead-free reflow soldering. Alternative bumping metallurgies such as electroless nickel/gold and gold, or epoxy bumps, have poor self-alignment properties and higher cost. Other examples of almost unavoidable exemptions include lead in piezoelectric crystal devices (e.g., oscillators, filters) for microwave telecommunication applications, and lead in die attach solders for power applications. Regardless of exemptions, certain manufacturers in exempted industries (e.g., medical electronics, avionics, military electronics) that purchase commercial-off-the-shelf (COTS) electronic parts, which are the subject of the legislation, may be driven to use lead-free technologies, due to part availability and cost considerations /4/. The desire of component manufacturers and other elements of the supply chain is to operate a single line of products, rather than dual lead-free and lead-based production /22, 23/. Furthermore, the exemptions will be subjected to periodic review by the EU legislative bodies, with the intent to progressively eliminate them /23/.

2.2 Certification of Compliance

Once the legislation becomes effective, equipment manufacturers will have complete responsibility for compliance with the RoHS directive. Although no approach has been specified in the EU directives to report compliance with the legislation, at this time it is recommended that OEMs adopt the self-certification approach, for which the majority of the EU member states have indicated their preference /24/. Precedents for self-certification in the EU include the CE mark. Lead-free compliance self-certification should be supported by 'compliance' documentation from the suppliers, certifying that the procured materials, parts and subassemblies not exempted by the legislation meet the requirements of the RoHS directive, in terms of the maximum concentration of lead. Guidance to verify the compliance of procured items is provided in Section 2.2.1.

[5] *Legislative requirements pertaining to lead-free electronics should be regularly monitored for revisions. New and revised standards applicable to lead-free assembly process, qualification test, and inspection should also be identified (Section 17). A map of which products (and their quantity) are being sold into which regions should be established. The regulatory body, regulation/standard and its effective date, that the products must comply with, as well as corresponding regulatory requirements (e.g., banned materials, associated threshold limits including the level at which it should be measured, recycling requirements, and reporting methods) should be identified.*

A market surveillance will be conducted by national enforcement authorities to verify producers' compliance with EU regulations. Upon request of the enforcement authority, producers will be required to demonstrate compliance by providing satisfactory evidence. Inspections will be conducted, involving product chemical composition analysis (see Section 2.2.2).

At this time, the WEEE legislation itself only states that penalties applicable to breaches of the national provisions of the directives should be "effective, proportionate and dissuasive" /1/, but EU member states will determine the actual penalties. Regardless, non-compliance could lead to a decrease in market share and reputation.

2.2.1 Verification of compliance for procured materials, parts, and sub-assemblies

To ensure that the final product is lead-free, assurance should be obtained from all related material, part and sub-assemblies suppliers that their products do not contain lead with a concentration above the RoHS restricted level (0.1% by weight). Manufacturers will be required to maintain a record of their suppliers' compliance documentation, that can be shown to the enforcement authorities in the course of an inspection. The declaration obtained from the supplier will constitute a legal documentation.

No format or time frame for producing such compliance documentation has been specified. At this time, it is recommended that OEMs issue a formal letter to suppliers and assemblers, requesting self-certification on the basis of chemical composition analysis of the supplied material and/or parts. It should be noted that the transmitting material safety data sheet is not sufficient, because elements with content levels below 1% by weight are not shown. Examples of lead-free/RoHS compliance statements from electronic part manufacturers include /25-30/.

The self-certification request issued to the supplier should be supplied along with the company's RoHS position statement, and a list of requirements and restrictions for the procured material, part, or sub-assemblies, including the threshold concentration value of lead. The lead-free certification request may be included as part of a material declaration questionnaire (also referred to as green procurement survey or supply chain questionnaire) that manufacturers may already issue to their suppliers, to verify lead-based product compliance to other regulatory requirements /31/. An example of environmental requirements set by an equipment manufacturer for its procured materials, parts and sub-assemblies is provided in /32/. Suppliers may use different units for defining the concentration of hazardous substances (e.g., part per million, percentage by weight, percentage by mass). Caution should be taken when examining lead content data, because the lead concentration threshold set by the RoHS legislation is expressed by weight. The verification documentation obtained from suppliers and assemblers should be re-obtained or re-signed whenever there is a change in materials used in supplied parts or end products, process, or regulatory requirements.

For all procured lead-free items, a lead-free compliance notation/record should be included in the material management system or database that the company may already employ to convey material chemical data for lead-based products. This will permit the lead-free compliance of the procured items to be verifiable throughout the enterprise (e.g., design, production and logistic departments) and supply chain.

If no appropriate compliance documentation is available from the supplier, equipment manufacturers should consider an alternative supplier with lead-free capability, or conduct a chemical analysis of the procured part. Chemical analysis methods and providers of lead-free compliance assessment services are listed in Sections 2.2.2 and 3, respectively.

2.2.2 Chemical analysis

Conducting a chemical analysis of the procured materials, parts and sub-assemblies may be necessary to ensure compliance with legislative requirements, when the legal compliance documentation is not available from the supplier(s). Lead can be found in many electronic packaging materials, namely: solders, component terminal finishes (i.e., lead finish for leaded packages or solder ball for area array packages and flip chip interconnections), separable connector terminations, PCB pad surface finishes, solder-based die attach materials, as an alloying element in aluminum-based die-casting materials, polyvinyl chloride (PVC), PVC wiring, balance weights for large Titan motors, paints, plastic additives, tinned cables, resin stabilizers and additives, optical materials, and ferroelectrics.

Two standards have been published on assessing the lead content of electronic products. EIA/ECCB-952 /33/ describes the required elements of a plan to assess the lead content of a product, in terms of high-level requirements and areas of concern that must be addressed by the process. /34/ defines test procedures to assess the lead content of polymeric and metallic materials, and electronic parts and assemblies[6].

[6] *Analysis procedures include the use of Energy Dispersive X-Ray Fluorescence (EDXRF) or Wavelength Dispersive X-Ray Fluorescence (WDXRF) for material/part qualitative and quantitative screening. The use of inductively coupled plasma-atomic emission spectroscopy (ICP-AES), inductively coupled plasma-mass spectrometry (ICP-MS), or atomic absorption spectroscopy (AAS) may be used to confirm the lead content /34/. These experimental methods are discussed in /35/, along with Energy Dispersive X-Ray analysis, Spark Emission and DC Arc Emission Spectroscopy, Glow Discharge Optical Emission Microscopy, and Polarography.*

Considering the level of expertise required for compositional analysis of electronic assemblies (e.g., in terms of potential limitations of the experimental method and equipment, instrument calibration), manufacturers should consider subcontracting such analysis to specialized providers (see Section 3).

Databases such as offered by i2 /36/ and Underwriters Laboratories /37/, which contain information of the chemical content of certain electronic materials and components, may help identify non-compliant electronic parts, lead-free alternatives and their suppliers. i2's database provides material composition data at component level, including RoHS-restricted substances. UL's database covers plastic materials and is expected to expand in the near future to include information on restricted substances. However, parts and materials change, and it is critical that guarantees for accuracy and compliance be obtained.

3. Which companies can test electronic materials, parts and sub-assemblies for lead-free compliance?

Material, part, sub-assembly and product compliance analysis can be subcontracted to third parties such as material analysis companies with lead-free compliance assessment capabilities. The cost of chemical analysis services typically varies from US 500 dollars for standard elemental composition analysis by energy dispersive x-ray spectroscopy (EDS) or XRF spectroscopy, up to a few thousand US dollars for highly sensitive analysis techniques such as mass spectrometry. Although no particular provider of chemical analysis services is advocated, examples include /38-42/.

4. How should we get started with the design of lead-free products?

All materials and parts in final product, which may contain RoHS restricted substances in the Bill of Materials (BoM), should be identified. The BoM may represent a single product or assembly, or a family of products. As outlined in Section 2.2.2, identification of such materials and parts may require material analysis. Any impacted parts and products should be documented in a database.

Non RoHS-compliant materials and parts should be replaced with RoHS compliant alternatives that are selected based on availability, manufacturability, reliability and cost considerations. Manufacturability considerations include compatibility between lead-free materials used as component terminations, PCB pad finishes and solders; material and part compatibility with the lead-free manufacturing processes (reflow, wave, rework), and component terminal and PCB pad solderability. Potential reliability concerns specific to lead-free materials and processes include component moisture and thermal sensitivity, excessive intermetallic growth, tin whiskering, electro-chemical migration, solder joint manufacturing defects (e.g., poor wetting, fillet lifting, voiding, cold joint), and material/process incompatibilities in assemblies combining lead-free and lead-based metallurgies.

When outsourcing manufacturing, the part selection process should be co-ordinated with the assembly house to ensure compatibility of the procured parts with the manufacturing processes. Examples of EMS providers with lead-free capability include /43-46/.

5. How do we assess our suppliers' ability to offer lead-free parts and assemblies?

The capability of part, design and manufacturing service providers should be assessed based on the same criteria as those employed for providers of lead-based products. In addition, evidence of the provider lead-free capability should be obtained, particularly when considering less established providers. Such evidence should include lead-free/RoHS compliance certification for the procured parts (Section 2.2), and proof of a qualified lead-free manufacturing process for EMS providers. Lead-free part suppliers and EMS providers can be evaluated based on the following criteria.

Inspections of in-coming materials and parts should be performed, to ensure conformance of the procured items to quality and reliability requirements applicable to lead-free technology and/or lead-based products. Requirements for lead-free components and boards are outlined in Sections 6 and 7, respectively.

Component moisture and/or thermal sensitivity (see Section 6.2) should be addressed using standardized or recognized storage, packing, handling and transportation procedures and using qualified lead-free reflow, rework/repair processes.

Assembled boards should meet standardized quality and reliability criteria (e.g., requirements defined by and tested in accordance with global standards such as IPC, IEC, and JEDEC, or regional standards, such as JPCA and JEITA in Japan). The board assembler should demonstrate willingness to co-operate with the equipment manufacturer, as well as component, board and solder suppliers, to successfully design and produce reliable lead-free products.

Appropriate lead-free product designations (e.g., part number change, date code differentiation, marking) should be employed to trace lead-free materials, parts and assemblies throughout the supply chain. Product change notices (PCNs) and alerts should be provided by the supplier, to notify equipment manufacturers of the replacement of lead-based items by lead-free ones (see Section 16).

The offering, availability and scheduling of assembled lead-free parts and systems, including lead-times for a given production volume, should be compatible with the equipment manufacturer's plans for lead-free products. Any possible change in cost due to a material change should be monitored.

The manufacturing house personnel, including operators, technicians, process engineers, and managers should receive appropriate and up-to-date lead-free education and training, and have access to suitable information resources (see Section 18).

6. Is there anything unique that we need to do when selecting lead-free components?

The main considerations for lead-free component selection (including IC, passive and optoelectronic components, and connectors) include terminal finish, moisture and thermal sensitivity, material and process compatibility, and part tracing.

6.1 Part terminal finish

At present, pure tin (matte finish) is the most widely adopted finish material for leadframe components, followed by nickel-palladium-gold leadframe pre-plating /3/. Other lead-free leadframe finishes include tin-bismuth, tin-copper, and tin-silver.

For array components, tin-silver-copper solder ball metallurgy has been widely adopted.

For connectors, tin-copper (Sn97.3-Cu0.7) and tin-silver-copper (e.g., Sn-Ag3~4-Cu0.5~0.7) finishes can be employed as replacements of tin-lead solder contact finishes. These lead-free alloys exhibit better hardness and resistance to fretting corrosion than tin-lead /47, 48/. For cost-driven applications, pure matte tin may be used.

Tin whiskers are hair-shaped crystals that can grow spontaneously on the plating surface, and could cause electrical short circuits across part terminals, such as connectors. The whisker tolerance level of the specific product and application considered should be identified. For long-duration or high-reliability applications (e.g., medical, avionics, space, and defense applications), the risk tolerance may be sufficiently low as to warrant consideration of mitigation strategies /3/. Standard JESD22A-121 /49/, released this year, specifies test methods to assess the propensity for whisker's growth on tin and tin alloy surface finishes. iNEMI has submitted tin whisker acceptance test requirements /50/ for review to JEDEC and IPC. iNEMI has also proposed mitigations approaches that include the use of thick tin coating (with thickness greater than 8 ěm) or nickel under-plating (with thickness greater than 1.27 ěm) over copper base metal, and recommends avoiding the use of pure bright tin plating without a mitigation strategy /51/. The effectiveness of various mitigation strategies is discussed in /3, 52/. Examples of non-standard vendor tin whisker qualification tests are given in /53, 54/.

Nickel-palladium or nickel-palladium-gold leadframe component finishes are not prone to whisker growth /51/. However, there are also potential disadvantages associated with the use of these finishes /3/, including cost, solderability, and susceptibility to creep corrosion /55, 56/.

An example of procurement guidelines set by an equipment manufacturer for lead-free components is given in /57/. In this example, the equipment manufacturer specifies its preferred termination finishes, and a number of requirements for tin-based finishes, including plating process control, plating characteristics known or suspected to influence whisker growth, and tin whisker qualification tests.

6.2 Component moisture and thermal sensitivity

Components may be more prone to mechanical damage (e.g. delamination, cracking, popcorning) when exposed to lead-free reflow soldering temperature profiles compared with standard tin-lead reflow.

Organic IC packages. The moisture sensitivity of organic IC packages is characterized in terms of component floor life when stored in a PCB assembly environment, outside moisture-proof packaging. For lead-free assembly, package moisture sensitivity, as defined per IPC/JEDEC J-STD-020C /58/ classification, should not exceed moisture sensitivity level (MSL) 3. The IPC/JEDEC MSL rating of a plastic component has been found to decrease by up to one or two ratings for every 10°C increase in peak reflow temperature /3/. For example, an MSL 1-rated component at a tin-lead assembly temperature of 220°C would become MSL 2 or MSL 3 at a lead-free assembly temperature of 240°C. Qualification tests performed by component suppliers should include moisture sensitivity level tests. Equipment manufacturers also need to ensure that the time out of moisture-proof packaging is appropriately monitored throughout the supply chain, by component manufacturers, distributors and contract manufacturers. Baking moisture sensitive components (125°C, 24 hours) before lead-free reflow soldering may be a good precaution.

Component temperature rating requirements for lead-free assembly and rework depend upon package volume and thickness, and are specified in standards IPC/JEDEC J-STD-020C /58/ and JEITA ED-4701-301A /59/. Large, thin organic packages (e.g., BGAs, TQFPs, CSPs) are generally more prone to hygrothermal stress-induced failures. Small volume, thin SMD packages (i.e., with small thermal mass) reach higher body temperatures during reflow soldering to boards that have been profiled for larger packages. Therefore, it should be verified that such components are rated at the appropriate temperature specified by the standard. Equipment manufacturers need to ensure that component vendors following JEDEC J-STD-

020 use the latest version of the standard, in which temperature rating requirements have been revised compared with J-STD-020B. Other standards relating to the handling and assembly of moisture and/or thermally sensitive components include IPC/JEDEC J-STD-033C /60/ and Mil-Std 202G Method 210F /61/.

Passive components. For passive components such as chip capacitors and resistors, it should be verified that the component temperature rating is sufficient for lead-free soldering. In addition, the allowable PCB flexure specified by the component supplier may need to be considered, as passive ceramic components may be more susceptible to mechanical damage (e.g., cracking) due to higher soldering temperature than for tin-lead soldering, and possibly due to different solder joint metallurgies. Large chip components (1210 in size and above) tend to be more exposed to flexure-induced damage than smaller components.

Optoelectronic components. Optoelectronic components, such as light emitting diodes (LEDs), are very temperature-sensitive and could suffer optical property degradation or mechanical damage when exposed to lead-free reflow soldering profiles. Temperature-sensitive devices may require a separate assembly process that is performed after standard reflow of other components. Thermally-sensitive devices may be assembled using either press-fit, hot bar soldering, laser soldering, hand soldering and/or a conductive adhesive attachment method. Wave soldering may be suitable for devices having intrusive leads. Assembly should be performed based on the component manufacturer assembly guidelines.

Connectors. The majority of connector housings are made of plastic materials, and can be prone to hygrothermal stress-induced defects such as popcorning, similarly to IC plastic packages. It should be verified with the manufacturer that the connector is rated to a sufficiently high temperature for lead-free assembly.

6.3 Material and process compatibilities

Due to part availability and cost considerations, equipment manufacturers may be constrained or tempted to combine lead-free and lead-containing materials and parts in PCB assemblies. The use of lead-free and lead-based material combinations could potentially affect solder joint reliability, and examples of such situations are given below, both for forward and backward assembly incompatibility. Forward compatibility refers to a component with lead-based terminations soldered using lead-free solder and a lead-free temperature profile. Forward incompatibility issues can arise due to unavailability of a lead-free component in the transition period. Backward compatibility refers to a component with lead-free terminations soldered with tin-lead solder and a tin-lead temperature profile. Exempted products may be exposed to backward incompatibility issues when lead-based components become unavailable. When possible, the following situations should be avoided.

6.3.1 Forward incompatibility

Lead in lead-based component termination (leadframe or solder ball) can interact with bismuth-containing lead-free solder (e.g., Sn-Bi, Sn-Ag-Bi, Sn-Zn-Bi, Sn-Ag-Cu-Bi) during assembly, to form a low-melting point phase (Sn-51Bi-32Pb, melting point = 96°C) which can cause cracking in solder joints /62/.

Lead-containing component termination with lead-free Sn-Ag-Cu or Sn-Ag solder can result in poor solder joint mechanical reliability, due to the formation of a Sn-Pb-Ag eutectic (62Sn-36Pb-2Ag, melting point = 179°C) during the cooling phase of the assembly process. This phase has different microstructural characteristics compared with the bulk of the solder joint, and can cause solder joint fillet lifting in through-hole joints /63/.

6.3.2 Backward incompatibility

BGA packages with Sn-Ag-Cu solder balls assembled to a PCB using a conventional tin-lead soldering temperature profile may result in the formation of "cold joints". A hybrid soldering process, which uses higher reflow temperatures compared with standard tin-lead reflow, may be required to melt the balls.

Tin-lead hot air solder leveling (HASL) PCB pad finish can cause solder joint fillet lifting in through-hole lead-free nickel-palladium-gold coated components soldered with lead-free Sn-Ag solder /3/. This is due to the formation of 62Sn-36Pb-2Ag eutectic during the cooling phase of the assembly process.

Tin-lead HASL PCB pad finish with lead-free Sn-Ag-Cu solder can result in weak joints with voiding. This has been attributed to depletion of tin from the pad coating, which results in the formation of a weak lead-rich phase /64/.

6.4 Solderability and reliability

Conformance to standardized solderability criteria (per IPC/EIA-J-STD-002B /65/) and reliability criteria, already applicable to lead-based components, should be ensured. However, caution should be exercised, as the wettability of most lead-free solders is not as good as that of eutectic tin-lead solder, causing potential quality and reliability issues. The shelf life of the lead-free component finish, which impacts on solderability, should be obtained from the supplier.

There are two known trends with regard to the thermo-mechanical reliability of lead-free solder joint interconnections in temperature cycling conditions. Lead-free solder joint thermo-mechanical fatigue durability is expected to be equivalent or better relative to tin-lead eutectic joints (considering the same package and board) at small levels of mechanical loading (i.e., small thermal expansion mismatch between the component and board, which generally applies to plastic packages, and moderate thermal cycling). Conversely, lead-free solder joint thermo-mechanical fatigue durability may be lower relative to tin-lead eutectic joints (considering the same package and board) at high levels of mechanical loading (i.e., high thermal expansion mismatch between the component and board, which generally applies to ceramic leadless and ceramic ball grid array packages, and severe thermal cycling).

The use of reliability qualification tests should be considered to assess joint thermo-mechanical reliability for the specific product and application environment. Further information on lead-free electronics reliability can be found in /3/.

7. Is there anything unique that we need to do when designing or selecting lead-free circuit boards or circuit assemblies?

Considerations for lead-free board design include PCB pad finish and laminate material selection.

7.1 PCB pad finish

The primary lead-free alternatives to tin-lead HASL are immersion silver, immersion tin, electroless nickel/immersion gold (ENIG), and organic solderability preservative (OSP). Unlike for lead-free component termination finishes, there is a history of use for lead-free board finishes. PCB finish selection is based upon the finish wetting characteristics with lead-free solders, shelf life, pad planarity, and cost. Reported concerns associated with each finish are summarized below.

Immersion tin used in PCBs subjected to multiple reflow temperature profiles can be prone to Sn-Cu intermetallic formation, resulting in a degradation of pad solderability. Immersion silver is known to generally better survive multiple reflows than immersion tin due to the lower growth rate of Sn-Ag intermetallics compared with Sn-Cu intermetallics, but silver migration may pose a reliability risk for certain applications.

Due to the thinness of OSP and immersion silver finishes, these coatings may be more prone to mechanical damage (e.g., surface scratches) during board handling operations, that could expose the underlying metal and thus impact pad solderability.

ENIG is considered a multifunctional (applicable to soldering, aluminum wire bonding, press fit connections and contact surface), corrosion resistant surface finish, but can be prone to "black pad" defects /66/. Black pads are characterized by separation of the solder joint from the surface of the electroless nickel underplate. This is commonly attributed to excessive phosphorous contamination of the electroless nickel.

The shelf life of all finishes impacts solderability, and should therefore be obtained from the supplier. Immersion tin and immersion silver are more cost-effective relative to ENIG.

7.2 PCB laminate material

PCB laminate material selection should follow the same criteria as for lead-based products, with some exceptions. It should be ensured that the laminate can withstand multiple reflows and rework at the appropriate lead-free processing temperature without thermo-mechanical damage. Although FR-4 laminates with glass transition temperatures of approximately 140°C may be suitable, applications exposed to high temperature environments (e.g., under-the-hood, oil well applications) may require materials with higher glass transition temperature, such as high-glass transition temperature FR-4 (e.g., 170°C). Potential concerns associated with assembly at lead-free soldering temperature profiles include increased board warpage, which could cause planarity problems with large components /67/, increased through-plane thermal expansion, which could affect plated-through hole (PTH) reliability, or possibly delamination of the metallization /68, 69/. According to /68/, one-third of the U.S. industry has switched to higher glass transition temperature materials (e.g., 170°C) for a greater margin in rework.

The laminate material should not contain polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). These halide-containing flame retardants are prohibited by the RoHS legislation. Furthermore, the laminate moisture absorption properties should be verified with the supplier, as well as any specific storage conditions/duration or pre-baking that may be required before assembly.

7.3 PCB layout

In general PCB design rules for lead-free soldering are same as tin-lead soldering. However, because of inferior lead-free solder wettability and less superheat (temperature above the liquidus) during reflow, there will be differences in optimized layout between lead-free and lead-based designs. The following guidelines for PCB layout for lead-free soldered product may be considered.

It is a good practice to design the PCB to achieve even spread of high and low thermal mass components (to minimize temperature gradients and peak temperature).

PCB design may also need to accommodate hand soldering of some thermally sensitive components (due to higher reflow temperature associated with lead-free soldering).

In some designs, insufficient component spacing can result in secondary reflow of adjacent leadframe components during lead-free rework operations of BGA/CSP components, particularly in high-density component-board assemblies. Typically, the minimum component spacing between BGA/CSP and leadframe components should be 150 mils /3/.

In some applications, pad width may have to be reduced to minimize the exposed pad (without solder coverage) due to the reduced spreading (wetting) of lead-free solder.

The product designer should consult with PCB manufacturer and assembler to minimize manufacturing concerns

8. Is there anything unique that we need to do when selecting lead-free solder alloys?

The International Tin Research Institute (ITRI), International National Electronics Manufacturing Initiative (iNEMI), European Consortium BRITE-EURAM and Japan Electronics and Information Technology Industries Association (JEITA) recommend Sn-Ag-Cu eutectics as the most promising lead-free solder metallurgies[7], endorsing Sn-4.0Ag-0.5Cu, which is the most widely-characterized alloy /3/, as well as Sn-3.0Ag-0.5Cu (JEITA's recommendation), Sn-3.9Ag-0.6Cu (iNEMI's recommendation), and Sn-3.8Ag-0.7Cu (BRITE-EURAM's and Soldertec's recommendations) /70/.

Both for reflow and wave soldering, Sn-3Ag-0.5Cu (liquidus temperature, 217-220°C) currently appears to be the leading candidate adopted by the industry, due to cost considerations. 99.3Sn-0.7Cu (liquidus temperature, 227°C) is a low cost alternative for wave soldering, recommended by iNEMI /71/.

Equipment manufacturers should verify the licensing agreements of the lead-free solder supplier, and verify that the solder supplier is aware of any potential patent issues in the country of manufacture as well as country of sale or customer re-sale. Typically, royalty cost account for 2 to 8 % of the solder paste cost. If the procured lead-free solder is not properly licensed, the alloy composition should be obtained, and an explanation of why the solder supplier believes no license is necessary should be sought. In addition, the equipment manufacturer should verify whether their company has a worldwide intellectual property (IP) non-infringement warranty and indemnity in place with the solder supplier or assembly house, as appropriate. Such warranty should be application-specific, and may help the equipment manufacturer to recover damages in the event of patent infringement issues. However, an indemnity is not an alternative to due diligence. Firstly, an indemnity would not protect the equipment manufacturer from being sued. Secondly, the equipment manufacturer would never be fully compensated for the damage caused to customer relationships by missed shipments. Furthermore, small sub-contractors or solder suppliers may not have the financial strength to honor the indemnity.

9. Is there anything unique that we need to do when selecting fluxes?

The industry is migrating to no-clean flux systems for both cost and environmental reasons. Because tin-silver-copper pastes have lower wettability than tin-lead ones on copper, no-clean flux systems using slightly more aggressive wetting agents than conventional commercial fluxes (employed with lead-based solders) may be required. Such fluxes tend to leave a higher amount of residues on the board after reflow, compared with conventional fluxes. This may cause reduced surface insulation resistance and increase the risk of electrochemical migration. In addition, the flux residues are harder than those formed with tin-lead soldering due to higher reflow temperatures, which can cause probing difficulties due to increased electrical contact resistance.

Although water-soluble flux systems eliminate potential surface insulation resistance and electrochemical migration issues, little progress has been made to develop such formulations due to lack of industry demand. On the other hand, solder paste manufacturers are actively working on the development of improved no-clean solder pastes.

Japanese end-users have successfully implemented lead-free wave soldering with Sn0.7Cu, Sn3.5Ag, and Sn-Ag-Cu alloys using rosin-based no-clean fluxes. In North America and Europe, the preference is to use volatile organic compound (VOC) no-clean fluxes.

10. How do we modify the approved vendor and part lists for the lead-free supply chain?

Once the lead-free part and corresponding vendor are approved, this information should be updated in the company's material and vendor database or management system, in the same manner as for lead-based products.

A monitoring scheme of supplier PCNs and supplier alerts of the replacement of lead-based parts by lead-free ones should be established. The PCN-alert database service, and Government-Industry Data Exchange Program (GIDEP) are examples of alert databases.

11. How do we mitigate supply interruptions related to the bill of materials?

It is expected that lead-based products may become unavailable as electronic suppliers transit to lead-free technology. Consequently, manufacturers of exempted applications (e.g., medical electronics) that develop non-RoHS compliant products may be exposed to the discontinuation of parts, making design, production and maintenance risky. The potential issues associated with assembling lead-free parts to a PCB using tin-lead solder and processes were summarized in Section 6.3.

7 *An overview of lead-free soldering alloys and their characteristics (including constitutive properties, durability, and cost), suppliers and users is provided in /3/, with corresponding solder joint characteristics (including metallurgical reactions, mechanical properties, electromigration- and current carrying capability).*

Manufacturers relying on lead-based technologies must monitor PCNs, and identify whether their suppliers have any plans to discontinue the production of lead-based products. If this is the case, the time line for the discontinuation should be obtained.

Life time buy practices are a possible solution to resolve supply interruptions. However, potential disadvantages of such practices include significant on-time expenditure, increased inventory on the balance sheet, the requirement for proper storage space (with appropriate temperature, humidity, and handling conditions), and the potential for future unplanned requirements (e.g., significant changes in product technology or upgrades).

12. What are the storage and handling requirements for lead-free parts and sub-assemblies?

The shelf life and specific storage and handling requirements of the procured items should be obtained from the suppliers. Finish shelf life (e.g., PCB pad-, component- and connector termination finishes) will impact solderability.

The moisture and thermal sensitivity of leaded and lead-free components and board laminates is different. Handling, packing, and shipping requirements for moisture/reflow sensitive surface mount devices are specified by JEDEC standard J-STD-033C /60/.

If thin immersion silver or OSP pad finishes are used, care must be taken to avoid surface defects or scratches.

Lead-free solder paste should be stored in a container with appropriate labeling and identification to distinguish it from tin-lead solder paste. The solder paste should be stored in the refrigerator between 35 and 45°F and should be used on a first-in/first-out (FIFO) inventory control basis. The shelf life of tin-silver-copper solder pastes at the recommended storage temperature (35 to 45°F) may be reduced from the typical six months expected for tin-lead solder paste, to three to four months. The materials used in fluxes developed for use with tin-lead solder paste may attack the higher tin-containing lead-free solder powder (>95% tin by weight) more than standard tin-lead solder powder (63% tin by weight), hence reduce the shelf life of the lead-free paste. Solder paste manufacturers are in the process of developing flux chemistry formulations to improve the shelf life of lead-free pastes. The solder paste should be maintained at room temperature for four hours before opening the container /3/.

In addition, the storage and handling scheme of electronic parts should prevent the mixing of lead-free and lead-based items. This can be achieved through appropriate part identification, as detailed in Section 16.

13. How should we perform lead-free component-board assembly?

The following guidelines for surface mount and through-hole assembly are adapted from /3/.

13.1 Reflow Soldering

Surface-mount assembly consists of three steps: screen printing, pick and place, and reflow. Only qualified lead-free materials should be available on the production floor. In addition, it should be ensured that the materials selected for assembly are free of other impurities that may impact on manufacturability and/or reliability.

Stencil printing. Studies conducted by many companies have shown that the same type of stencil printer can be used for lead-free solder paste as for tin-lead solder. The stencil design guidelines are identical to those for tin-lead systems. As noted in Section 7.3, there is currently no change in PCB pad design guidelines for soldering lead-free components. The print volume (transfer rate) of lead-free paste has been found comparable to that of lead-tin paste /3/. The same printing settings can be applied to lead-free solder pastes as for tin-lead. Settings include printing speed, squeegee pressure, on or off contact, separation speed, separation distance, and cleaning frequency. For the screen-printing process, high squeegee pressure and low printing speed have been found to yield better printing results for tin-silver-copper paste /3/. The stencil release rate has a minimal effect on the printability of lead-free solder pastes. Typical settings tested for lead-free pastes are: squeegee blade pressure (16-inch blade length) = 18 kg, printing speed = 10-20 mm/s, snap-off rate = 1mm/s /3/.

Pick and place. No change is required to pick-and-place machines to accommodate lead-free components.

Reflow oven equipment. Most eight-to ten-zone convection reflow ovens are capable of lead-free soldering. Ten-zone ovens enable a more precise control of spatial temperature variations across large boards. Currently-available ten-zone convection ovens have a 325 to 350°C temperature rating. Typical oven settings would normally not exceed 300°C in the reflow zones, and are capable of heating the boards and components to the temperature range (240°C to 250°C) required for lead-free soldering of most products. If necessary, higher temperature can be achieved by lowering the conveyor speed. The use of a nitrogen atmosphere may contribute to improve the wetting of the lead-free parts, and to reduce the amount of no-clean flux residue deposits on probe surfaces for In Circuit Testing /3/. However, nitrogen can increase tombstoning (solder joint lifting) /71/.

Reflow temperature profile. Typical reflow profile parameters for lead-free tin-silver-copper paste (melting point = 217°C) are: ramp rate = 1-2°C/sec or less than 3°C/sec; soak time and temperature range = 100 seconds at

170-217°C; reflow peak temperature = minimum solder joint peak temperature (235°C to 245°C); reflow time above 217°C for tin-silver-copper = 45-75 sec or less than 90 seconds; cooling rate higher than 2°C/sec if possible, or lower than 6°C/sec. An example of lead-free reflow process qualification is given in /72/.

13.2 Wave Soldering

As the wave soldering process window for Sn-3Ag-0.5Cu solder is narrower than for tin-lead wave solder, more precise process control is required. Using the correct process parameters, lead-free wave soldering can be achieved successfully.

Atmosphere. The use of a nitrogen atmosphere typically enables soldering temperature to be reduced by 10°C, improves the process window, and yields a more reliable joint, but at a higher cost compared with air.

Equipment. Wave soldering machines used for lead-free assembly may require longer contact time to achieve the desired wetting, due to the lower wettability of lead-free solders relative to tin-lead ones. Once the equipment is modified or upgraded for lead-free processing, a tin-lead process can no more be employed. The wave soldering machine must have an adequate preheating capacity to maintain thermal shock to the assembly when it enters the solder wave to within 100°C.

The solder pot needs to be drained, cleaned, and refilled with lead-free solders. The surface coatings on the pot pump assembly and nozzle can be a major issue when handling multiple tin-based chemistries. When normally filled with wet solder, the pot is protected from reaction with the atmosphere. With too frequent drainage of wet solder and re-filling with new solder, the solder pot is highly stressed from high to low temperature and vice versa. Improper cleaning or incorrect cleaners can cause further damage to the anti-rust and anti-corrosion material layer on the surface. Furthermore, high tin-containing solder alloys require the pot coating to be non-reactive, as stainless steel components in the wave solder pots are attacked (corroded) by lead-free alloys over time. Similarly, the compatibility of the lead-free solder paste with the pump impellor and solder bath nozzles should be verified.

Wave soldering machines for which the pot show signs of poor performance and aging when used for tin-lead assembly should not be considered for lead-free production. New solder pots, pump assemblies, and lead-free compatible flow ducts should be used where appropriate. If required, the wave soldering machine supplier should be contacted for a lead-free upgrade of the equipment.

For existing wave soldering machines that are still relatively new, it is advisable to modify the pump assembly, nozzle, and flow duct of each chip wave and Lambda wave by applying a coating to protect the equipment from erosion. Typical lead-free upgrade package components include: first wave (chip wave), pump assembly, nozzle (with coated layer), flow duct, and secondary wave (Lambda main wave).

Certain wave machines with stainless steel pots cannot be upgraded for lead-free wave soldering due to the need for solder pot replacement. The jacking stand for the stainless steel pot may not support the new cast iron pot and needs to be changed. Recently, wave solder equipment manufacturers have been offering lead-free compatible parts as standard options.

Process parameters. For lead-free wave soldering with Sn0.7Cu, the peak temperature registered on the bottom of the board is 255°C, whereas the peak temperature recorded on the top side is 198.8°C. The dwell time in the main contour wave (Lambda) is 3.5 seconds and the total time above the liquidus temperature (227°C 217-220°C) is 9.7 seconds.

Solderability, wettability. As most lead-free solders have a higher melting temperature than eutectic tin-lead solder (e.g., 217 to 227°C versus 183°C), oxidation of high-tin solders can become a greater issue. A higher rate of dross (a metallic oxide) formation can be observed on the surface of molten lead-free solder in the presence of air, compared with tin-lead solder. Although the rate of dross formation varies depending upon the lead-free solder used, this result in degradation of solder performance. Conventional no-clean fluxes may dissipate or become inactive before reaching the peak solder temperature. Solderability studies of lead-free alloy and component finish in both air and nitrogen have concluded that lead-free solder has lower solderability than tin-lead solder, especially when weaker no-clean VOC-free fluxes are used. In addition, the necessary removal of dross, which adheres to the solder pot surfaces as it cools, causes product interruption and additional labor cost. Studies have also shown that solderability is considerably improved when processing takes place in an inert (nitrogen) atmosphere.

The required process temperatures for good wetting can be reduced with the use of nitrogen, thereby reducing the potential damage to temperature-sensitive components. Nitrogen atmosphere may be necessary, especially with complex boards with varying finishes and thermal requirements. The oxygen levels in nitrogen atmosphere should generally be kept below 350 SCFH when using no-clean VOC-free fluxes, to minimize soldering defects and maximize wetting.

For thick PCBs (such as 14-layer boards), the hole fill capability is not as good using lead-free solders as for tin-lead solders. Solutions such as press-fit connectors or selective soldering technology are being investigated for such situations.

Lead contamination may cause fillet lifting at high temperature. Therefore, tin-lead HASL boards should not be used with lead-free wave solder. Lead-free coated components should be used wherever possible. In addition, the cooling rate/profile needs to be well controlled. Lead contamination resulting from the processing of lead-based parts using lead-free wave soldering equipment can be regarded as "intentionally added" substances.

14. How should we perform lead-free repair and rework?

Rework is conducted for defective components using either hand soldering irons for leadframe and chip termination components, or BGA/CSP rework equipment for BGA/CSP components. Challenges in reworking lead-free soldering assemblies include: spacing between BGA/CSP and leadframe components to avoid secondary reflow of leadframe components during BGA/CSP rework, selection of lead-free rework materials which should be able to cater to both surface-mount and wave-assembly operations, rework process temperature profile to minimize the risk of internal delamination or popcorning in moisture-sensitive plastic components.

Rework on lead-free assemblies can be performed with existing rework equipment, both for hand soldering rework and BGA/CSP rework. However, modifications to existing equipment may be required, as detailed below for the temperature setting of hand soldering equipment. It should be ensured that tools for rework and repair are identified as lead-free. In addition, the rework station should be separately located (although most of the rework equipment for tin-lead can still be used for the lead-free solders).

Lead-free rework is conducted at higher temperatures (typically, 30°C higher) than for tin-lead solder. As previously noted, the typical minimum keep-out spacing for BGA/CSP components from leadframe components is 150 mils (3.81 mm). This distance is necessary to avoid localized secondary reflow of adjacent components during rework operations.

Flux and solder selection are critical. For BGA/CSP rework, the solder paste should be the same as that used for assembly. The recommended lead-free wire for hand soldering rework is Sn3.5Ag, due to its long history of use. Sn3Ag0.5Cu and Sn0.7Cu are the preferred lead-free wave solder alloys.

The hand soldering equipment temperature settings may need to be raised by one or two settings to accommodate the higher melting temperature of the lead-free solder wire (221°C for Sn3.5Ag, versus 183°C for tin-lead). Alternatively, the same settings may be used as for tin-lead, but the hand soldering equipment tip should be left on the reworked part (solder pad and component lead) for a longer time than for tin-lead solder before applying the solder wire to ensure reflow. Whether this may cause the solder tip to wear out more quickly needs to be verified.

Further information on the rework of lead-free assemblies is provided in /3/.

15. How should we perform lead-free inspection and testing?

The purpose of inspection is to detect manufacturing nonconformities, both by visual assessment of the appearance of solder joints (e.g., bridging, insufficient solder, misalignment, opens, non-wetting) using optical microscopes, and by automated inspection using X-Ray imaging and in-circuit testing. Currently, the same inspection equipment is employed for lead-free and tin-lead joints. However, retraining of the inspectors and operators may be required due to differences in inspection criteria between lead-free and tin-lead joints.

Acceptance guidelines for lead-free solder joints at optical inspection. The criteria for inspecting visual defects are typically set by industry standards such as IPC-A-610D /73/, which has been revised to incorporate visual inspection criteria for lead-free solder joints. This revision is due to differences in solder joint visual appearance between lead-tin and lead-free joints (due to the differences in the solidification behavior), which are characterized by dullness, reduced surface smoothness, lower wettability and potentially more cratering compared with tin-lead joints. Although dull or shiny joints are acceptable, reduced wetting is not.

At this time, pre-existing cracks can be induced by thermal and/or mechanical fatigue of the solder joints from reliability testing. This method can be used in conjunction with electrical continuity measurements to determine open or partially open solder joints and their distribution for a specific component.

Acceptance guidelines for lead-free solder joints at automated inspection. Current automated optical inspection criteria, which have been optimized for lead-based assemblies, are not suitable for lead-free assemblies due to differences in solder joint visual appearance. However, using a proper reference standard, the inspection system can be programmed to categorize good, marginal, or poor quality lead-free or tin-lead joints. This is possible as most of the combinations of solder alloys and surface finishes have an impact on the appearance of solder joints that can be characterized. Therefore, automated optical inspection (AOI) settings require to be adjusted depending on the solder alloy-surface finish combination being inspected.

Regarding automated X-Ray inspection, the coefficient of X-ray absorption of lead-free alloys is reduced relative to that of tin-lead alloys, which can alter X-ray images. Calibration coupons can be employed to program the X-ray system for lead-free joint inspection.

Acceptance guidelines for in circuit test of lead-free assemblies. There are no differences in functional testing between lead-free and tin-lead soldered boards.

16. How do we trace lead-free materials, parts and sub-assemblies from lead-based ones?

The change-over to lead-free manufacturing requires that lead-free materials, parts, sub-assemblies and final product can be distinguished from the corresponding lead-based ones. This is important for production, as well as rework and repair of field returns and recycling. Lead-free products can be identified by their part number or serial number, lead-free marking applied on both parts and sub-assemblies within the product, as well as on the outer packaging, the effective date of designation change, PCNs, traceable documentation systems, and staff training.

It is recommended that all lead-free materials, components and boards should have new (unique) supplier part numbers (PNs) assigned to distinguish them from tin-lead ones /74, 75/. Suffix or prefix additions to existing P/N structures are acceptable. A survey conducted by Avnet and Technology Forecasters in November 2004 estimates that only 52% of component suppliers are planning to issue new part numbers for lead-free parts, and that 42% plan not to change part numbers, and instead to identify lead-free components using designation printed on component packaging (37%), date of manufacture (31%), or marking on the components (27%) /9/.

Standards for marking lead-free parts and assemblies include JEDEC JESD-97 /76/, JEITA ETR-7021 /77/, and IPC-1066 /78/. These standards permit the type of lead-free materials contained in the part to be identified, and for JESD-97 and IPC-1066, the part process compatibility (maximum process temperature) to be assessed by the end-user. Equipment manufacturers should familiarize themselves with these marking methods, and should identify the effective date of change in part designation.

However, many electronic manufacturers use non-standard marking methods, and consequently the same part may be designated using different marking schemes in different countries. If the lead-free part supplier uses a non-standard marking scheme, it should be ensured that part identification meets the following requirements:

(i) All components of sufficient size should have their termination composition identifiable (with reference to a datasheet). On smaller components, where no marking is possible, the innermost packaging material should specify the termination finish composition.

(ii) The inner packaging (tray, tube, and reel) of all components should be marked with traceable information that indicates that no lead is present in the components.

(iii) No lead-free markings are required on the outer packaging boxes as long as suppliers can track their lead-free products versus their lead-containing ones and ensure that only one type of part is being delivered to the customer.

(iv) Part datasheets should indicate the termination solder composition, maximum part temperature rating, recommended and absolute reflow profile limits, and moisture sensitivity rating. If this information is not provided in the datasheet, a reference to where it can be located should be included.

Manufacturers should monitor PCNs issued by their part suppliers when transitioning to lead-free electronics. As per JESD46-B /79/, all changes on existing parts should be documented by a PCN issued by the part manufacturer to notify their customers of product transition to lead-free. An example of PCN issued by a component manufacturer is available in /80/. Any changes related to lead-free components should be considered major changes. Sample devices and qualification data should be available to customers at the time the PCN is issued or the new product is introduced.

All manufacturers who provide notification that they will be producing lead-free products should provide a product roadmap to their customers indicating the planned changes and timeframe for availability. 75% of the component suppliers surveyed in /9/ stated that they will deliver compliant parts with the same lead times as for current parts. Only 2% indicated that lead times will increase for lead-free parts /9/. More than half (53%) of the component suppliers surveyed did not expect to increase prices for compliant parts, which is likely to be associated with high production volumes, while 35% of suppliers expected a potential price increase /9/. However, the production of exempted parts in reduced quantities has also prompted concerns with the pricing of such parts /17/.

Any discontinuances of existing parts must be published to the customers, per standard JESD48-A /81/. Based on the survey previously mentioned /9/, many component suppliers do not plan to totally discontinue lead-containing products, as they anticipate a continuing demand for leaded products from exempted sectors. Component suppliers who plan to discontinue non-compliant parts typically intend to give customers a six-week to 24-month time frame to return non-compliant products after a PCN or end of life announcement is issued /9/.

Finally, it is recommended that manufacturers conduct the shipment and use of tin-lead coated leadframes and chip termination components to depletion, followed by the introduction of lead-free coated components.

17. What are the standards applicable to lead-free assembly processes, qualification and inspection?

The release of new and revised standards applicable to lead-free assembly process, qualification and inspection should be monitored, as these operations may have an impact on the design.

IPC is currently revising or has recently revised standards /49, 58, 60, 65, 73, 82-86/ to address lead free assembly. Standards /65, 82-86/ relate to solderability requirements and testing of electronic parts and boards, and requirements for soldering materials. IPC-A-610D /73/ has been revised to incorporate visual inspection criteria for lead-free solder joints.

J-STD-020C /58/, JEITA ED-4701-301A /59/, J-STD-033C /60/ and Mil-Std 202G Method 210F /61/ relate to component moisture and thermal sensitivity classification, and the handling, packing and assembly of moisture sensitive components.

JESD22A-121 /49/ specifies procedures for measuring whisker growth on tin-based finishes.

Other standards applicable to lead-free assembly process, qualification and inspection, include /87-89/. PCB qualification standards /90-93/ address lead-free PCB finishes. Common lead-free platings and coatings are also covered in PCB design /94-97/ and multichip module design /98/ standards.

18. What education, training and information resources are available to help in the successful implementation of lead-free product development?

Providers of education, training and information resources on lead-free electronics include research organizations /38, 99-101/, consulting companies /38, 102-104/, contract manufacturers /105/, vendors of electronic manufacturing products /106, 107/, and component/equipment manufacturers such as /108/. Such providers cover topics ranging from lead-free legislation, implementation, material and part selection, design, manufacturing, to lead-free reliability.

Closure

Key issues in the assembly of lead-free electronics that have not been fully resolved include component moisture and thermal sensitivity, solder joint manufacturing defects, backward and forward compatibility, and lead-free part traceability throughout the supply the chain.

The current state-of-knowledge on lead-free manufacturing and reliability is not as extensive as for lead-based electronics, which has a 40-year legacy. Although the electronics industry is aware of potential reliability risks specific to lead-free technologies, including excessive intermetallic growth, tin whiskering, and electrochemical migration, the long-term reliability of lead-free assemblies remains to be quantified. There is a need for studies addressing this concern, covering the range of available solder metallurgies, component terminal metallurgies and PCB pad finishes. Since the majority of studies on lead-free solder joint reliability have focused on single loading conditions (e.g, temperature cycling, high temperature aging), combined loading conditions (e.g., temperature cycling and vibration) need to receive more attention.

References

/1/ European Union, (February 13, 2003). "Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on Waste of Electrical and Electronic Equipment," Official Journal of the European Union, pp. L37/24-L37/38, http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_037/l_03720030213en00240038.pdf, last accessed May, 2005.

/2/ European Union, (February 13, 2003), "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," Official Journal of the European Union, pp. L37/19-L37/23, http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_037/l_03720030213en00190023.pdf, last accessed May, 2005.

/3/ Ganesan, S., and Pecht, M., 2004, "Lead-free Electronics," CALCE EPSC Press, College Park.

/4/ Pecht, M., Fukuda, Y., and Subramanian, R., 2005, "The Impact of Lead-free Legislation Exemptions on the Electronics Industry," accepted for publication in the IEEE Transactions on Electronics Packaging Manufacturing, Vol. 27, No. 4.

/5/ Nevison, G., 2005, "RoHS in Europe - the Current Position - An Update to NEDA, January 2005," National Electronic Distributors Association (NEDA), Lead-free Summit Presentations, http://www.nedassoc.org/Nevison.ppt, last accessed May, 2005.

/6/ Lemmon, S., 2005, "Cost of Intel's Lead-free Move Hits $100M, and Counting," May 16, http://www.itworld.com/Comp/2076/050316intellead/, last accessed May, 2005.

/7/ Hewlett Packard, 2004, "HP's Compliance with the Restriction of Hazardous Substances (RoHS) Directive," http://www.hp.com/hpinfo/globalcitizenship/environment/pdf/leadposition.pdf, last accessed May, 2005.

/8/ Valliere, T., 2005, "NEDA Industry Summit: Negotiating the Economic and Logistic Challenges of RoHS/Lead-free Compliance," National Electronic Distributors Association (NEDA), Lead-free Summit Presentations, http://www.nedassoc.org/Valliere.ppt#625, last accessed May, 2005.

/9/ The Electronic Source Book, 2004, "Progress on lead-free components spotty," Article no. 20041117, November 17, 2004, http://www.sourceesb.com/configurable/article20041117.html, last accessed May, 2005.

/10/ Czerwonka, J., 2005, "RoHS/Lead-Free Compliance Issues," National Electronic Distributors Association (NEDA), Lead-free Summit Presentations, http://www.nedassoc.org/Czerwonka.ppt, last accessed May, 2005.

/11/ European Commission, July 2004, "Guidance Document, Directive 2002/96/EC on Waste Electrical and Electronic Equipment and Directive 2002/95/EC on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment."

/12/ European Commission, Technical Adaptation Committee (Ghyssaert, M.), "Email Communication," Brussels, Belgium, January 29, 2004.

/13/ Department of Trade and Industry, UK, "Unofficial Note of Technical Adoption Committee Meeting, June 23, 2003, in Brussels," http://www.dti.gov.uk/sustainability/weee/tacmeeting070503.pdf, last accessed May, 2005.

/14/ European Communities, (October 21, 2000), "Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on End-of Life Vehicles," Official Journal of the European Communities, pp. L269/34-L269/42, http://europa.eu.int/eur-lex/pri/en/oj/dat/2000/l_269/l_26920001021en00340042.pdf, May 18, 2004, last accessed May, 2005.

/15/ European Communities, (October 21, 2000), "Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on End-of Life Vehicles," Official Journal of the European Communities, pp. L269/34-L269/42, http://europa.eu.int/eur-lex/pri/en/oj/dat/2000/l_269/l_26920001021en00340042.pdf, last accessed May, 2005.

/16/ Japanese Ministry of the Environment, enacted June 1998, "Law for the Recycling of Specified Kinds of Home Appliances," effective since April 2001.

/17/ The Electronic Source Book, 2005, "Are the Military and Telecommunications Industries off the Hook on RoHS?," Article no. 20050126, January 26, 2005, http://www.sourceesb.com/configurable/article20050126.html, last accessed May, 2005.

/18/ Department of Trade and Industry, UK, December 2004, "Unofficial note of the Technical Adaptation Committee on the WEEE & RoHS Directives," http://www.dti.gov.uk/sustainability/weee/TAC_10_December.pdf, last accessed May, 2005.

/19/ Department of Trade and Industry, UK, March 2005, "Unofficial note of the Technical Adaptation Committee on the WEEE & RoHS Directives," http://www.dti.gov.uk/sustainability/weee/TAC_Unofficial_Note_March2005.pdf, last accessed May, 2005.

/20/ European Parliament, Committee on the Environment, Public Health and Food Safety, March 2005, "Motion for a Resolution, On the draft Commission decision amending for the purposes of adapting to the technical progress the Annex to Directive 2002/95/EC of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment," (CMT-2005-151 and CMT-2005-642).

/21/ European Commission, December 2004, "Stakeholder Consultation on Adaptation to Scientific and Technical Progress Under Directive 2002/95/EC of The European Parliament and of The Council on The Restriction of The Use of Certain Hazardous Substances in Electrical and Electronic Equipment for the Purpose of a Possible Amendment of the Annex," http://forum.europa.eu.int/Public/irc/env/rohs/library?l=/&vm=detailed&sb=Ti, last accessed May, 2005.

/22/ Smetana, J., Horsley, R., and Lau, J., 2003, "HDPUG's Lead-Free Design, Materials and Process of High-Density Packages," Proceedings of the IPC Surface Mount Equipment Manufacturers Association (SMEMA) Council APEX conference, March 31-April 2, Anaheim, USA, pp. S42-12-1 to S42-1-13.

/23/ HDP User Group International, Inc., 2004, "General Purpose Lead-free Assembly System Implementation Guideline," Document Pbf04001 Date 04-01-21, Rev 1.

/24/ Department of Trade and Industry, UK, "Unofficial Note of the Technical Adoption Committee on the WEEE and RoHS Directives, Brussels, March 16, 2005," http://www.dti.gov.uk/sustainability/weee/TAC_Unofficial_Note_March2005.pdf, last accessed May, 2005.

/25/ Advanced Interconnections Corp., "Policy Statement, Lead-free Initiative and Elimination of Banned Substances,"

http://www.advintcorp.com/lead_freestart.html?http://www.advintcorp.com/leadfree_policy.html, last accessed May, 2005.

/26/ Euroquartz Ltd., "RoHS Directive - Company Statement," http://www.euroquartz.co.uk/pdf/RoHS.pdf, last accessed May, 2005.

/27/ ITT Industries, Cannon, "Roadmap for RoHS Complying Product," http://www.ittcannon.com/RoHS/docs/RoHS_Roadmap_Conn.pdf, last accessed May, 2005.

/28/ Midcom Inc., 'Midcom Policy Statement on RoHS Compliance and Lead-Free Products," http://www.midcom-inc.com/lead-free/Lead-Free.pdf, last accessed May 2005.

/29/ Pulse Engineering Inc., 2004, "Position Statement on Lead-free Products and RoHS Compliance," http://www.ttiinc.com/ object/LF_pulse_position.html, last accessed May, 2005.

/30/ Texas Instruments Inc., 2004, "Certificate Concerning Pb-free Semiconductor Products," http://focus.ti.com/download/qlty/presentation/RoHS_Certificate.pdf, last accessed May, 2005.

/31/ EIA/EICTA/JGPSS, April 2005, Joint Industry Guide, "Material Composition Declaration for Electronic Products (JIG-101)," http://www.eia.org/resources/2003-09-19.10.pdf, last accessed May, 2005.

/32/ IBM, July 28, 2003, "IBM Environmental Requirements for Materials, Parts, and Products," http://www.ibm.com/ibm/environment/products/46g3772_072803.pdf, last accessed May, 2005.

/33/ Electronic Industries Alliance (EIA), Standard, EIA/ECCB-952, September 14, 2004, "Standard for Plans to Determine Lead Content of Electronic Components and Related Equipment," http://www.eia.org, last accessed May, 2005.

/34/ IEC (International Electrotechnical Commission) ACEA (Advisory Group on Environmental Aspects) ad hoc Working Group, December 2004, "Procedures for the Determination of Levels of Regulated Substances in Electrotechnical Products."

/35/ Goodman, P., Robertson, C., Skipper, R., and Allen, J., April 2004, "Possible Compliance Approaches for Directive 2002/95/EC (The RoHS Directive)," ERA Report 2004-0134, ERA Project 043121262, Final Report, pp. 48-60.

/36/ I2, Hazardous Materials Management (HAZMAT), http://www.i2.com/solutionareas/sixone/content/hazmat.cfm, last accessed May, 2005.

/37/ Underwriters Laboratories Inc., UL iQ™ for Plastics, http://data.ul.com/ULiQ_Link/index.asp, last accessed May, 2005.

/38/ CALCE Electronic Products and Systems Center, University of Maryland, College Park, MD, USA, www.calce.umd.edu, last accessed May, 2005.

/39/ Agilent, http://www.agilent.com, last accessed May, 2005.

/40/ ERA Technology, UK, http://www.era.co.uk, last accessed May, 2005.

/41/ Polar, http://www.polarinstruments.com, last accessed May, 2005.

/42/ Soldertec, St. Albans, Hertfordshire, AL2 2DD, UK, http://www.tintechnology.biz/soldertec/soldertec.aspx?page_id=0, last accessed May, 2005.

/43/ Benchmark Electronics, http://www.bench.com, last accessed May, 2005.

/44/ Celestica, http://www.celestica.com, last accessed May, 2005.

/45/ Jabil, http://www.jabil.com, last accessed May, 2005.

/46/ Solectron, http://www.solectron.com, last accessed May, 2005.

/47/ Wu, J. Pecht, M.G. and Mroczkowski, R.S., 2002, "Electrical Characterization of Lead-Free Solder Separable Contact Interfaces," Journal of Surface Mount Technology, Vol. 15, pp 25-29.

/48/ Wu, J. and Pecht, M.G. 2004, "Contact Resistance and Fretting Corrosion of Lead-free Alloy Coated Electrical Contacts," Proceedings of the International IEEE Conference on the Asian Green Electronics, pp 127-135.

/49/ JEDEC/EAI JESD22A-121, May 2005, "Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes," www.jedec.org, last accessed May, 2005.

/50/ iNEMI, July 2004, Tin Whisker Acceptance Test Requirements," .http://thor.inemi.org/webdownload/projects/ese/tin_whiskers/Tin_Whisker_Accept_paper.pdf, last accessed May 2005.

/51/ iNEMI, May 2005, "Recommendations on Lead-free Finishes for Components Used in High-Reliability Products," NEMI Tin Whisker User Group, http://thor.inemi.org/webdownload/projects/ese/tin_whiskers/User_Group_mitigation_May05.pdf, last accessed May, 2005.

/52/ Fukuda, Y., Fang, T., Pecht, M., and Osterman, M., 2004, "Effect of Heat Treatment on Tin Whisker Growth," Proceedings of the International SMTA Conference, Chicago, September 26-30, pp. 717-723.

/53/ Lal, S., 2003, "Tin Whiskers: Their Appearance and Minimization in Electronic Connectors," Proceedings of AESF SUR/FIN, pp. 267-288.

/54/ Hilty, R.D., Chou, G.J.S., and Myers, M.K., 2005, "Tin Whisker Qualification Testing-Eye-of-the-Needle Compliant Pin Products: Revision O," Tyco-electronics, Document number 503-1006, http://tycoelectronics.com/environment/leadfree/pdf/503-1006_Tin_Whisker_Qualification_Testing_CompliantPin.pdf, last accessed May, 2005.

/55/ Zhao, P. and Pecht, M., 2003, "Field Failure due to Creep Corrosion on Components with Palladium Pre-plated Leadframes," Microelectronics Reliability, Vol. 43, No. 5, pp. 775-778.

/56/ Zhao, P., and Pecht, M., 2005, "Mixed Flowing Gas Studies of Creep Corrosion on Plastic Encapsulated Microcircuit Packages With Noble Metal Pre-Plated Leadframes," to be published in IEEE Transactions on Device and Materials Reliability, vol. 5, no. 2.

/57/ Hewlett Packard, 2003, "Testing and Control of Tin-based Platings on Lead-free Components For External Use," Procurement Guidelines for lead(Pb)-free components to be used in HP products for external use, http://www.psma.com/HTML/FILES/forums/lead-free/hp_guidelines_whiskers.pdf, last accessed May, 2005.

/58/ IPC/JEDEC J-STD-020C, July 2004, "Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices", http://www.ipc.org/, last accessed May, 2005.

/59/ JEITA ED-4701-301A, August 2002, Japan Electronics and Information Technology Industries Association, "Resistance to Soldering Heat for Surface Mounting Devices (SMD)," http://tsc.jeita.or.jp/EDS/DATA/sdr/ED4701-301.pdf, last accessed May, 2005.

/60/ IPC/JEDEC J-STD-033C, July 2004, Joint Industry Standard, "Handling, Packaging, Shipping and Use of Moisture/Reflow Sensitive Surface Devices," www.jedec.org, last accessed May, 2005.

/61/ Mil-Std 202G, Method 210F, 2002, Department of Defense, Test Method Standard, Electronic and Electrical Component Parts, "Resistance to Soldering Heat," http://www1.mod.go.th/opsdx/military_type/std202.pdf, last accessed May, 2005.

/62/ Bradley III, M., and Hranisavljevic, J., 2000, "Characterization of the Melting and Wetting of Sn-Ag-X Solders," Proceedings of the IEEE Electronic Components and Technology Conference, pp. 1443-1448.

/63/ Miric, A.Z., and Grusd, A., 1998, "Lead-free Alloys," Soldering and Surface Mount Technology," Vol. 10, No. 1, pp. 19-25.

/64/ Zheng, Y., Hillman, P., and Mc Cluskey, P., 2002, "Effect of PWB Plating on the Microstructure and Reliability of SnAgCu Solder Joints," Proceedings of the American Electroplaters and Surface Finishers Society (AESF) SUR/FIN, June 24-27, Chicago, IL, USA.

/65/ IPC/EIA-J-STD-002B, (February 2003), Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires, http://www.ipc.org/, last accessed May, 2005.

/66/ Roepsch, J., Champaign, R., and Waller, B., 2003, Black Pad Defect: Influence of Geometry and Other factors," Proceedings of the Surface Mount Technology Association (SMTA) International Conference, pp. 404-411.

/67/ Crum, S. 2000, "How Lead-Free Solder Affects PCB Manufacturability." Electronic Packaging and Production," January edition, http://www.reed-electronics.com/semiconductor/index.asp?layout=article&articleid=CA73017&industryid=3026, last accessed May, 2005.

/68/ CALCE Electronic Products and Systems Center, 2004, "Global Transition to Pb-free/Green Electronics," http://www.calce.umd.edu/lead-free/calcePbfree_AIA.pdf, last accessed May, 2005.

/69/ IPC, "PCB Materials," http://leadfree.ipc.org/LF_4-3.htm, last accessed May 2005.

/70/ Lau, J., Dauksher, W., and Smetana, J., 2003, "HDPUG's Design for Lead-Free Solder Joint Reliability of High-Density Packages," Proceedings of the IPC Surface Mount Equipment Manufacturers Association (SMEMA) Council APEX conference, March 31-April 2, Anaheim, USA, pp. S42-2-1 to S42-2-13.

/71/ Bardini, D., "Applied Lead-free Materials in Soldering Processes," Advanced Packaging/Connector Specifier/SMT Lead-free Series Webcast: Materials and Components, May 18, 2005.

/72/ Ghalib, N., Chu, Q., and Wable, G.S., 2003, "Lead- Free Reflow Profile Study," IPC-JEDEC Fourth International Conference on Lead- free Electronic Components and Assemblies, October 21-22, Frankfurt, Germany.

/73/ IPC-A-610D, April 2005, "Acceptability of Electronic Assemblies," http://www.ipc.org/, last accessed May, 2005.

/74/ The International Electronics Manufacturing Initiative (iNEMI), 2005, "iNEMI Members Want Unique Part Numbers for RoHS-Compliant Components," http://www.inemi.org/cms/newsroom/PR/2005/PR04272005.html, last accessed May, 2005.

/75/ National Electronic Distributors Association (NEDA), 2004, "Distributors' Position Paper on Lead-free Product Transition and RoHS Compliance," http://www.nedassoc.org/leadfree.pdf, last accessed May, 2005.

/76/ JESD97, May 2004, "Marking, Symbols, and Labels for Identification of Lead (Pb)-Free Assemblies, Components, and Devices," http://ak-bleifrei.izm.fraunhofer.de/servlet/is/2288/JESD97.pdf?command=downloadContent&filename=JESD97.pdf, last accessed May, 2005.

/77/ JEITA ETR-7021, June 2004, Technical report of Japan Electronics and Information Technology Industries Association, "Guidance for the Lead-Free Marking of Materials, Components and Mounted Boards used in Electronic and Electric Equipment," http://www.pbfree.com/pdf/japan_regulatory_activity/LeadFree_Labeling_guidance_by_JEITA.doc, last accessed May, 2005.

/78/ IPC-1066, January 2005, "Marking, Symbols and Labels for Identification of Lead-Free and Other Reportable Materials in Lead-Free Assemblies, Components and Devices," http://www.ipc.org/TOC/IPC-1066.pdf, last accessed May, 2005.

/79/ EIA / JEDEC JESD46-B, August 2001, "Customer Notification of Product/Process Changes by Semiconductor Suppliers," www.jedec.org, last accessed May, 2005.

/80/ NIC Components Corporations, October 2004, "RoHS Compliance Notice and Roadmap, ACTION#2-RoHS Compliant Material Identification, Product Change Notice, http://www.niccomp.com/NIC_RoHS_Compliance_Statement_1004.pdf, last accessed May, 2005.

/81/ EIA / JEDEC JESD48-A, August 2001, "Product Discontinuance," http://www.jedec.org/download/search/jesd48a.pdf, last accessed May, 2005.

/82/ IPC-J-STD-001D, February 2005, "Requirements for Soldered Electrical & Electronic Assemblies," http://www.ipc.org, last accessed May, 2005.

/83/ IPC-J-STD-003A, February 2003, "Solderability Tests for Printed Boards," http://www.ipc.org/, last accessed May, 2005.

/84/ IPC-J-STD-004A, January 2004, "Requirements for Soldering Fluxes," http://www.ipc.org/, last accessed May, 2005.

/85/ IPC-J-STD-005, January 1995, "Requirements for Soldering Pastes," http://www.ipc.org, last accessed May, 2005.

/86/ IPC-J-STD-006A, May 2001, "Requirements for Electronic Grade Solder Alloys and Fluxed and Non-Fluxed Solid Solders," http://www.ipc.org/, last accessed May, 2005.

/87/ AEC-Q100-Rev E/Mil-STD-833, "Mechanical shock and vibration."

/88/ AEC-Q-100-Rev E/JESD22-A103A, "High temperature storage."

/89/ IPC-A-9701, January 2002, "Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments," http://www.ipc.org/, last accessed May, 2005.

/90/ IPC-6012B, August 2004, "Qualification and Performance Specification for Rigid Printed Boards," http://www.ipc.org/, last accessed May, 2005.

/91/ IPC-6013A, January 2005, "Qualification & Performance Specification for Flexible Printed Boards," http://www.ipc.org/, last accessed May, 2005.

/92/ IPC-6015, February 1998, "Qualification & Performance Specification for Organic Multichip Module (MCM-L) Mounting & Interconnecting Structures," http://www.ipc.org/, last accessed May, 2005.

/93/ IPC-6016, May 1999, "Qualification & Performance Specification for High Density Interconnect (HDI) Layers or Boards," http://www.ipc.org/, last accessed May, 2005.

/94/ IPC-2221A, May 2003, "Generic Standard on Printed Board Design," http://www.ipc.org/, last accessed May, 2005.

/95/ IPC-2222, February 1998, "Sectional Standard on Rigid PWB Design."

/96/ IPC-2223A, June 2004, "Sectional Design Standard for Flexible Printed Boards."

/97/ IPC-2224, January 1998, "Sectional Standard of Design of PWB for PC Cards."

/98/ IPC-2225, May 1998, "Sectional Design Standard for Organic Multichip Modules (MCM-L) and MCM-L Assemblies."

/99/ American Competitiveness Institute (ACI), http://www.aciusa.org/wwwaci/html/frames.html, last accessed May, 2005.

/100/ National Physical Laboratory (NPL), http://www.electronicsweekly.com/Article37920.htm, last accessed May, 2005.

/101/ Soldertec (Tin Technology), http://www.tintechnology.biz/soldertec/soldertec.aspx?page_id=583&SelectedMenu_ID=179, last accessed May, 2005.

/102/ Bolton Institute, http://www.ami.ac.uk/courses/marketing/ lfi/index.html, last accessed May, 2005.

/103/ Cookson Electronics and Partners, http://www.automatedlearning.com/resources/cookson_press.cfm, last accessed May, 2005.

/104/ FlipChips Dot Com, http://www.flipchips.com/apnotes/Hwangleadfreecourses.htm, last accessed May, 2005.

/105/ Circuit Technology center, http://www.circuittechctr.com/training/0250033.shtml, last accessed May, 2005.

/106/ AIM solder, http://www.aimsolder.com/lead_free.cfm?section=training, last accessed May, 2005.

/107/ Kester, http://www.kester.com/en-us/leadfree/lfsku_kesteruniversity.aspx, last accessed May, 2005.

/108/ Oki, http://www.oki.com/en/eco/2004/22.pdf, last accessed May, 2005.

Valérie Eveloy, Sanka Ganesan, Yuki Fukuda, Ji Wu, and Michael G. Pecht

CALCE Electronic Products and Systems Center, University of Maryland, College Park, MD 20742, USA
Phone: +1-301-405-5323 Fax: +1-301-314-9269
Email: pecht@calce.umd.edu www.calce.umd.edu

Prispelo (Arrived): 14. 09. 2005; Sprejeto (Accepted): 28. 10. 2005