ABSTRACT

Title of Thesis: TRANSITION OF LOW-VOLUME COMPLEX ELECTRONIC SYSTEM INDUSTRIES TO LEAD-FREE ELECTRONICS

Subramanian Rajagopal, Master of Science, 2003

Thesis Directed by: Professor Michael G. Pecht

Department of Mechanical Engineering

The European Parliament's Waste Electrical and Electronic Equipment (WEEE) legislation requires manufacturers to bear responsibility for the mandatory collection, reuse and recycling of electronics products. The Restriction of the use of Hazardous Substances (RoHS) in electrical and electronic equipment legislation bans use of lead and other hazardous substances in certain electronics products by July 2006. Japanese electronics companies in general have adopted the “green electronics” movement for environmental consciousness and market differentiation.

This thesis identifies and analyses the risks to low-volume complex electronic system (LVCES) industries due to the transition to lead-free electronics. The relevance and significance of the lead-free legislation exemptions to the low-volume complex electronic system industries has been analyzed along with how various sectors of the industries can respond to the lead-free legislation exemptions in their product development. Recommendations to mitigate these risks have been developed.

TRANSITION OF LOW-VOLUME COMPLEX ELECTRONIC SYSTEM INDUSTRIES TO LEAD-FREE ELECTRONICS

by

Subramanian Rajagopal

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2003

Advisory Committee:

Professor Michael Pecht
Professor Davinder Anand
Professor Peter Sandborn

ACKNOWLEDGMENTS

I am grateful to Dr. Pecht, and Dr. Das for giving me the opportunity to work in CALCE as a research assistant. Without their guidance this work would not have been possible. I am greatly thankful to all my colleagues at CALCE for their help and support throughout these years. My special thanks to Sanjay and Yuki. More special thanks to Vidya, Niranjan, Anoop, Satya, Raju, Sheng and Sachi for all the discussions and help.

Next, I wish to acknowledge the support and encouragement of my roommates – Shaju, Sud and Rahul. My regards and gratitude to my brothers and sister for their constant support and motivation.

Thank you all

TABLE OF CONTENTS

LIST OF TABLES

Chapter 1

Low-volume complex electronic system industries

Low-volume complex electronic system (LVCES) industries can be defined as those industries that manufacture highly complex engineered systems that are produced and demanded in low volume compared to volume driven complex electronic product (VDCEP) industries.

1.1 Characteristics of Low-Volume Complex Electronic System Industries

LVCES industries cater to specialized, critical and high-reliability applications. Some key factors that distinguish the LVCES industries from the VDCEP industries are.

1. Low volume
2. Complex application
3. Unique part requirements
4. Supply web, which is indirect or logistically complex
5. Life cycle, which is significantly longer
6. Environment, which is specialized and often hostile and harsh
7. Critical applications for our health, security or economy
8. High-Reliability
9. Regulation, which may impose special constraints or liabilities
10. Cost structure, which does not benefit from economies of scale

1.2 LVCES Supply Chain

VDCEP industries have a well-defined and focused vertical infrastructure for their supply chain. In contrast, the LVCES industries do not have a unique vertical infrastructure, and must therefore rely on components and products either developed for the volume driven industries or developed by custom manufacturers. The lack of a dedicated vertical supply chain is driven by market dynamics. The typically small volume of ICs used along with concerns about liability issues are discouraging factors that make the mainstream IC suppliers reluctant to support the LVCES market segment.

Reliance of LVCES industries on components from supply chains dedicated to other products is called "cross-vertical product integration". This creates a supply web and introduces business and technical risks that are not present for volume driven electronic products. The lead-free transition in the VDCEP industries thus poses significant risks to the LVCES industries.

Chapter 2

Lead-free legislation

The commercial electronics industry is in the process of transition to lead-free products [1]. In Europe, the Waste from Electrical and Electronic Equipment (WEEE) legislation requires manufacturers of electronic products to be responsible for product recycling. The Restriction of Hazardous Substances (RoHS) legislation bans lead and other hazardous substances used in electronics. These two legislations are applicable from July 2006 in all member states of the European Union [1].

Japanese law mandates the takeback of household electrical appliances, effective as of 2001. There is no ban on lead, but the Ministry of International Trade and Industry (MITI) set a lead reduction timeline for total lead use. Japanese companies in general have adopted the "green electronics" movement for environmental consciousness and market differentiation [1]. Due to the legislative pressures and voluntary adoption of "green electronics", the electronics industry is transitioning to lead-free products [2].

2.1 Scope of the WEEE legislation

The WEEE directive identifies ten categories of electrical and electronic equipment (Table 1). The WEEE legislation is applicable only to the ten categories of electronic products [3]. The ten categories listed range from large and small household appliances to automatic dispensers with specific examples of electronic products in

Table 1 Categories of electrical and electronic equipment covered by WEEE legislation

Serial No.	Categories	Type of equipment
1	Large household appliances	Large cooling appliances, refrigerators, freezers, other large appliances used for refrigeration, conservation and storage of food, washing machines, clothes dryers, dish washing machines, cooking, electric stoves, electric hot plates, microwaves, other large appliances used for cooking and other processing of food, electric heating appliances, electric radiators, other large appliances for heating rooms, beds, seating furniture, electric fans, air conditioner appliances, other fanning, exhaust ventilation and conditioning equipment
2	Small household appliances	Vacuum cleaners, carpet sweepers, other appliances for cleaning, appliances used for sewing, knitting, weaving and other processing for textiles, irons and other appliances for ironing, mangling and other care of clothing, toasters, fryers, grinders, coffee machines and equipment for opening or sealing containers or packages, electric knives, appliances for hair-cutting, hair drying, tooth brushing, shaving, massage and other body care appliances, clocks, watches and equipment for the purpose of measuring, indicating or registering time, scales.
3	IT and telecommunications equipment	Centralized data processing: mainframes, minicomputers, printer units personal computing: personal computers (CPU, mouse, screen and keyboard included) laptop computers (CPU, mouse, screen and keyboard included) notebook computers, notepad computers, printers, copying equipment, electrical and electronic typewriters, pocket and desk calculators, and other products and equipment for the collection, storage, processing, presentation or communication of information, by electronic means, user terminals and systems, facsimile, telex, telephones pay telephones, cordless telephones, cellular telephones, answering systems, and other products or equipment of transmitting sound, images or other information by telecommunications
4	Consumer equipment	Radio sets, television sets, video cameras, video recorders, hi-fi recorders, audio amplifiers, musical instruments, other products or equipment for the purpose of recording or reproducing sound or images, including signals, or other technologies for the distribution of sound and image than by telecommunications
5	Lighting equipment	Luminaries for fluorescent lamps with the exception of luminaries in households, straight fluorescent lamps, compact fluorescent lamps, high intensity discharge lamps, including pressure sodium lamps and metal halide lamps, low pressure sodium lamps, other lighting or equipment for the purpose of spreading or controlling light with the exception of filament bulbs.
6	Electrical and electronic tools (with the exception of large-scale stationary industrial tools)	Drills, saws, sewing machines, equipment for turning, milling, sanding, grinding, sawing, cutting, shearing, drilling, making holes, punching, folding, bending or similar processing of wood, metal and other materials, tools for riveting, nailing or screwing or removing rivets, nails, screws or similar uses, tools for welding, soldering or similar use, equipment for spraying, spreading, dispersing or other treatment of liquid or gaseous substances by other means, tools for mowing or other gardening activities

7	Toys, leisure and sports equipment	Electric trains or car racing sets, hand-held video game consoles, video games, computers for biking, diving, running, rowing, etc., sports equipment with electric or electronic components, coin slot machines
8	Medical devices (with the exception of all implanted and infected products)	Radiotherapy equipment, cardiology, dialysis, pulmonary ventilators, nuclear medicine, laboratory equipment for *in-vitro* diagnosis, analyzers, freezers, fertilization tests, other appliances for detecting, preventing, monitoring, treating, alleviating illness, injury or disability
9	Monitoring and control instruments	Smoke detector, heating regulators, thermostats, measuring, weighing or adjusting appliances for household or as laboratory equipment, other monitoring and control instruments used in industrial installations (e.g. in control panels)
10	Automatic dispensers	Automatic dispensers for hot drinks, automatic dispensers for hot or cold bottles or cans, automatic dispensers for solid products, automatic dispensers for money, all appliances which deliver automatically all kind of products

each category. The examples of electronic products in each category are only meant to indicate the scope of each category. Other electronics products which fit into the description of the categories must be included as part of the WEEE legislation, even though they may not be mentioned in the examples list [3].

2.2 Scope of the RoHS legislation

The Restriction of Hazardous Substances (RoHS) legislation prohibits the manufacture of electronics products containing lead, cadmium, hexavalent chromium, polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs) after July 2006. The RoHS legislation has been designed to supplement the WEEE legislation to reduce future recycling costs by eliminating the need for special handling of hazardous substances in electronics. The RoHS legislation is only applicable to all the products covered in the ten categories of the WEEE legislation as outlined in Table 1 with the exclusion of categories 8 and 9 (medical devices and monitoring and control instruments) [4].

2.3 Completion and revision of lead-free legislation

Many of the details of the WEEE and ROHS legislations are still in the process of being defined. This review process is expected to be finalized in late 2004. For example, the exact percentage of allowable lead content is dependent upon the definition employed for lead-free products. The legislation does not specify whether the lead content is measured as a percentage of the final electronic product or as a percentage in the homogeneous material (e.g. solders or subassemblies) [5].

Many of the existing provisions of the WEEE and RoHS legislation can be subject to future revisions. For example, the RoHS legislation specifies that ”The Commission shall evaluate the applications for lead in solders for servers, storage and storage array systems, network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunications (with a view to setting a specific time limit for this exemption), and as a matter of priority in order to establish as soon as possible whether these items are to be amended accordingly”[4].

The process of future revisions of the existing provisions of the directive will follow the “scientific and technical process” [3], [4]. The “scientific and technical process” will consider whether the elimination of materials via changes in design or materials is technically or scientifically possible. The impact of whether replacing existing materials will outweigh environmental, health and consumer benefits will also be analyzed. This review will be conducted every four years. The review committee is required to consult stakeholders, including producers, recyclers, environment, employees and consumer organizations.

2.4 Who is responsible: The definition of producer

Producer responsibility means that the ‘producer of the electronic product’ is responsible for the product once it is discarded as waste. Under the existing law, the company or individual disposing of waste is responsible for the costs of its disposal or recycling. Waste management is financed through individual tax payments and businesses pay waste collection companies to remove and manage their waste. However, the WEEE legislation requires producers of electronic products to finance the recycling, recovery or disposal of their products once they are discarded as waste [3].

The European legislation defines ‘producer’ to encompass the whole distribution channel of electronic products. This includes companies that manufacture electrical or electronic products, and also importers of electrical and electronic products. Producers will also include retailers who sell their own branded products and assembly companies selling their own branded products [5]. This broad definition of producer can pose problems in determining who is responsible for finance the recycling, recovery or disposal of electronic products

Member states of the European Union are required to integrate the WEEE legislation into their existing environmental laws. Thus, the WEEE legislation could have additional local and national clauses. The producer definition does not take account of the fact that but in common European market, electronic products are increasingly purchased centrally in one member state for the whole European Union, stocked centrally in another member state(s) and then shipped to retail outlets all over.

National brand owners could thus be held responsible for goods they never sold but which were nonetheless legally put on the market by others not covered by the legislation [5].

2.5 Penalties for non-compliance

Penalties for noncompliance have not been explained in the legislation. According to the WEEE and RoHS legislation, member states of the European Union are required to provide for “effective, proportionate and dissuasive” penalties for producers breaching the legislation [3], [4]. Since producers of electronics producers are covered by legislation in the member country in which they are based, penalties for non-compliance may vary considerably from one country to another. For example, in certain member states, breaches of environment regulations are a matter for civil law, whereas in others it represents a criminal offence [5].

Chapter 3

Risks to LVCES industries due to lead-free transition

The issues faced by the LVCES industries that arise due to lead-free transition in the electronics industry, include:

- Reliability of lead-free electronics subject to harsh environmental conditions, long-term storage and long-term usage
- Compatibility of lead-free electronics with LVCES
- Availability and traceability of lead-free parts
- Repair and rework of LVCES

3.1 Reliability of lead-free electronics subject to harsh environmental conditions, long-term storage and long-term usage

The ability of equipment to perform reliably when subject to harsh environmental conditions is often a requirement for the electronics used in LVCES applications. Over the past decades, it was possible to design LVCES to meet harsh environmental conditions, because of the accumulated data on failure mechanisms of lead-based electronics. The transition to lead-free electronics affects this underlying basis of design, manufacture and use of LVCES [7]. Reliability of lead-free electronics under harsh environmental conditions, long-term storage and long-term usage should be evaluated before they can be adopted by the LVCES because of the possibility of hitherto unknown failure mechanisms.

Example 1: Reliability data for lead-free alternatives does not fully match up across the spectrum to the data available for lead-based processes even under normal operating conditions. This issue becomes exacerbated at harsh environmental conditions. Tin-lead eutectic solder has a low melting point, high thermal conductivity, and high resistance to fatigue and thermal cycles but many lead-free solder alloys do not measure up to the tin-lead solder alloy properties. For example,

- Alloys containing bismuth have melting points comparable to lead-based solders (210 – 215^{o}C) but can be prone to fillet lifting [8].
- Antimony bearing alloys (96.2Sn/2.5Ag/0.8Cu/0.5Sb) lack the desired mechanical properties at high temperatures [10].
- Zinc bearing alloys also have comparable melting points but exhibit reduced solderability and are susceptible to corrosion. Sn91/Zn9 [11].

Example 2: Many lead-free alloys being considered for high-temperature applications have a high percentage of Sn. However, tin forms intermetallics with pad surfaces plated with copper, silver or gold/nickel. Intermetallics growth increases particularly at high temperature, resulting in the formation over time of a thick layer of brittle intermetallic material. This brittle intermetallic is prone to fracture, especially in the presence of voids created by asymmetric interdiffusion [12].

Example 3: The effect of life cycle stresses and associated failure mechanisms under harsh environments that were applicable to traditional SnPb solders must be reconsidered for lead-free materials. Higher processing temperatures with lead-free solder stress constituent parts more compared to the tin-lead process.

For example, the higher melting point of SnAgCu solder alloy compared with SnPb demands higher peak reflow temperatures in lead-free soldering process. Increased reflow temperatures can worsen reliability of lead-free COTS electronics, particularly during their use at harsh environmental conditions because it can increase the susceptibility to delamination and popcorning. Degradation of moisture sensitivity level (MSL) may increase with increasing profile dwell above 200°C and MSL typically degrades by one level for every 5 to 10°C increase of peak reflow temperature [13]. This can result in an increased need to pre-bake parts and more stringent storage methods. Reliability of lead-free alternatives (e.g. SnAgCu compared to SnPb) is also strongly dependent upon use temperature [14].

Example 4: Component vendors are being forced to switch from tin/lead to pure tin component finishes because of the movement towards lead-free electronics. During the last several years, many electronic component manufacturers have increased the use of pure-tin coatings. The use of lead-free alloys can lead to hitherto unforeseen failure mechanisms in harsh environments that were not directly applicable or relevant for traditional SnPb based LVCES. Life test data for many components at these higher processing temperatures is less comprehensive than it is for SnPb finishes.

For example, many lead-free alloys show susceptibility to fretting corrosion due to their high tin content [15]. Fretting corrosion tests at different temperatures show that increased temperature greatly accelerates the fretting corrosion rate.

Example 5: The increasing lead-free efforts in electronic components may favor noble metal pre-plated leadframe as a strong candidate to replace tin-lead coating. Ni/Pd/Au plating has been applied to be an enhancement of existing nickel/palladium plating in cost saving and solderability improvement. As a development in IC packaging, noble metal pre-plated leadframe have started to appear in surface-mount, fine-pitch devices. Noble metals such as gold and palladium are effective corrosion inhibitors. However, noble metal pre-plated leadframes are prone to some surface damages, e.g., cracks on lead bend and exposed copper at dam bar removal area during leadframe trim/form process. When damage does occur, corrosion products can form during field use [16]. The most deleterious effect of this event is that noble metals provide an ideal surface for the migration of corrosion products since noble metals do not oxide or corrode in ambient surroundings. Creep corrosion behavior is dependent upon the corrosion product, the surface material, and the environments and operating conditions [16].

Example 6: Pure tin finishes can give rise to the growth of tin whiskers leading to failure in LVCES due to shorting. The ability of whiskers to bend due to electrostatic attraction increases the probability of causing a short. In addition, the whiskers can break loose, causing mechanical damage [17]. Also, in low-pressure environments, it is possible for arcing to occur from the tin whisker to an adjacent conductor in the PWB, causing significant damage.

Example 7: The real impetus in lead-free electronics development has taken place only in the latter part of the last decade. The focus of these efforts has been only on the commercial electronics industry with its typical short electronic product lifecycle of just a few years. Thus there is a lack of adequate data on the long-term reliability of lead-free electronics, both during continuous long-term storage and during long active field operations. Lead-free solder alloy formulations use a number of materials and processes. The prevalence of different lead-free alternatives further aggravates these concerns because test results for all the lead-free alloy formulations will need to be assessed before incorporation into LVCES can take place.

Example 8: In lead-based electronic products, corrosion of solder joints has seldom been a problem because of the relatively stable lead oxide that is formed on a tin/lead alloy. However, most tin-based lead-free alloys form a tin oxide that is easily eroded or mechanically damaged. Testing is necessary to understand the long-term effects of galvanic coupling, environmental exposure, and the effects of specific chemicals. Samples of bulk alloys that were steam-aged for eight hours exhibited severe corrosion. The presence of zinc in lead-free solder alloys can lead to oxidation and corrosion. Zinc-containing solder alloys have been known to react with the flux medium, resulting in a hard paste [10].

3.2 Compatibility of lead-free electronics with LVCES

Compatibility issues arise mainly due to the new failure mechanisms that arise due to the contamination of lead-free components with lead present in the existing PWB. Because of the widespread prevalence of tin-lead coated circuit boards and components in the LVCES, it is reasonable to assume that any movement towards lead-free products can only take place over a period of time. The exact mechanism by which lead contamination affects the reliability of the lead-free electronics systems depends on the application. This implies that any introduction of lead-free components and processes in existing LVCES should only take place after due assessment of all the possibilities of alloy inter-mix and the associated failure mechanisms.

Example 1: Contamination of lead-free solder joints with existing lead in the circuit board decreases the strength of the joint thereby posing risks during field operation of the LVCES. The decrease in strength of the solder joint can arise due to various types of failure mechanisms [18]. During the lead-free soldering process, lead, as an impurity, migrates to that area of the solder-joint that solidifies at the end of the cooling process. Typically, this area occurs under the middle of the component lead at the solder joint-PCB interface. The lead-rich regions are lower in melting temperature and cause dewetting during soldering. When using a lead-free alloy to solder to tin-lead coated component leads, lead can also create voids in the solder joint that can result in joint failure [19]. The probability of failure thus increases at this point compared to other parts of the interface.

Example 2: Many lead-free solders develop low-melting binary or ternary phases in combination with lead. Lead contamination of lead-free solders causes the formation of low melting phases, affecting the mechanical integrity of the solder joint. For example, contamination due to lead in the SnBi lead-free alloy can lead to the formation of bismuth and lead pockets (secondary eutectic) which melts at 96°C [20]. This decreases the reliability of the whole assembly when exposed to any thermal stress. This is evident in a reduced temperature cycling resistance at higher temperatures.

The ternary phase diagram of Sb-Pb-Bi indicates the presence of a ternary eutectic composition of Sn16/Pb32/Bi52, with a melting temperature of 96°C. The maximum solid solubility of Pb in Sn is 2.5%, and the solid solubility of Pb in Sn at room temperature (300°K) approaches zero. Therefore the Pb atoms in a Sn/Ag/Bi system precipitate as second phase particles. With the presence of the softer Pb particles in the Sn matrix, plastic deformation tends to concentrate on these particles. This, in turn, may cause an early fracture. The fatigue cyclic strain is also concentrated on the soft lead inclusions, leading to a deterioration of the fatigue life. Additionally, the distribution of secondary phase lead in the microstructure also plays a role in the fatigue mechanism. A small amount of lead precipitates preferentially at the grain boundaries, causing early grain boundary fracture [20].

Example 3: Current assembly reflow and rework process temperatures run between 210 - 220°C, or about 30 to 35°C above Tin-Lead eutectic solder's 183°C melting point. This increment is necessary to achieve complete solder fluidity and adequate wetting within reasonable periods of time. The most popular lead free substitute alloys, SnAg, or SnAgCu, have melting points in the range of 217 - 221°C. It is necessary that the peak reflow temperatures may reach the 245-255°C range. With an increase in peak reflow time from current typical 60 seconds to the order of 90 seconds, acceptable wetting by these alloys can only be accomplished with a peak temperature of 235-240°C. The required increase in process temperature will affect the materials and components, many of which are only marginally capable of withstanding today's process conditions. Subjecting temperature sensitive components to temperatures above 230°C may result in die cracking, adhesive degradation, or delamination. Common circuit board materials such as FR-4 can also degrade and delaminate because the organic portion of the laminate has limited ability to withstand elevated temperatures for extended periods of time. The composition is complex and includes not only epoxy resins and glass fiber but also glass couplers and other substances, all of which have their own thermal limitations and expansion rates. Similarly, many of the solder masks currently employed have limited resistance to the elevated temperatures that will be experienced at reflow and may exhibit color changes and blistering.

Example 4: A critical factor in the transition to lead-free assembly is the Moisture Sensitivity Level (MSL) rating of components. Moisture sensitivity performance of IC packages is a concern for the LVCES because of the potential for "popcorning" and delamination caused by expansion of moisture trapped inside the encapsulated device interfaces at high temperature and during rework and reflow [13].

Since there is no drop-in replacement for tin-lead solders in LVCES applications and due to the prevalent use of different lead-free alloy combinations in the manufacture of electronic parts, the risks due to hitherto unknown failure mechanisms caused by contamination can affect the field performance of LVCES.

3.3 Availability and traceability of lead-free parts

The LVCES Original Equipment Manufacturers (OEMs) may need to ensure that the lead-free parts needed are available and compatible with the manufacturing process. The many component and PWB coatings, as well as several possible solder alloys results in a huge matrix of potential material intermix, and can complicate materials management. The bottlenecks that can arise due to the adoption of lead-free parts by the LVCES relate to the availability and traceability of lead-free parts in the supply chain.

Example 1: Part change notifications (PCN) are issued by part manufacturers. A PCN includes part identification (part numbers, product lines etc.), description of change, PCN number, reason for change, implementation date, effects on quality and reliability, methods for distinguishing old parts from new parts, qualification data and a person to contact with any questions. Continuous monitoring of PCNs will be required during the lead-free transition [21] .

Major manufacturers provide change-notification in a manner compliant with the EIA/JEDEC specifications. However, manufacturers reserve the right to make changes or discontinue parts without notice. Part change notification policies for lead-free parts vary depending on manufacturer, customer type and geographical location [21].

Manufacturers have varying methods of naming lead-free part numbers. For example, Analog Devices uses the letter "Z" as a suffix to the existing part number [23] . The Z suffix appears at the end of the part name i.e. generally after the character that denotes the package style. But in the case of Fairchild Semiconductors, there are no part number changes associated with the conversion to lead-free parts [23]. Philips Semiconductor uses the symbols “G”, “E” or “N”, to denote lead-free parts [24]. Symbol G denotes those product which meets RoHS legislation, symbol “E” denotes those products which includes parts which meet both RoHS legislation and exemptions and symbol “N” denotes those products which do not meet RoHS legislation requirements. Fujitsu adds the symbol “E1” to denote lead-free products.

Some of the manufacturers add an additional marking directly on the devices. For example, Analog Devices adds a “#” sign to the lead-free parts to distinguish it from lead-based parts [23]. However, lead-free parts cannot be distinguished only by observing the marking on parts. For instance, since several small packages like Small Outline Transistor (SOT) are too small to accommodate an additional character, these devices have no direct marking on them to distinguish them as a lead-free device [23]. There is no industry standard lead-free marking which manufacturers can follow.

Package and component reliability parameters are also part of the part change notification. The reliability parameters in the PCN relevant to the lead-free transition includes solderability of components finishes with lead and lead-free solders, package moisture sensitivity level (MSL) classification, and tin whisker test compliance of finishes. All of the above parameters need to be continuously monitored by following the PCN for the part.

The lead-free processing temperature is typically higher than the tin-lead processing temperature by 30-40^{o}C [10]. All the parts used in lead-free assembly will need to reclassified according to the IPC/JEDEC J-STD-020B moisture sensitivity level classification. The MSL-classification also indicates the required information for shipping and handling of products before reflow board assembly. The PCN should be monitored for the correct MSL rating for the part. This is because subjecting temperature sensitive components to temperatures above their rating can result in popcorning, delamination and die cracking. Also any inter-mix of lead-based and lead-free parts during assembly may result in either assembly or field failures of the LVCES.

The PCN will also need to be monitored for change in component finishes. For example, components lead-free finishes can be pure Sn, matte Sn, Pd/Ni, Au/Ni, and Pd/Au/Ni. Adequate qualification and testing may be necessary before such components can be used in the assembly for high-reliability electronics systems. Monitoring component finishes is important in deciding the soldering profile to be used together with the soldering alloy and flux.

Part change notifications are typically issued through either distributors, contract manufacturers or through independent service providers [21]. Low-volume OEMs who have not brought enough parts for a long time may be dropped from the part change notification list.

Example 5: Dual inventory of lead-free and lead-based electronic parts may be needed to offset the diminishing product lines of critical parts. For example, there can only be a single-source for a particular lead-based part, or the production of a strategic part might be discontinued due to lead-free transition. OEMs will need to determine the part obsolescence impact on life cycle sustainment costs for the long field life electronic systems based on future production projections, maintenance requirements and part obsolescence forecasts.

The dual inventory strategies will need to consider common obsolescence mitigation approaches in either a short-term (until the next redesign) or long-term (until the end of support of the product). Short-term approaches include ‘third party’ buy, and ‘last-time’ buy. Long-term approaches include ‘life-time’ buy, finding a substitute part, emulation, and uprating similar part [21].

In a lifetime (also called life-of-type buy), the equipment supplier buys sufficient parts to meet the systems' lifetime needs of lead-based parts from the original part manufacturer, before the anticipated close of production. This is one of the cheapest solutions because it doesn't require reengineering, re-qualification, or redesign. The equipment supplier should determine last date for order processing minimum order quantity, or value and the latest delivery dates for the lead-based part from the manufacturer's product discontinuance notice [25].

Aftermarket describes the period after the original manufacturer has phased a part out of production. Aftermarket sources cater to the continued demand for discontinued parts. If part specifications and test, acceptance and related technical data are complete and available, then OEMs can utilize them to have access to lead-based parts during the transition phase [26].

Uprating is a process to assess the ability of a part to meet the functionality and performance requirements of the applications in which the part is used outside the manufacturers' specification range [27]. The most common application of this technique is to thermal uprating. This is used to assess the capability of a part to meet the functionality and performance requirements when it is used outside the manufacturer-specified temperature range.

The OEMs will need to determine the optimum design refresh plan for lead-based and lead-free parts during the field-support life of the product. The design refresh plan will need to consist of the number of design refresh activities, and their content and respective calendar dates that minimize the life cycle sustainment cost of the product. When design refreshes are encountered (their date is defined either by the user or by the methodology during its optimization process) the change in the design at the refresh must be determined and the costs associated with performing the design refresh must be computed. At a design refresh, a long-term obsolescence mitigation solution is applied (until the end of the product life or possibly until some future design refresh), and nonrecurring, recurring, and re-qualification costs computed [26].

Example 3: Re-qualification of suppliers of lead-free parts and sub-assemblies may be required by OEMs. The requalification process of suppliers should take into account the procedures adopted by the suppliers across their manufacturing, quality, product, purchasing divisions to ensure that the materials used are compatible with the lead-free requirements [21].

Supplier requalification methods are required to align the lead-free conversion roadmap of OEMs and suppliers. Some of the parameters to be considered during supplier qualification include aspects like component availability date, expected lead-times, schedule for qualification, and production schedule. Additional information including supply line flexibility and notification of expected potential issues during manufacturing of the component [28].

Supplier requalification methods should also take into account technology characteristics of the components supplied by the suppliers. For example, available component surface finishes, alloy composition, plating thickness with specified tolerances will need to be evaluated for compatibility with the OEM's assembly processes. Suppliers may also be required to provide test data to validate process compatibility. For example, whisker concerns with matte tin component finish coatings requires the development of an accelerated test for testing the potential of whisker growth in any lead finish components, a whisker acceptance criteria and an industry standard [30].

OEMs will need to evaluate the suppliers for all the anticipated cost issues that may affect the supplier's ability to supply parts during or after the lead-free transition. For example, assessment of supplier capacity may include dual manufacturing capability and utilization plans, tooling lead times and service. OEMs may also need to work in tandem with suppliers and industry forums to resolve technological issues during the transition [21].

Supplier requalification methods should asses the willingness of suppliers to maintain and upgrade their environmental management systems. For instance, suppliers might be required to reduce and eliminate environmentally hazardous substances as per industry standard roadmaps.

Example 4: The number of patents making lead-free solder compositions proprietary has been increasing rapidly since the mid 1990's. As the amount of intellectual property rises, so too does the complexity and coverage of the claims. Infringement on lead-free intellectual property rights may be difficult to avoid. Thus the LVCES OEMs will need to ensure that they don't infringe on any proprietary solder alloy compositions during the sourcing and also during assembly [30].

Example 5: The long-term reliability concern extends not just to the selection of lead-free solder alloy use in LVCES applications but also in other aspects of the operational and logistical requirements. Storage is required for strategic or obsolete electronics components in the LVCES markets. Optimum storage conditions for these lead-free components need to be determined. Storage in a dry, inert cabinet can eliminate concerns of moisture and oxidation damages over time.

3.4 Repair and rework of LVCES

The risks to the LVCES during repair and rework of electronics system encompasses a whole spectrum of challenges in technical, logistical, and strategic settings. While the technical challenges stems from the necessity of new procedures and processes, the logistical challenges involves operator retraining and change of guidelines. The strategic concern relates to the investment and expenditure in new equipment for lead-free rework and repair and its associated cost-benefit analysis. This is especially important in the LVCES setting because of the complex nature of the electronics in systems.

Rework involves multiple thermal cycles for component removal and replacement. Each cycle in lead-free rework subjects components and electronic assemblies to elevated temperatures beyond those typical for today's assembly and rework processes. Some of the key risks in lead-free repair and rework are:

- Melting temperature of solders
- Alloy requirements – compatibility and intermix
- Temperature gradient requirement
- Flux type, flux concentration and flux volatility/spatter
- Nitrogen assistance requirement

Example 1: Operators must understand the key requirements of lead-free soldering and will need to be re-trained for lead-free rework because of the differences in procedures both for the actual rework procedures and also for the inspection criteria. For example, lead-free solders do not flow as well as the traditional SnPb solder and this entails special retraining in the hand soldering process. If more than one alloy is in use in the production process (i.e., Sn/Ag/Cu for SMT and Sn/Cu for wave soldering), operators should be trained to use the correct wire for each part. It may not be possible to use a single solder alloy for all assembly operations and hence operators will need to understand the unique soldering requirements for all the lead-free alloys which might be possibly be used during the repair and rework process. As with any change of flux chemistry, in changing wire solders, operators should pay particular attention to the operating window it offers [31].

Example 2: A key risk during the repair and rework process of LVCES is the possible requirement to use the same lead-free solder alloy as originally used on the solder joint during the manufacture of the electronics system. Any post soldering manual rework to touch up boards, install special components, or implement last-minute design fixes must use the same lead-free solder because mixing of different lead-free solder formulations on the same joint can lead to field failures. Thus, this implies that identification of the particular type of solder alloy used in the manufacturing of the myriad PWBs and parts need to be known before repair and rework is undertaken.

In general, mixing of different lead-free solder formulations on the same board might lead to failures during field operation. Since the lead-free domain has different alloys and thus different potential problems, the data collected for one specific alloy may not be useful for understanding the immediate production issues and longer-term reliability of other alloys. Such logistical problems underline the need of the importance of the lead-free transition for the LVCES [32].

Example 3: Rework and repair equipment obsolescence is a key risk during the repair and rework process for lead-free LVCES. Most of the existing equipment for repair and rework is tuned to the lead-based electronics processing. However, desoldering and soldering stations used for repair and rework of lead-free LVCES equipment need to be suitable for the varying technical and process requirements. For example, the soldering stations should be able to reach the necessary higher temperatures required for lead-free soldering. Though most equipment in use can provide the necessary heat, the set point temperature needs to be raised by 20 to 40°C for lead-free soldering [32].

Lead-free soldering can wear out tips at a much higher rate than tin/lead [34]. Most modern wave solder machines can provide the necessary heat (preheat and wave) for lead-free soldering. However, the high-tin lead-free alloys rapidly dissolve the materials often used in wave solder equipment. Stainless steel pots, nozzles, impellers and other parts will need to be replaced with cast iron and other materials available from wave soldering equipment manufacturers or be covered with an appropriate paint that should protect the parts for many years. In addition, a nitrogen blanket may be required, depending upon the alloy and flux selected. The reflux and wave-soldering processes are dependent upon many factors including the temperature and heat energy that the board must see to melt the solder, and the profile of the heat-up and cool-down phases that occur before and after the solder reaches the melting point. The concern for the LVCES will be to ensure that this equipment can also properly control the overall ramp-up, soak, and cooling cycle profile.

Example 4: Repair and rework of lead-free LVCES equipment necessitates additional attention to process details. For example, during repair with lead-free solders, the use of nitrogen is needed to permit better wetting. The nitrogen reduces the oxidation of the flux system and enables the flux to sufficiently reduce the surface tension of lead free alloys. Without the use of nitrogen the repair quality tends to be below optimum [31].

The process window for lead free solder reflow will become extremely small. The margin between the minimum temperature for reliable reflow and maximum temperature for materials safety will all but disappear. The difficulties are exaggerated when performing rework due to extra thermal cycles (component removal, site dressing, and component replacement) and the difficulty of maintaining the thermal process on a localized rework site. It is evident that, whatever thermal excursions are required, they should be as benign as possible (shortest time at lowest temperature) consistent with achieving the required result. The ability to optimize these conditions is a critical requirement. The melting temperature of this alloy is 227^{o}C and therefore good solder tip temperature is essential for good wetting.

Example 5: Flux formulations are still being evaluated for their effectiveness in meeting requirements of lead free soldering. Higher temperatures, new pad finishes and new alloy constituents will impact flux formulations. Activators that clean joint surfaces as reflow temperatures are approached need to be reevaluated for their effectiveness and ability to withstand the higher temperatures of lead free alloys. Because of the difficulty in cleaning flux residues from underneath surface mount components, flux manufacturers need to develop products that leave very little to no corrosive or conductive residues. The inert residue remaining after soldering must be tack free, and exhibit low levels of ionic contamination. Flux cored solders are required during assembly in all types of processing namely in wave soldering or a reflow oven, and also during hand assembly. These wire solders should be capable of being drawn and should be made available in water-soluble and rosin configurations with differing diameters. This can also imply the need for stronger cored wire fluxes. Changes in flux chemistry and board-washing techniques may reflect back into component selection, how components are attached [34].

Wetting characteristics of Sn3.5Ag and the SnAg3.8Cu0.7 solders on copper is inferior compared to the traditional 60/40 tin-lead solder. Flux spattering was also observed at these higher temperatures. Use of lead-free flux cored solder necessitates that the flux percentages should be slightly higher than the traditional 2-3%. The added flux is needed to assist in better wetting of the lead-free solder. Water-soluble flux systems offers better wetting with lead-free alloys due to their higher activity attributed to halide additions.

Example 6: One of the prime concerns for the LVCES in the lead-free transition is the critical infrastructure and process changes that might be required in test and inspection procedures. The challenge of inspection of lead-free electronics can be attributed to the changes brought about by the new characteristics of lead-free processes.

The visual appearance of joints is significantly different from that using conventional SnPb solder. Eutectic Sn/Pb joint have a reflective surface and is smooth in appearance when viewed under present optical inspection techniques but lead-free joints are generally dull and grainy. Moreover, the range of dull surface types varies widely. With quick cooling down periods, surfaces become comparatively smoother. There is a correlation between solder surfaces and their reflective characteristics, which depends on the time it takes the solder to solidify. A Sn/Pb solder fillet surface is smooth and its surface comparatively even, the conditions prompting a reflective surface. Occasionally, lead-free solder will exhibit a reflective surface similar to that of Sn/Pb solder only to become dull and non-reflective, depending on the cooling temperature conditions. When lead-free solder hardens and becomes totally non-reflective, it appears both dull and slightly white in color. These changes are not covered in existing visual guidelines. “Copper halos” can also occur using lead-free solders.

Example 7: Another test and inspection concern includes variation in the fillet shape of the lead-free solder joints. Since the final fillet shapes is dependent on variables are varied as assembly-line conditions, component-plating technologies, flux selection and wavesolder reflow temperature, there is no universal benchmark through which the lead-free joints can be evaluated. Typically, lead-free alloys’ surface tension is stronger than that of conventional Sn/Pb solder. Hence, when the lead-free solder melts, it has more difficulty spreading along surfaces. The soldering capacity is dependent on the wettability characteristics of the lead-free alloy to the integrated circuit (IC)-lead plating, thus making fillet shape an important factor of solder inspection.

The solder joint inspection criterion needs to be updated to account for lead-free solders. Programming methods for these new methods of inspection may need to be changed; with due attention to suitable new algorithms, and the provision of a suitable voltage source, to compensate for reduced image contrast due to the absence of lead.

Chapter 4 Impact of lead-free legislation exemptions on LVCES industries

4.1 Exemptions

The WEEE and RoHS legislation contain a number of exemptions. The rationale for the exemptions given in the RoHS legislation is that "exemptions from the substitution requirement should be permitted, if substitution is not possible from the scientific and technical point of view or if negative environmental or health impacts caused by substitution are likely to outweigh the human and environmental benefits of the substitution"[4]. Substitution is defined in the RoHS legislation as using "safe or safer materials" instead of the identified hazardous substances (i.e., mercury, cadmium, lead, hexavalent chromium, polybrominated biphenyls and polybrominated diphenyl ethers) in electrical and electronic equipment [4].

The exemptions range from specific electronic industries to electronic product categories. Electronics specifically manufactured for the military is exempt from the WEEE legislation. This is stated in the WEEE legislation as "equipment which is connected with the protection of the essential interests of the security of member states, arms, munitions and war material shall be excluded from this directive. This does not, however, apply to products which are not intended for specifically military purposes" [3].

The 'Annex' of the RoHS legislation lists the following exemptions.

- Lead in glass of cathode ray tubes, electronic components and fluorescent tubes.
- Lead in high melting temperature type solders (i.e. tin-lead solder alloys containing more than 85% lead)
- Lead in solders for servers, storage and storage array systems (exemption granted until 2010)
- Lead in solders for network infrastructure equipment for switching, signaling, transmission as well as network management for telecommunication
- Lead in electronic ceramic parts (e.g. piezo-electronic devices)

The RoHS legislation does not cover medical electronics and monitoring and control instruments. This is stated in the RoHS legislation as “Without prejudice to Article 6, this Directive shall apply to electrical and electronic equipment falling under the categories 1, 2, 3, 4, 5, 6, 7 and 10 set out in Annex IA to Directive No 2002/96/EC (WEEE) and to electric light bulbs, and luminaries in households”[4]. Medical electronics is category 8 and monitoring and control instrument is category 9 in the WEEE directive. Thus, these two categories are outside the scope of the RoHS directive.

Avionics and automotive electronics have not been specifically mentioned among the categories of electronics covered by the WEEE and RoHS legislations [4]. Thus, they can be considered to be outside the scope of the WEEE and RoHS legislation. However, automotive electronics is covered by the scope of the End-of-life Vehicle

(ELV) legislation. The ELV legislation specifically exempts lead used in solders for automotive electronics [66]. Oil and gas electronics is exempt from the RoHS legislation if they are equipment for control and monitoring [4]. Batteries used in electrical and electronic equipment are not covered by the scope of the RoHS legislation. The WEEE legislation applies to spent batteries collected as part of the recycling and recovery of electronic products [35]. Upon removal from electrical and electronic equipment, spent batteries are part of a separate legislation called the 'Battery Directive' [36].

Spare parts for electrical and electronic equipment 'put on the market before 1 July 2006' are outside the scope of the RoHS legislation [4]. This is stated in the RoHS legislation as "This Directive does not apply to spare parts for the repair, or to the reuse, of electrical and electronic equipment put on the market before 1 July 2006". However, the RoHS legislation does not define the difference between spare parts and consumables. Consumables of electronic products include toner cartridges for printers and flash memory cards for digital cameras.

4.1.1 Lead in glass of cathode ray tubes, electronic components and fluorescent tubes

Cathode ray tubes (CRTs) are used as desktop computer displays and in televisions. The CRT display consists of a faceplate (glass panel), a shadow mask, a leaded glass funnel, and an electron gun. CRT displays accelerate electrons towards a luminescent material (phosphor) that is deposited on the faceplate. The decelerating electrons produce radiation. Lead is added to the glass in CRTs to act as a shield against radiation.

Lead accounts up to eight percent of the overall composition of CRT by weight [37]. Lead is used in the CRT glass parts (funnel, panel and neck glass), the sealing frit, and the solder on the printed wiring boards within the CRT.

Table 2 Lead content in computer displays

Part	**Display Type**	**Quantity** kg	**% Lead content (PbO)** (by weight)
Funnel	CRT	0.91	22-28%
Front panel	CRT	0.18	0-4
Neck	CRT	0.012	26-32
Frit	CRT	0.026	70-80
Printed wiring boards (total)	CRT	0.051	NA
Printed wiring boards (total)	LCD	0.043	NA

There is no commonly available and inexpensive substitute for lead used in CRTs. Although CRTs containing lead can still be manufactured, they are subject to recycling regulations [39], [40]. The U.S Environmental Protection Agency (EPA) has proposed regulations for the collection, reuse, and recycling of CRTs [41]. The WEEE legislation requires producers to setup separate treatment facilities to remove fluorescent coatings from cathode ray tubes [3].

The display market is already transitioning from CRTs to Liquid Crystal Displays (LCDs) [42]. Toshiba and Matsushita will terminate production of cathode ray tubes used in televisions by September 2004 in Japan [43]. Sony has phased-out its 17-inch and 19-inch CRT computer monitors [44]. Hitachi stopped production of CRTs in 2001 and has now totally transitioned to LCDs [45].

An LCD is composed of two glass plates surrounding a liquid crystal material. The orientation of the liquid crystal molecules determines the illumination of the pixel. The combination of the alignment layer, electrical charge, and polarizer that are laminated to the glass panels determine the color and brightness of the LCD pixel. The backlight supplies the light source for the display by fluorescent tubes [38]. Lead is present only in the printed wiring boards of LCDs.

Glass frits are used in electronic components for sealing purposes. The chemical composition of glass frits is dependent on the relative percentage of the lead and silicon oxides. For example, lead borosilicate glasses have the following composition: (60-75 wt%)-PbO (2-25 wt%)-SiO_2 (2-20 wt%)-B_2O_3 [46]. The sintering temperature of glass frits (560-590^oC for lead borosilicate glass) is reduced as the percentage of lead oxide in the mixture increases. The percentage of lead oxide in glass frits also determines physical and chemical properties including refractive index and chemical durability. For example, lead borosilicate glasses are used to join the substrates in plasma display panels. The thermal expansion coefficient of the glass frits is adjusted to match that of the glass substrate by controlling the relative percentage of PbO in the composition [46].

Lead in glass of electronic components is exempted from the RoHS legislation because there is no alternative material to PbO in glass frits that can provide the same versatility in changing the material property of glass frits [47].

The fluorescent tube consists of a glass tube coated with phosphor in the inner surface. A phosphor is a substance that fluoresces when energized by radiation from the charged mercury vapor inside the tube. The lead is present in the glass of fluorescent tube. Lead-free glasses are available from different vendors. The exemption to lead in glass of fluorescent tubes is not vital since alternatives are available.

4.1.2 Lead in high melting temperature type solders

Lead in high-melting temperature solders is exempt from the RoHS legislation. The RoHS legislation states the percentage of lead content in the exempt solder alloys as greater than 85% [4]. This lead percentage does not refer to the composition of intermetallics formed after soldering.

Solders containing greater than 85% lead have melting point in the range of 270^{o}C to 320^{o}C. High melting temperature solders are used as die-attach and flip chip bumps [48].

High lead alloys are used as die-attach in high-temperature applications in power electronics. Epoxy die attach cannot be used at temperatures greater than 200^{o}C. This is because, use of epoxy die attaches above their glass transition temperature, which is usually in the range of 75^{o}C to 125^{o}C, requires that allowance be made for a higher coefficient of thermal expansion, a lower modulus and lower strength [49]. High temperature storage and use may also release ionic chlorine from the epoxy which can lead to increased metallization corrosion [50]. The commonly used high-lead alloys for die-attach include 90Pb90-10Sn and 95Pb-5Sn [49].

Lead-free alternatives for high-lead solders include gold-based eutectic, silver filled glasses and aluminum nitride filled glass [49]. The gold-based eutectic (80Au20Sn) is preferred for high power circuits, because of its superior electrical and thermal conductivity. The drawbacks of gold-based eutectic include high-cost and problems during rework. Silver filled glasses have electrical and thermal conductivity one magnitude lesser than that of gold eutectic. Aluminum nitride or beryllia filled glasses provide thermal conductivity combined with electrical insulation [51]. High temperature packages requiring that very little stress be imparted to the die, such as those with large dies or thin leadframes, can use cyanate ester die attaches, which combine a modulus of rigidity (400 MPa) which is 2.5 times less than epoxy, with thermal stability at temperatures up to 300^{o}C [52].

Flip chip bumps are made of high-lead alloys such as 97Pb3Sn [48]. The high melting point (greater than 300^{o}C) of solder bumps prevents remelting when the module or bumped die is attached to the board during the reflow process [53]. Alternatives to high-lead solder bumping include electroless nickel/Au bumps, epoxy bumps and gold bumps. The drawbacks of these alternatives include higher cost and lack of comparable self-alignment. Higher placement accuracy may be required [54].

4.1.3 Lead in solders for servers, storage and storage array systems

A server centrally manages resources that are used by multiple users in a computer network. Servers are classified based on their role. Office servers are usually dedicated to specific tasks including storing files, managing print queues and hosting the company's email system. An enterprise server system supports thousands of desktop computers, performs database management, data warehousing, and e-business transactions. These enterprise systems are multi server systems with adequate redundancy built in their organization. This is to minimize down time. The main goal of servers and storage array systems are to supply information to multiple devices on demand [55].

The RoHS legislation grants exemption to the use of lead in solders for servers, storage and storage array systems till the year 2010 [4]. Servers, storage and storage array systems is the only category of exemption where the RoHS legislation has specified a time limit. From the hardware point of view, servers and desktop computers are based on similar technology. Servers typically have access to more processing power, memory, and storage capacity compared to desktop computers. However, the desktop computer market is already transitioning to lead-free [1].

The transition time granted to servers, storage and storage array systems till 2010 can ensure that manufacturers of servers and storage array systems build on the learning curve of transitioning to lead-free electronics in computers Fujitsu has already introduced a lead-free network server [56].

4.1.4 Lead in solders for network infrastructure equipment

The RoHS legislation grants exemption to the use of lead in solders for network infrastructure equipment [4]. The legislation does not define the categories of electronics that should be considered as network infrastructure equipment. Network infrastructure equipment can mean all the various electronic devices used in the telecommunications industry including routers, switches, signaling and transmission equipment. Because of the recent proliferation of the IEEE standard 802.11b wireless devices enabling access to the network, this exemption can even be considered to apply to broadband routers sold to home users.

Many communications and logic device makers are transitioning towards lead-free products. For example, LSI Logic has introduced lead-free ball-grid array chip packages for communications and storage peripheral applications. LSI Logic worked with material suppliers to qualify processes and the lead-free alloy and meet industry standards for moisture sensitivity. In addition, LSI Logic has qualified its mainstream package families, PBGA and EPBGA, with a lead-free alloy utilizing tin/silver/copper [57].

Table 3 Application categories of electronics products affected by legislation exemptions

Applications	Related products
Lead contained in glazing glass as thick film insulators	High voltage resistors, hybrid ICs, resistors, resistor networks, RC networks, capacitor networks, resistor arrays, magneto-resistive elements, ceramic heaters etc.
Lead in glass frit used for electronic parts	Chip resistor networks, chip capacitor networks, chip RC networks, resistor networks, magneto resistive elements, trimmer, potentiometer etc.
Lead in thermal fusing materials used for electronic components	Fuse resistor, thermal cut off, tantalum electrolytic capacitor with fuse etc.
Lead contained in low melting point glass for packaging for CCD or laser diodes and for sealing semiconductor packages	Light emitting, receiving devices or semiconductor diodes such as CCD, laser diodes
Lead contained in high melting temperature type solder used within an electronic components for internal connection purpose between functional element and wires, terminals, heat sinks etc.	Resistors, capacitors, chip coil, resistor networks, capacitor networks, power semiconductors, discrete semiconductors, ICs, chip EMI, chip beads, chip inductors, chip transformers etc.
Lead contained in high melting temperature solder used for mounting electronic components onto sub assembled module or sub-circuit board.	Hybrid ICs, modules etc.
Lead in high melting temperature type solder to seal metal roof and ceramic package etc.	SAW (surface acoustic wave) filters, quartz resonators and filters etc.
Lead contained in glass for fluorescent or other light housings	
Lead contained in bonding glass for magnetic head	Magnetic heads
Lead in glass passivation for semiconductor chip	Diode, thyristor, power transistor etc.

Lead contained in thick film resistive layers	RC networks, potentiometers, hybrid ICs, chip resistors, chip resistor networks, chip RC networks, chip capacitor networks, chip resistor arrays, trimmer potentiometers etc.
Lead contained in video head glass	
Lead in glass of plasma display panel	
Lead in lead-zirconate-titanate (PZT)	High dielectric layer for semiconductor memory chip FeRam, piezo-electronic components including most sensors

The transition towards lead-free electronics in the network communications industry is accelerated by the move by leading industry players towards lead-free. For example, the entire Texas Instruments logic portfolio is now available in lead-free solutions. Texas Instruments (TI) has chosen the nickel palladium gold (NiPdAu) finish as the preferred lead-free finish for all lead-frame based packages [58]. TI has now converted all of its logic devices to lead-free finishes. TI logic packages are now classified per the J-STD-020B lead-free parameters. TI has also qualified lead-free solder ball alloys for its LFBGA, VFBGA, and WCSP logic packaging offerings. The MicroStar BGA and the NanoFree logic packages use SnAgCu alloys [59], [60].

4.1.5 Lead in electronic ceramic parts

In a ceramic package, the ceramic substrate is sealed to the lid using either glass frit [61]. Common ceramic substrate materials include alumina (Al_2O_3), beryllia (BeO), and aluminum nitride (AlN) [62]. Lead borosilicate glass (i.e., 'glass+ceramics') have been used as a ceramic substrate material. Lead is also present in the glass frit. The composition of the glass frit used in sealing the ceramic part belongs to the system PbO-B_2O_3-SiO_2-Al_2O_3-ZnO [63].

Lead-free glass frits are available with properties similar to lead-based glass frits [63]. They can be used to seal the ceramic package in place of lead-containing glass frits. Thus, the RoHS legislation exemption for lead in glass frits used to seal electronic ceramic parts is not crucial. However, in certain applications (e.g., sealing plasma display panels) the PbO content in glass frits influences relevant material properties like refractive index by reducing the temperature required for sintering.

In piezo-electronic ceramics, an electrical charge is generated by a mechanical stress, and conversely, an electrical field is produced by mechanical displacement. The common piezoelectric ceramic material which contains lead is lead zirconate titanate (PZT) [64]. This piezoelectric property is a result of the crystal structure of PZT [65].

Currently, PZT piezo-electronic ceramics comprise the sensing element in transducers since they comparatively show the highest generative forces, accurate displacements, and high frequency capabilities. Alternate lead-free piezo-electronic materials like alkaline niobates [e.g., $KNbO_3$ (KN) and (K, Na)NbO_3 (KNN)] possesses piezo-electronic properties that are inferior to those of lead based compositions [65].

4.2 Impact of exemptions

The lead-free legislation is influencing the electronics industry to transition to lead-free products through evaluation of alternatives and associated risks. The exemptions in the lead-free legislation can help some sectors of the electronics industry to plan the lead-free transition in a more cost-effective manner. They can achieve this by concentrating their efforts to finding lead-free alternatives for non-exempt products.

Among the industry categories that have been exempted, the impact of the legislation exemptions affects some classes of products much more than others. For example, though the WEEE legislation exempts military electronics, the legislation also clearly states that this exemption is not applicable to products not manufactured for specifically military purposes [3]. The leverage offered by the exemption is substantially reduced since the military electronics industry procures a significant percentage of its electronics from commercial-off-the-shelf electronics manufacturers.

Some of the industry and product categories exempted from the RoHS legislation are still under the purview of the WEEE legislation. For example, medical electronics and 'monitoring and control instruments' are outside the scope of the RoHS legislation [4]. However, both medical electronics and 'monitoring and control instruments' are still covered by the WEEE legislation [3]. Thus, medical electronics industry is liable to establish mechanisms for recycling and recovery of electronics as per WEEE. But since they are outside the scope of the RoHS, they are not liable to remove lead from their products.

Some industry categories have not been included as part of either the WEEE or RoHS legislation but are part of other separate legislations covering a different class of product altogether. For example, automotive electronics is covered by a separate allied End-of-life Vehicle (ELV) directive which exempts the use of solders in electronics of vehicles, including automobiles [66]. However, automotive electronics have not been specifically mentioned among the categories of electronics covered by the WEEE and RoHS legislations.

The impact of the legislation exemptions on various sectors of the electronics industry are discussed below.

4.2.1 Military electronics

Over the past decade, the US military has transitioned from military-specific electronics to the use of commercial-off-the-shelf (COTS) electronics to have access to affordable, leading-edge technology [67]. Electronics specifically manufactured for military are exempt from the WEEE and RoHS legislation. However, the legislation also states that this exemption is not intended for electronic products which are not manufactured for specifically military purposes [3], [4]. Thus, any commercial-off-the-shelf (COTS) electronics used in military equipment must comply with the requirements of the WEEE legislation.

The cathode ray tube, widely used in previous generations of displays continues to drop in defense market share. More than half of the total defense displays is now based on some form of flat panel display technology, especially thin-film-transistor (TFT) active matrix liquid crystal display. The exemption of lead in glass of cathode ray tubes doesn’t affect the military electronics industry. This is because as much as 80% of displays used by U.S military are COTS designs, while the remaining 20% of defense displays are custom designs to meet the additional performance requirements [68].

Ceramic ICs are used by U.S military (i.e., assembled in hermetically-sealed ceramic packages) under harsh environment applications where plastic parts cannot be used reliably. The majority of these ceramic packages are through-hole mountable, with surface-mount packages developed predominantly as leadless chip carriers that must be mounted on ceramic circuit cards [67]. Glass frits containing lead are used to hermetically seal the ceramic components. Thus, the exemption to the use of lead in ceramic parts is vital from the military perspective. However, due to the increasing use of COTS components in military electronics, the share of the ceramic packages is much less compared to the plastic parts.

COTS servers are used by US military for processing data gathered through surveillance and reconnaissance. For example, Compaq ProLiant 8500 computer server is used for signal processing applications in the Integrated Undersea Surveillance System (IUSS). The server has eight Intel Pentium III Xeon microprocessors [69]. The exemption for servers and storage array systems in the RoHS legislation is thus significant from the perspective of the military. Procurement decisions for COTS servers in future will need to take into account the risk of change in legislation and exemptions.

The U.S military uses COTS routers and switches to integrate combat, command-and-control and navigation systems [70]. For example, in the U.S navy’s new "Sea Power 21" plan, COTS electronics is used for routing, switching, and systems-management to enable ship sensors, communication systems, and weapons to support "network-centric warfare" [71]. Leading vendors in the network infrastructure equipment industry are already transitioning towards lead-free electronics. The U.S military cannot be dependent on the exemption to lead used in network infrastructure equipment.

Piezo-electronic ceramics are comprised in many of the transducers used in military applications such as hydrophones, sonobuoys, depth sounders, fuse devices, telephony and sub sea profilers. The exemption to lead used in piezoelectronic ceramics affects many classes of electronics systems used in U.S military. However, there is no reliable alternative material to lead zirconate titanate used in piezoelectronic ceramics. Sensors and transducers, including those used in the military, will continue to use lead in piezoelectronic ceramics.

4.2.2 Automotive electronics

Electronics is now firmly established as an integral part of the modern road vehicle's engineering. Automobile electronics can be classified into three major categories; power train management, body electronics and information processing units [72]. Power train management includes electronic control units that control ignition timing and the amount of fuel injected into the cylinders. Body electronics controls dashboard displays, suspension settings, and environment in the passenger compartment. Information processing electronics refers to the broad category of electronics that maintain communication with the outside world, and includes entertainment systems (often called the telematics or infotainment system). Based on application environment, automotive electronic components can be classified into two categories, namely “under hood” components and components used in the passenger compartment.

Automotive electronics have not been specifically mentioned among the categories of electronics products covered by the WEEE and RoHS legislations [3],[4]. Rather, they are under the scope of the End-of-life Vehicle (ELV) legislation. The ELV legislation specifically exempts lead used in solders for automotive electronics [66]. Nevertheless, automotive electronics manufacturers are already transitioning towards lead-free solders and assembly processes [73]. For example, Delphi Automotive Systems has been researching lead-free solders for use in automotive applications [74]. Most leading automotive electronics companies have already introduced lead-free products [75],[76]. For example, Nissan Motors uses lead-free solder on printed circuit boards for only keyless entry systems since July 2000 [77]

Automotive displays are used in navigation panels, telematics, dashboard instrumentation, and in rear-seat entertainment. Exemptions for lead in cathode ray tubes are not relevant for the automotive electronics industry since automotive displays are based on liquid crystal display (LCD) technology. For example, BMW uses a color LCD which combines all the separate displays scattered around a dashboard in its ‘7 Series’ of cars [78]. Alternative technologies include LED-based displays and heads-up displays (HUDs). Issues relating to the manufacture and integration of displays for automotive instrumentation to include cost, reliability, weight, and footprint by adopting advanced packaging technologies.

Automotive electronics industry uses high lead solders in flip chip bumps. Flip chip packaging is widely used in the automotive electronics industry due to advantages in size, performance, flexibility, reliability, and cost over other packaging methods. Flip chip bare die mounted on high-density laminate with heat sinks is used in engine control applications. Alternate materials for flip-chip bumps in automotive electronics are being researched. For example, a flip chip process can be based on electroless Ni/Au bumping and stencil printing of lead-free solder paste [79].

The exemption to the lead used in solders for network infrastructure equipment is relevant for the automotive electronics industry. The category of automotive electronics that can be considered as network infrastructure equipment includes telematics, infotainment system, navigation guidance using global positioning systems (GPS) and fly-by-wire systems [80]. Automotive electronics manufacturers can continue to use tin-lead solder in the development of these electronic systems.

Piezoelectronic devices comprise many of the transducers used in the automotive sector that use piezo-electronics are automotive, knock sensors wheel balances, radio filters, seat belt buzzers, tread wear indicators, air flow, airbag sensors, fuel atomization, tire pressure indicators, spark ignition, audible alarms and keyless door entry. The development of smart sensors has enabled the design of subsystems like integrated power train traction control, onboard diagnostics, navigation and integrated electronic braking, steering and suspension [80]. There is no reliable alternative material to lead zirconate titanate used in piezoelectronic ceramics. Automotive sensors and transducers will continue to use lead in piezoelectronic ceramics.

4.2.3 Avionics

Avionics refers to the electronics used on aircraft and spacecraft for navigation, communications, and control systems. Avionics systems are a complex mix of computers, sensors, actuators, and control and display units. The operating life cycle of avionics is considerably longer and more stringent than those for mass-produced electronic components commonly available.

Avionics has not been specifically mentioned among the categories of electronics products covered by the WEEE and RoHS legislations. The exemptions list to the WEEE and RoHS legislations also does not specifically list avionics [3], [4].

There is a widespread use of COTS components in avionics systems. System integrators in the avionics industry are gradually transitioning towards lead-free electronics. Boeing and BAE Systems, in conjunction with its suppliers have been investigating the issues of reliability of lead-free electronics in commercial avionics [14].

Exemptions granted to lead in CRTs are not relevant to the avionics industry since avionics displays are already transitioning to LCD technology. Active Matrix Liquid Crystal Display (AMLCD) technology has been widely used in avionics [82]. In AMLCDs, each picture element on the display screen is connected to a small thin film transistor that can transfer and store enough voltage to switch each liquid crystal pixel. The resulting image exhibits superior speed, brightness, and contrast over other liquid crystal displays and cathode ray tubes [83].

Liquid crystal display technology is used in both commercial and military avionics. AMLCDs satisfy both the military and commercial avionics requirements. Military requirements include high brightness and color contrast due to the open canopy and high-altitude operation, night vision compatibility and fast response times. Many new commercial aircraft are also incorporating AMLCDs. For example, Honeywell D-size display is a wide-field-of-view AMLCD developed for the Boeing 777 and 737 airliners.

Network infrastructure equipment in avionics includes those electronics products that enable radio communication and navigation with the ground, products that control and monitor functions in the passenger cabin such as passenger address, audio entertainment and cabin crew telephone communications. The exemption to the lead used in solders for network infrastructure equipment is relevant for the avionics industry. Avionics manufacturers can continue to use tin-lead solder in the development of these electronic systems

Avionics uses a number of piezoelectronic sensors. Avionics sensors are used to control and monitor airframe systems such as propulsion, fuel systems, hydraulics and electrical power. There is no reliable alternative material to lead zirconate titanate used in piezoelectronic ceramics. Avionics sensors and transducers will continue to use lead in piezoelectronic ceramics.

The avionics industry is controlled by regulatory authorities, including the Federal Aviation Administration (FAA) [84]. The lead-free transition in avionics products will require regulatory approval before end-use. Regulatory agencies do not approve specific electronic components. Rather, approval is dependent on satisfactory performance of the equipment. When a new equipment design is certified, the parts used in the design are included in the certification. If the lead-free transition makes it necessary to replace a lead-based part in equipment that has already been certified, the process for approving the replacement part is based on proving, by test or analysis, that the equipment function is maintained by the lead-free part replacement. Avionics companies may need to develop test plans to demonstrate compliance with the regulations.

4.2.4 Oil and gas well electronics

Oil and gas electronics instrumentation can be broadly divided into three major types: logging instrumentation, measurement while-drilling instrumentation and permanent gauge instrumentation.

Logging instrumentation is deployed for gathering snapshot information revealing the quality and potential production potential of the well. These can be wire-connected (wireline tools, receiving power and communications from the surface) or cable connected (self-powered instrumentation which contain its own memory and is retrieved with the tool).

Measurement while drilling instrumentation is used for directional drilling information such as hole inclination, hole azimuth, and the tool face direction. In addition, other measurements are now performed including resistivity, natural gamma, and neutral density. Downhole weight on bit, torque, vibration levels, accelerations are sometimes also incorporated into the measurement.

Permanent gauges are installed in producing wells and monitored at the surface periodically over the course of several years. Temperature, pressure, chemical and flow sensors are part of the instrumentation. A basic permanent monitoring system in oil and gas installations consists of down hole gauges to measure temperature and pressure, a surface acquisition system to collect the data measured down hole, a data link to the control facility and computers to control and monitor the data [85].

Electronics used for oil and gas exploration and production applications experience a wide range of stresses owing to the varied load (operational and non-operational) conditions experienced by the system during its life. These devices must have good long term reliability without susceptibility to premature wearout mechanisms. This lifecycle environment requires endurance to high vibrations and shock and thermal cycling. Because of the high cost of drilling operations, oil and gas electronics instrumentation needs to be highly reliable.

‘Monitoring and control instruments in industrial installations’ are classified as category 9 in the WEEE legislation [3]. Oil and gas electronics used for monitoring and control are exempt from the ROHS legislation. Irrespective of whether oil and gas electronics industry is exempted in the WEEE and RoHS legislation, the industry may still be vulnerable to the lead-free transition. This is because of the fact that a multitude of COTS electronics is used in the oil and gas electronics instrumentation. For example, commercial-off-the-shelf (COTS) electronics are used in surface acquisition systems, data link layers and computers to monitor logging data [86].

Oil and gas electronics uses a number of high-lead solders in down hole harsh environments. Currently, high-lead solders with lead content greater than 85% are exempt from the ROHS legislation [4]. However, even if the oil and gas electronics industry uses tin-lead solder with lead percentage greater than 85%, it might happen that some solder intermetallics or sub-assemblies can have homogeneous material with lead content less than 85% after the assembly process.

The RoHS legislation does not specify whether the lead content is measured as a percentage of the final electronic product or as a percentage in the homogeneous material (e.g. solders or subassemblies). This specification of 'maximum concentration value' of lead has still not been issued by the European Commission. It is apparent that this value will not be a percentage of the final product but some measure of the materials used. (e.g., by weight per homogeneous material or by weight per applied material)

Lead-free alternatives to high-lead solder alloys are currently being in the research and development stage. This includes antimony based alloys (Sn65Ag25Sb10 and Sn95Sb5), eutectic gold-tin alloy (Au80Sn20) [87]. These alloys are comparable to high-lead solders in creep behavior and corrosion resistance. However, some of their drawbacks include high cost and manufacturability concerns.

There is a widespread use of ceramic components in down hole electronics. A typical PCB used in downhole electronics has a mix of active and passive parts – ceramic dual inline ICs, ceramic capacitors, ceramic inductor, ceramic resistors, ceramic diodes and metal transistors. The ceramic ICs are generally rated in the temperature range of -55°C to 125°C. The availability of ceramic components can decrease if the exemption provided to the use of lead in glass frits of ceramic components is removed and manufacturers transition wholly towards plastic parts.

Oil and gas electronics industry uses a variety of sensors to measure the lifecycle environment of the oil well. Currently, lead-zirconate-titanate (PZT) based piezo-electronic ceramics are the mostly widely used sensors since they comparatively show the highest generative forces, accurate displacements, and best high frequency capabilities. The RoHS legislation currently exempts the lead in piezo-electronic ceramics. Alternate lead-free piezo-electronic materials (e.g., alkaline niobates) in general possess piezo-electronic properties that are inferior to those of lead based compositions. Alternate materials to PZT aren't commercially available and the exemption to lead in piezo-electronics ceramics will be present for many more years.

4.2.5 Industrial electronics

Industrial electronics includes computer control systems, robotics, factory communications and automation, flexible manufacturing, data acquisition and signal processing, vision systems, and power electronics.

'Monitoring and control instruments in industrial installations' are classified as Category 9 in the WEEE legislation. This category is exempt from the ROHS legislation. Thus most factory control systems and measuring equipment can be considered to be exempt from the RoHS legislation.

The RoHS legislation grants exemption to the use of lead in solders for network infrastructure equipment [4]. The legislation does not define the categories of electronics that should be considered as network infrastructure equipment. Network infrastructure equipment can mean all the various electronic devices used in the telecommunications industry including routers, switches, signaling and transmission equipment. Because of the recent proliferation of the IEEE standard 802.11b wireless devices enabling access to the network, this exemption can even be considered to apply to broadband routers sold to home users.

Many communications and logic device makers are transitioning towards lead-free products. For example, LSI Logic has introduced lead-free ball-grid array chip packages for communications and storage peripheral applications. LSI Logic worked with material suppliers to qualify processes and the lead-free alloy and meet industry standards for moisture sensitivity. In addition, LSI Logic has qualified its mainstream package families, PBGA and EPBGA, with a lead-free alloy utilizing tin/silver/copper [57].

The transition towards lead-free electronics in the network communications industry is accelerated by the move by leading industry players towards lead-free. For example, the entire Texas Instruments logic portfolio is now available in lead-free solutions**.** Texas Instruments (TI) has chosen the nickel palladium gold (NiPdAu) finish as the preferred lead-free finish for all lead-frame based packages [58]. TI has now converted all of its logic devices to lead-free finishes. TI logic packages are now classified per the J-STD-020B lead-free parameters. TI has also qualified lead-free solder ball alloys for its LFBGA and WCSP logic packaging offerings. The MicroStar BGA and the NanoFree logic packages use SnAgCu alloys [59], [60].

The use of lead in solders in the electronics of servers and storage networks has been exempted in the lead-free legislation till the year 2010. This exemption has mainly arisen because of the tasks performed by these servers at the enterprise level.

The exemption granted to the use of lead in piezo-electronics ceramics is relevant to the industrial electronics industry because of the wide variety of the transducers that use piezoelectric ceramics. These include ultrasonic cleaners, ultrasonic welders, touch sensors, ultrasonic probes, thickness gauging, seismic sensors, level indicators, pyroelectric detectors, ultrasonic drilling, vibrators, geophones, delay lings, ignition systems, fans, relays, ink printing, alarm systems and strain gauges. The lead in piezo-electronics ceramics is present in the form of lead-zirconate-titanate (PZT). Alternate materials to PZT aren't commercially available and the exemption to lead in piezo-electronics ceramics will be present for many more years.

4.2.6 Medical electronics

Medical electronics encompass a wide variety of devices used in the healthcare industry for diagnosis and cure. Medical electronics comes under the scope of WEEE legislation but is exempted from the ROHS legislation [3], [4]. Thus, medical electronics manufacturers are can continue to use lead-based electronics in their products. However, they will need to establish recycling and recovery systems as per the WEEE legislation.

Medical electronics implanted within the body (e.g., pacemakers) are exempt from both WEEE and RoHS legislations. However, the medical electronics products used outside the body (e.g., blood pressure measuring device) will be covered by the WEEE legislation. Commercial-off-the-shelf (COTS) electronics is used in all the three major product categories in the medical electronics industry, (i.e.) for diagnostic, therapeutic and analytical products. The lead-free transition in COTS electronics affects all the medical electronics product categories [88].

The exemption offered to cathode ray tubes is not relevant to the medical electronics industry since the medical electronics displays are transitioning to active matrix liquid crystal displays (AMLCDs).

The development of AMLCDs has traditionally been driven by the need for compact, low-power, lightweight displays for portable systems. Such displays have also been used in portable patient monitoring systems. This has led to the development of portable diagnostic tools, such as handheld ultrasound imagers. AMLCDs are useful for applications such as magnetic resonance imaging (MRI) because of their low susceptibility to electromagnetic interference. AMLCD images are inherently immune to distortion by external magnetic fields, eliminating bulky shielding that is often needed with CRTs. This simplifies the design of MRI systems. AMLCDs that provide an alternative to film-based x-ray systems, enabling fully digital systems with on-demand remote access to images, telemedicine, and archiving.

The product development cycle in the medical device is considerably long due to the lengthy nature of clinical testing and regulation. The medical electronics industry is controlled by regulatory authorities, including the Food and Drug Administration (FDA). The lead-free transition in medical electronics products will require regulatory approval before end-use. The certification process will need to conform to the FDA certification process if the design is changed due to the lead-free transition [89].

Medical electronics manufacturers can continue to use lead-based electronics in the next few years because of the exemption from the ROHS legislation. However, their dependence on COTS components implies that they may need to redesign and get regulatory approval for their medical devices before the exemption is removed [90].

Chapter 5

Recommendations for risk mitigation

The lead-free legislation is influencing the electronics industry to transition to lead-free products through evaluation of alternatives and associated risks. The exemptions in the lead-free legislation can help some sectors of the electronics industry to plan the lead-free transition in a more cost-effective manner. They can achieve this by concentrating their efforts to finding lead-free alternatives for non-exempt products. The exemptions in the lead-free legislation do not cover a broad gamut of electronic products. This implies that electronics companies, especially in the low-volume complex electronics industries, will need to adopt risk mitigation strategies including maintaining dual inventory, requalification of suppliers and continuously monitor part change notifications.

LVCES companies will need to determine the reliability of lead-free commercial-off-the-shelf components and lead-free solders under harsh environmental and long-term usage conditions. They will need to ensure that they only use components that have been reclassified according to the revised moisture sensitivity level J-STD-020B standard for higher temperature lead-free reflow process. LVCES companies will need to work with consortia, suppliers, industry groups in determining the acceleration factors for lead-free packages to board interconnect durability. Mitigation strategies for risks of tin whiskers will need to be implemented. This might include solder dipping the plated surfaces in tin-lead solder, applying conformal coats and annealing. The impact of the choice of solder alloy and reduced wetting characteristics on long-term reliability will also need to be determined. The effect on long-term reliability due to the degradation of solder joints by increased tin-copper and tin-nickel intermetallics will need to be analyzed.

Dual inventory of lead-free and lead-based electronic parts may be necessary to offset parts made obsolete by the lead-free transition. For example, there can only be a single-source for a particular lead-based part, or the production of a strategic part might be discontinued due to lead-free transition. LVCES companies will need to determine the part obsolescence impact on life cycle sustainment costs for the long field life electronic systems based on future production projections, maintenance requirements and part obsolescence forecasts [22].

LVCES companies may need to adopt common obsolescence mitigation approaches in either a short-term or long-term. Short-term approaches include ‘third party’ buy, and ‘last-time’ buy. Long-term approaches include ‘life-time’ buy, finding a substitute part, emulation, and uprating similar part [22].

LVCES companies may need to buy sufficient parts to meet the systems’ lifetime needs of lead-based parts from the original part manufacturer before the anticipated close of production. This is called a lifetime buy or life-of-type buy. This is one of the cheapest solutions since it doesn’t require reengineering, re-qualification, or redesign. The equipment supplier should determine last date for order processing minimum order quantity, or value and the latest delivery dates for the lead-based part from the manufacturer’s product discontinuance notice [25].

LVCES companies will need to determine the optimum design refresh plan for lead-based and lead-free parts during the field-support life of the product. The design refresh plan will need to consist of the number of design refresh activities, and their content and respective calendar dates that minimize the life cycle sustainment cost of the product. When design refreshes are encountered (their date is defined either by the user or by the methodology during its optimization process) the change in the design at the refresh must be determined and the costs associated with performing the design refresh must be computed [26].

Re-qualification of suppliers of lead-free parts and sub-assemblies may be required by automotive electronic original equipment manufacturers (OEMs). The requalification process of suppliers should take into account the procedures adopted by the suppliers across all their divisions to ensure that the materials used are compatible with the lead-free assembly requirements [22]. The parameters to be considered during supplier qualification include component availability date, expected lead-times, schedule for qualification, production schedule, supply line flexibility and notification of expected potential issues during manufacturing of the component.

Supplier requalification methods should also take into account technology characteristics of the automotive electronics components supplied by the suppliers. For example, available component surface finishes, alloy composition, plating thickness with specified tolerances will need to be evaluated for compatibility with the lifecycle environment conditions of automotive electronics. Suppliers may also be required to provide test data to validate process compatibility.

LVCES companies will need to evaluate the suppliers for all the anticipated cost issues that may affect the supplier’s ability to supply parts during or after the lead-free transition. For example, assessment of supplier capacity may include dual manufacturing capability and utilization plans, tooling lead times and service [22].

Part change notifications (PCN) are issued by electronic part manufacturers. A PCN includes part identification details, description of change, PCN number, reason for change, implementation date, effects on quality and reliability, methods for distinguishing old parts from new parts, qualification data and a person to contact with any questions. LVCES manufacturers will need to evaluate the PCNs of their products to ensure that the changes do not affect the functionality of the final product in which the part is used [22].

Part change notifications (PCN) are issued by part manufacturers. A PCN includes part identification (part numbers, product lines etc.), description of change, PCN number, reason for change, implementation date, effects on quality and reliability, methods for distinguishing old parts from new parts, qualification data and a person to contact with any questions. LVCES companies may need to continuously monitor PCNs during the lead-free transition [22].

The effects of using lead-free electronics with existing LVCES during rework and repair will need to be evaluated. Operator retraining will be required to ensure lead-free process control during hand-soldering. Reconfiguration or replacement or upgradation of reflow ovens and other process equipments to handle higher lead-free reflow temperatures is necessary. The effects of lead-contamination on lead-free electronics should be evaluated, reliability test data about the effect of mixed solder alloy interactions of reworked hardware will need to be analyzed. Visual inspection method for lead-free solder joints, material handling, and cross-contamination of processes should be documented and updated.

The LVCES industries should continuously monitor the ongoing environmental legislative process. This is because many of the details of the WEEE and RoHS legislations are still in the process of being defined and can be subject to future revisions. The exemptions which have been granted are likely to phased-out in the coming years through the review process. The only exemptions that will remain will be those where the elimination of lead might not be possible from a technological and cost point of view.

REFERENCES

[1] Y. Fukuda, M. Pecht, K. Fukuda and S. Fukuda, "Lead-Free Soldering in the Japanese Electronics industry", *IEEE Transactions on Components and Packaging Technologies*, vol. 26, No. 3, pp. 616-624, Sep, 2003

[2] P. Casey and M. Pecht, "The Technical, Social and Legal Outlook for Lead-Free Solders", *IEEE International Symposium on Electronic Material and Packaging*, pp. 483-492, Kaohsiung, Taiwan, Dec, 2002

[3] P. Casey and M. Pecht, "Challenges for Adopting Pb-Free interconnects for "Green" Electronics", *IPC/JEDEC International Conference on Lead-Free Electronic Components and Assemblies*, pp. 21-32, Taipei, Taiwan, Dec, 2002

[4] European Commission (Feb 2003), "Directive of the European Parliament and of the Council on Waste Electrical and Electronic Equipment" http://europa.eu.int/comm/environment/docum/00347_en.htm (July 2003)

[5] European Commission (Feb 2003), "Directive of the European Parliament and of the Council on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment", http://europa.eu.int/comm/ environment/docum/00347_en.htm (July 2003)

[6] Orgalime (Dec 2002), "A Practical Guide to Understanding EC Directives on WEEE and RoHS", http://www.orgalime.org /publications/publications.htm (Nov 2003)

[7] Michael G. Pecht, "Issues Affecting Early Affordable Access to Leading Electronics Technologies by the US Military and Government", *Circuit World*, Vol. 22, No. 2, 1996

[8] InStat/MDR, "Electronics report-November 2002", http://www.instat.com/ whitepapers (Feb 2003)

[9] Takao, H, Hasegawa, H "Influence of alloy composition on fillet-lifting phenomenon in Sn Ag-Bi alloys**",** *Journal of Electronic Materials*, vol. 30, No. 9, pp. 1060-1067, Sep, 2001

[10] D. Naugler, M. Walz, (2001) "Lead-free: pushing the rework temperature envelope", http://www.teradyne.com/ prods/cbt/products/library/rework/ wp_lead_etrnx2001.pdf (Apr 2003)

[11] C. Handwerker, (Sep 1999) "Lead-free solders: A change in the electronics infrastructure", *CircuiTree*, vol. 12, No. 8, pp 94-98 (Nov 2003)

[12] J.K. Bonner, L. del Castillo, and A. Mehta, "Choosing the Right Lead-free Solder for Hi-Rel Printed Wiring Assemblies", *UC Smart sponsored workshop on Pb-free Solder for electronic, optical and MEMS packaging manufacturing*", http://www.seas.ucla.edu/ethinfilm/Pb-freeWorkshop/abs/bonner.html (Sep 2002)

[13] Y. Zheng, C. Hillman, P. McCluskey, "Intermetallic Growth on PWBs Soldered with Sn3.8Ag0.7Cu," *Proceedings of the 52nd Electronic Components & Technology Conference,* pp. 1226-1231, San Diego, 2002

[14] K. Seelig, D. Suraski, (March 2003) "A Practical Guide to Achieving Lead-Free Electronics Assembly", AIM Solder, http://www.aimsolder.com/ technical_articles.cfm (April 2003)

[15] Boeing Environmental Technotes, "An Update: Elimination of Lead from Electronics", vol. 7, No. 2, Nov 2002, http://www.boeing.com/companyoffices/doingbiz/environmental/TechNotes/TechNotes2002-11.pdf (Nov 2003)

[16] J. Wu and M. Pecht, "Fretting Corrosion Studies For Lead-Free Alloy Plated Contacts," *Proceedings of the 4th Electronics Packaging Technology Conference*, Singapore, pp. 20-24, Dec 2002

[17] P. Zhao and M. Pecht, "Field Failure due to Creep Corrosion on Components with Palladium Pre-plated Leadframes," *Microelectronics Reliability*, vol. 43, No. 5, pp. 775-778, 2003.

[18] Y. Zhang, C. Xu, J. Abys, A. Vysotskaya, "Understanding Whisker Phenomenon, Whisker Index and Tin/Copper, Tin/Nickel Interface", *IPC SMEMA Council APEX 2002*. pp. S06-1-1 thru S06-1-11, Jan 2002

[19] Q. Zhu et al, "Effect of Pb contamination on the microstructure and mechanical properties of SnAgCu and SnSbCu solder joints in SMT", *Soldering and Surface Mount Technology*, vol. 12, No.2, pp. 19-23, 2000.

[20] A. Gickler, C. Willi, "Contamination of lead-free solders**",** *SMT Surface Mount Technology Magazine*, vol. 11, No. 11, pp. 44-48, Nov 1997,

[21] J. Fishburn, (March 2003) "Lead-Free Soldering and Advances in Automatic Inspection", http://oeiwcsnts1.omron.com/pdfcatal.nsf/0/0508C738D07F800A86256C8B007AB584/$File/SMT_Lead_Free_White_Paper_1202.pdf?OpenElement (April 2003)

[22] M. Pecht, R. Solomon, P. Sandborn, C. Wilkinson, D. Das, "Lifecycle Forecasting, Mitigation Assessment and Obsolescence Strategies: A Guide to the Prediction

and Management of Electronic Parts Obsolescence", CALCE EPSC Press 2002, University of Maryland, College Park, Maryland, USA

[23] Analog Devices, "Lead-free parts FAQs" http://www.analog.com (Nov 2003)

[24] Fairchild Semiconductor, "Lead-free parts FAQs", http://www.fairchildsemi.com/products/lead_free/faqs.html (Nov 2003)

[25] Philips Semiconductor, "Lead-free parts FAQs", http://www-us.semiconductors.philips.com/green_roadmap/ (Nov 2003)

[26] P. Singh, P. Sandborn, T. Geiser and D. Lorenson, P. Singh, P. Sandborn, T. Geiser and D. Lorenson, "Electronic Part Obsolescence Driven Product Redesign Optimization", *International Journal of Advanced Manufacturing Systems*, vol. 3, No. 1, 2004

[27] P. Sandborn and P. Singh, "Electronic Part Obsolescence Driven Design Refresh Optimization", *Proc. FAA/DoD/NASA Aging Aircraft Conference*, pp. 134-142, Sep 2002

[28] L. Condra, R. Hoad, D. Humphrey, T. Brennom, J. Fink, J. Heebink, C. Wilkinson, D. Marlborough, D. Das, N. Pendsé and M. Pecht, "Terminology on use of electronic parts outside the manufacturers specified temperature", IEEE Transactions on Components and Packaging Technology, vol. 22, No. 3, pp. 355-356, Sep 1999

[29] V. Gupta, M. Harrigan, "Lead-free Communication for Intel Suppliers", https://supplier2.intel.com/ehs/ Lead-Free_Communication.ppt (Oct 2003)

[30] Q. Chu, "Lead to Lead-free Manufacturing-Issues and Challenges," Presentation at IPC/Maxtor Technical Conference-Making the Lead to Lead-free, August 2003

[31] P. Casey and M. Pecht, “The Technical, Social and Legal Outlook for Lead-Free Solders”, *IEEE International Symposium on Electronic Material and Packaging*, pp. 483-492, Kaohsiung, Taiwan, December, 2002.

[32] J. Ferry, “Who's afraid of lead-free rework? *Circuits Assembly* vol. 13, No. 11, pp. 24, Nov 2002

[33] B. Schweber, (April 2002) “Lead-free mandate plumbs new design challenges”, *EDN Mag*, http://www.e-insite.net/ednmag (April 2003)

[34] J.S. Hwang, G. Zhenfeng, “Effects of Bi contamination on Sn/Pb eutectic solder**”,** *SMT Surface Mount Technology Magazine*, vol. 14, No. 9, Sep 2000, pp. 91-92.

[35] B. Richards, “The reality of lead-free soldering”, National Physical Laboratory, http://www.npl.co.uk/ei/ documents/matworld.pdf (April 2003)

[36] European Portable Battery Association (Sep 2003), “Battery industry Coalition Statement on the Relationship Between WEEE, RoHS and Battery Directive”, http://www.styrax.org/demons/epba/positionpapers/statement WEEE%20rohs%20bd_sept03.pdf (Nov 2003)

[37] European Commission (Dec 1998), “Battery Directive on Batteries and Accumulators and Spent Batteries and Accumulators” http://europa.eu.int/comm/environment/waste/batteries/com2003723_en.pdf (Nov 2003)

[38] Tong et al., ”Review of the Current Status of CRT Technologies”, *Proceedings of SPIE - The International Society for Optical Engineering*, vol. 2641, pp. 10-19, Oct, 1995

[39] U.S Environmental Protection Agency, "Lifecycle Assessment of Electronic Computer Displays: Summary of Results", http://www.epa.gov/oppt/dfe/pubs/comp-dic/lca-sum/ (Nov 2003)

[40] Myers. B, "End of the CRT?" *Computer Graphics (ACM)*, vol. 31, No. 2, pp. 25-27, May, 1997

[41] Electronics Waste Recycling Act 2003, "Electronic Product Management in California" http://www.ciwmb.ca. gov/electronics/ (Nov 2003)

[42] U.S Environmental Protection Agency, "Economic Analysis of Cathode Ray Tube Management: Notice of Proposed Rulemaking", http://www.epa.gov/epaoswer/hazwaste/recycle/electron/econ-crt.pdf (Nov 2003)

[43] L. Greenmeier, "LCDs Win in Display Race", *Information Week*, Issue 959, pp.14, Oct, 2003

[44] Dow Jones Business News, "Toshiba, Matsushita To End Domestic Output of TV-Use CRTs", http://biz.yahoo.com/djus/031109/2347000518_1.html (Nov 2003)

[45] M. Hachman, "Sony To Phase Out 17-inch, 19-inch CRT Monitors", http://www.pcmag.com/Article2/ 0,4149,842023,00.Asp (Nov 2003)

[46] IT World, "Hitachi To Halt Production of PC Monitor CRTs", http://www.itworld.com/comp/3952/ idg010726hitachi/ (Nov 2003)

[47] G. Hwang, H. Jeon, Y. Kim, "Physical Properties of Barrier Ribs of Plasma Display Panels: Formation of Pores During Sintering of Lead Boro Silicate Glass Frits", *Journal of American Ceramic Society*, vol.85, No. 12, pp. 2956-60, Dec, 2002

[48] D. Chilimbu, “Investigation into the Use of Glass and Carbon Fiber Reinforced Piezoelectric Composites As Micro-Actuators” *Ferroelectrics*, vol. 224, No.1-4, pp 121-12, 1999

[49] H. Miller (July 2001), “Flip-Chip Packaging: A 32 Year Old infant Grows Up”, *Chip Scale Review Online*, http://www.chipscalereview.com/archives/ES/issues/0701/f1_01.html, (Nov 2003)

[50] P. McCluskey, L. Condra, T. Torri and J. Fink, “Packaging Reliability For High Temperature Electronics: A Materials Focus”, *Microelectronics International*, No. 41, pp. 23-26, Sep 1996

[51] Feinstein, L. (1989) "Die Attachment Methods," Electronic Materials Handbook, vol. 1 Packaging, ASM international, Materials Park, 1989

[52] Pecht, M. G. (1994) Integrated Circuit, Hybrid, and Multichip Module Package Design Guideline, John Wiley & Sons, New York, 1994

[53] I.Y. Chien, M. N. Nguyen (1994) "Low Stress Polymer Die Attach Adhesive For Plastic Packages," *Proceedings of the 44th Electronic Components and Technology Conference*, pp. 580-584, May 1994

[54] E. Jung, R. Aschenbrenner, C. Kallmayer, P. Coskina, H. Reichl, “Lead free alloys for flip chip bumping” *Proceeding of the International Symposium on Advanced Packaging Materials: Processes, Properties and Interfaces, 2001*, pp. 119-122, Mar 2001

[55] T. Tschan, (May 2001) “An Overview of Flip-Chip Technology”, *Chip Scale Review Online*, http://www.chipscalereview.com/issues/0501/tutorial_01.html (Nov 2003)

[56] J. R. Delaney (Aug 2002), "Buying Guide: Servers", *PC Mag*, http://www.pcmag.com/Article2/ 0,4149,487990,00.Asp (Nov 2003)

[57] Fujitsu, "Fujitsu Green Product Development Report 2003", http://eco.fujitsu.com/en/info/ 2003/2003report19_23_e.pdf (Nov 2003)

[58] Electronic News, "LSI Logic Debuts Lead-Free BGA Packages", http://www.reed-electronics.com/ electronicnews/index.asp?layout=article&articleid=CA93420 &rid=0&rme=0&cfd=1 (Nov 2003)

[59] D. Abbot, "Nickel/palladium finish for lead frames**",** *IEEE Transactions on Components and Packaging Technologies*, vol. 22, No. 1, pp. 99-103, Mar, 1999

[60] D. Abbot, D. Romm, "Palladium Plating: A Lead Free finish for IC Leadframes**",** *Proceedings - Electronic Components and Technology Conference*, pp. 1068-1072, May 1995

[61] Texas Instruments Lead-free Solutions, "TI Lead-Free Package Matrix", http://www.ti.com/sc/docs/ products/leadfree/ (Nov 2003)

[62] National Materials Advisory Board, "Materials For High-Temperature Semiconductor Devices", National Academy of Sciences, 1995

[63] F.P. McCluskey, L. Condra, T. Torri, and J. Fink, "Packaging Reliability For High Temperature Electronics: A Materials Focus", *Microelectronics International*, No. 41, pp. 23-26, Sep 1996

[64] R. Tummala, E. Rymaszewski, A. Klopfenstein, "Microelectronics Packaging Handbook: Semiconductor Packaging", Kluwer Academic Publishers, 2nd edition, Jan 1997

[65] D. Chilimbu, “Investigation Into The Use of Glass and Carbon Fiber Reinforced Piezoelectric Composites As Micro-Actuators” *Ferroelectrics*, vol. 224, No. 1-4, pp. 121-128, 1999

[66] A. Ballato, “Piezoelectricity: History and New Thrusts,” *Proceedings of the Ultrasonics Symposium*, vol. 1, pp 575-583, 1996

[67] European Commission, (Dec 2000), Directive 2000/53/Ec of the European Parliament and of the Council of 18 September 2000 on End-of Life Vehicles, Http://Europa.Eu.int/Eur-Lex/Pri/En/Oj/Dat/2000/L_269/ L_26920001021en00340042.Pdf (Nov 2003)

[68] M. Pecht, "Issues Affecting Early Affordable Access To Leading Electronics Technologies By the US Military and Government", *Circuit World*, vol. 22, No. 2, 1996

[69] Office of Technology Assessment, (Sep 1995) “Flat Panel Displays in Perspective”, http://www.wws.princeton. edu/cgi-bin/byteserv.prl/~ota/disk1/1995/9520/9520.pdf [July 2003]

[70] J. Keller, “Commercial Computer Servers Help Navy Ply the Ocean's Depths For Hostile Submarines”, *Military & Aerospace Electronics*, vol. 13 Issue 6, pp. 16-21, Jun 2002

[71] E. J. Walsh, “Networks Take Center Stage in Ship Systems”, Military and Aerospace Electronics, vol. 13 Issue 3, pp. 16, Mar 2002

[72] E.J. Walsh, “Navy stresses shipboard networking and connectivity”, Military and Aerospace Electronics, vol. 14, pp. 6-7, Mar 2003

[73] V. Sangiovanni, “Electronic System Design in the Automobile industry”, *IEEE Micro*, vol. 23, Issue 3, pp 8-18, May 2003

[74] Whitten, G, “Lead-free Solder Implementation for Automotive Electronics” *Electronic Components and Technology Conference*, pp. 1410 -1415, May 2000

[75] B. Baney, (March 2000) “Implementation of Lead-Free Solder For Automotive Electronics”, *SAE World Congress: Environmental Concepts For Automotive industry*, http://www.delphi.com/pdf/techpapers/2000-01-0017.pdf (Nov 2003)

[76] Visteon Press Release, (Dec 2000), “Visteon Announces Production of the Automotive Industry's First Lead-Free Solder Electronic Module” http://www.visteon.com/newsroom/press/2000/00story155.shtml (Nov 2003)

[77] Murata Electronics Press Release, (Mar 2003)“Murata Electronics introduces industry's First Smd Piezoelectric Buzzer For the Automotive Market”, http://www.murata-northamerica.com/murata/murata.nsf/pages/03242003 (Nov 2003)

[78] Y. Tanokura, (Dec 2000), “Nissan Uses Lead-Free Solder in Automotive Electronics”, Nikkei Electronics Asia, http://www.asiabiztech.com/wcs/frm/nea/200012/manu_118482.html (Nov 2003)

[79] Automotive Displays, http://www.displaysearch.com (Nov 2003)

[80] T. Teutsch, R. Blankenhorn, E. Zakel, “Lead-free Solder Bumping Process for High Temperature Automotive Application”, *Electronic Components and Technology Conference, 2003-Proceedings. 53rd* , pp. 1468 -1471, May 2003

[81] K. Wiggins, “Car Electronic Systems Accelerate”, *Electronic Engineering Times*, Issue 1124, pp. 52-53, Jul 2000

[82] Boeing Environmental Technotes, “An Update: Elimination of Lead from Electronics”, vol. 7, No. 2, Nov 2002

[83] D. Marvin, “The practical Use of AMLCD's in Avionic Applications**”,** *Proceedings of SPIE - the international Society for Optical Engineering*, vol. 4362, pp. 102-108, 2001

[84] A. Davis, “Transition from CRT to AMLCD on the Eurofighter Programme”, *Proceedings of SPIE - the international Society for Optical Engineering*, vol. 4022, pp. 304-312, 2000

[85] J.H. Williams, “Description of the FAA Avionics Certification Process” http://www.faa.org (Nov 2003)

[86] Baker Hughes (Aug 2002) , “What is Logging,” http://www.bakerhughes.com/ bakeratlas/about/log4.htm (Nov 2003)

[87] Schlumberger (Aug 2002), “Acquiring Better Data for Reservoir Characterization,” http://www.slb.com/ir/ aboutus/ofs-betterdata.html (Nov 2003)

[88] L. Chen and P. McCluskey, “Microsystem Packaging for High Temperature and Harsh Environments”, *MST (Microsystems) News*, pp. 41-42, Sep 2001

[89] Device Link, (Feb 2003), “Medical Devices Go Green”, *Medical Device and Diagnostic industry* http://www.devicelink.com/mddi/archive/03/02/002.html (Nov 2003)

[90] Device Link (Feb 2003), “Legal and Regulatory Sites of interest to Medical Device Manufacturers” http://www.devicelink.com/links/regulatory.html (Nov 2003)

[91] T. Adams (Feb 2002), “Moving to Lead-Free Solder for Medical Electronics”, *Medical Electronics Manufacturing*, http://www.devicelink.com/mem/archive/02/04/003.html (Nov 2003)