Green Electronics through Legislation and Lead Free Soldering

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Keywords: Electronic waste; E-waste; Lead-free; Soldering; Legislation

Abbreviations

CAF	Conductive anodic filament
CRT	Cathode ray tube
CTE	Coefficient of thermal expansion
DfE	Design for environment
EEE	Electrical and electronic equipment
LCA	Life cycle analysis
MSW	Municipal solid waste
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenylethers
TC	Toxicity characteristic
TCLP	Toxicity characteristics leaching procedure
PCB	Printed circuit board
PWB	Printed wire board
RoHS	Restriction of hazardous substances
WEEE	Waste electrical and electronic equipment

Abstract

Management of used electrical and electronic equipment (EEE) is becoming a major issue as each year around 20 to 50 million tonnes of electronic waste (e-waste) is generated worldwide. EEE contains over 1000 materials of which lead (Pb) has been one of the targets of the regulators forcing manufacturers to adopt lead free products. Industry has come up with several lead free solders with preference given to alloys containing tin, silver and copper but there is no ‘drop-in' substitute to leaded solder. Issues with lead free solders such as temperature, intermetallics, tin whisker, tin pest and reliability are yet to be resolved. The paper investigated the contribution of lead free soldering to green electronics in a holistic way. Global lead free movement has reached a point of no return. However, it is necessary to make sure that life span of EEE is not shortened thereby resulting in an unforeseen increase in e-waste or problem shifting does not occur by shifting a problem from one life cycle to another or from one category/media to another.

1 Introduction

Rapid advances in microelectronic design and technology in the recent decades have made modern day electrical and electronic equipment (EEE) obsolete within a very short period after their purchase resulting in mountains of electronic waste or e-waste to deal with in many countries around the world. United Nations estimate that collectively the world generates 20 to 50 million tonnes of e-waste every year [1]. The average lifespan of a new model computer has decreased from 4.5 years in 1992 to an estimated 2 years in 2005 and is further decreasing [2]. E-waste also is one of the fastest growing waste streams around the world today growing a rate of 3-5% per annum and around three times faster than normal municipal solid waste [1]. Studies have revealed that around 500 million computers will become obsolete in the United States alone between 1997 and 2007 [3] and every year over 130 million mobile phones in the United States and over 105 million mobile phones in Europe reach their end-of-life and are thrown away [4].

E-Waste is of major health and environmental concern due to the toxicity of some of the materials present in the waste stream. These include metals such as lead, mercury, hexavalent chromium and cadmium and chemicals such as polychlorinated biphenyls. Cathode ray tubes (CRTs) used in EEE are considered to be one of the major sources of lead in the municipal solid waste stream. Brominated-flame retardants such as polybrominated biphenyls (PBB) and polybrominated diphenylethers (PBDEs) used in EEE are both an occupational and environmental health hazard [5].

Lead in EEE is of a major concern to the public due its ability to leach from landfills and contaminate the human food chain causing serious health hazards. To address this issue and to make EEE manufacturing ‘green', European Union and countries such as China, Japan and Korea have passed legislation to remove lead from EEE. Commonly known as ‘Restriction of Hazardous Substances (RoHS)' such legislation attempts to create green electronics by the application of environmentally considerate design and manufacture to EEE. Lead-free soldering in EEE is one of the major drivers of the legislation forcing researchers and manufacturers to find suitable lead-free substitutes for the traditional leaded solders used for several decades. Despite significant investments being made on research and development of lead-free solders, to date no perfect substitutes have been found for lead based solders, although, few lead-free alloys have emerged as strong candidates. Currently there are various issues such as durability and reliability surrounding these candidates and the research is on-going.

The aim of this paper is to investigate the contribution of lead free soldering to green electronics in a holistic way. It examines why there is a need for lead-free soldering in EEE, describes some of the lead-free solders and discusses various issues related to lead-free soldering in the manufacturing of EEE.

2 Why Lead-free Soldering in EEE

Lead is naturally occurring metal in the earth's crust. It can be found in our environment as a result of human activities such as manufacturing, mining and fossil fuel burning. Lead itself does not break down but the characteristics of lead compounds could change as a result of environmental conditions. Once released into air, lead could stay in the atmosphere for a long time prior to falling and sticking onto soil with a possible leaching into groundwater.

Human toxicity of lead could result in cancer and also could adversely affect the liver and thyroid functions and the resistance to disease. Lead can affect almost every organ in the body including the nervous system, kidneys and reproductive system. The main effect of lead toxicity is for the central nervous system of the humans. High exposure of lead could also severely damage the brain and kidneys of the humans and could lead to miscarriage in pregnant women. High levels of lead could also affect the brain development of children and organs responsible for sperm production in men. Ecological toxicity of lead could occur as a result of direct exposure of algae, invertebrates and fish to lead. Fish exposed to high levels of lead could exhibit effects such as growth inhibition, mortality, reproductive problems and paralysis. Furthermore, at elevated levels of lead, plants could experience reduced growth, photosynthesis and water absorption. Birds and mammals could also suffer from lead poisoning resulting in damage to nervous system, kidneys and liver [6].

In electrical and electronic equipment (EEE), lead is mainly used in cathode ray tubes (CRTs) in monitors, tin-lead solders, cabling printed circuit boards and fluorescent tubes. The most significant use from the above list is the amount lead used in the manufacture of CRTs to shield the user from radiation. The main components of a CRT – the funnel, neck and the frit- contain between 0.4 kg and 3 kg of lead per monitor. In a typical CRT 65-75% of the lead could be found in the frit while 22-25% of the lead in the funnel glass and 30% in the neck [7]. In a typical desktop personal computer (including the monitor), lead amounts to 6.3% by weight [8]. Next to the CRTs, second largest source of lead in EEE can be found in tin-lead solders used to connect many components together. Lead is used in tin-lead solders (typically 60% tin and 40% lead) due to its good conductivity, high corrosion resistance and high melting point which are all essential factors for a sound connection between the components. It is estimated that the amount of lead used in soldering is about 50 g/m2 of the printed circuit boards [7].

The main environmental effect of lead is the leaching of lead ions from the broken lead containing glass (e.g. broken cone glass of CRTs) when mixed with acid waters in waste landfills. It is estimated that 40% of lead found in US landfills come from

EEE [2]. When printed circuit boards are heated to soften the lead solder during certain recycling operations, lead is released to the environment as fumes or as fine particulate dusts if they are shredded during the recycling operations. A recent study in EEE recycling workplaces in China and India found that concentrations of lead recorded in indoor dust samples in China are hundreds of times higher than typical levels recorded for indoor dusts in other parts of the world [9].

Several scientific studies have been undertaken to investigate the leaching potential of lead from landfill leachates. In the United States, as per regulations, the Toxicity Characteristics Leaching Procedure (TCLP) is commonly used to determine the leachability of a particular solid waste in a landfill although such concentrations may not accurately reflect the concentrations observed under actual landfill conditions. Jang and Townsend [10] leached printed wire boards from computers and CRTs from computers and televisions using the TCLP test and leachates from actual landfills. Majority of the samples exceeded toxicity characteristic (TC) limit of 5 mg/L although extractions using landfill leachates resulted in lower lead concentrations than those by TCLP. Jang et al [11] extended these experiments to laptop computers to find that discarded laptop computers containing lead solder could posses a reasonable potential of being TC hazardous wastes for lead similar to CRTs. However, they also found that pH value of the leaching liquid played a significant role in lead leaching. Li et al [12] conducted a TCLP test on metals such as lead, arsenic, barium, cadmium, chromium, mercury, selenium and silver of many personal computer parts including the printed wire board (PWB) and found lead to be the predominant element that exceeded the TC limit. Lead concentrations in the TCLP extracts of PWBs were found to be ranging from 150 to 500 mg/L, which were 30-100 times the regulatory level of 5 mg/L.

Although TCLP test is used as a guide by the regulatory authorities to determine the TC of waste materials, many critics have questioned its applicability to EEE in a real life landfill setting. The TCLP requires test specimens to be less than 1 cm in size and uses acetic acid to leach the metals which is more acidic than the landfill leachate. The critics also argue that TCLP tests to determine the leaching of lead are conducted on individual components of EEE (e.g. PWBs, CRTs), hence are not representative of whole EEE which are landfilled [13]. In order to address the above concerns Vann et al [14] developed a modified TCLP methodology which enabled to examine the effects caused by size reduction and sample composition. They found that size reduction of some EEE resulted in a lower TCLP lead (not higher as expected) due to impact of electrochemical properties of iron components in EEE demonstrating that TCLP results for various EEE can be significantly affected by sample composition questioning the validity of the TCLP results obtained from testing individual components of EEE such as CRTs and PWBs.

It is evident from the above literature that leaching of lead in landfills is not properly understood yet. The TCLP tests have clearly demonstrated that lead from many EEE do leach at high levels forcing regulatory authorities consider it as a hazardous waste. On the other hand, research also questioning the validity of TCLP for EEE disposed in landfills saying that lead may not be as mobile in landfills. To complicate the matters further researchers have still not understood the behaviour of lead during different stages of de-composition of wastes in landfills.

3 Related Legislation

Although there is some criticism of the TCLP procedures and other laboratory based tests carried out to determine the leachability of lead from EEE deposited in landfills, the regulatory authorities around the world are moving ahead rapidly in developing or implementing legislation to ban lead from some EEE. The Restriction of Hazardous Substances (RoHS) Directive was created by the European Parliament in 2003 recognising the fact that not all hazardous substances in WEEE can be recycled or disposed of in an environmentally sound manner, thus imposing a ban on the use of certain substances in electrical and electronic equipment. The RoHS directive came into effect on 1 July 2006 and applies to new electrical and electronic equipment put on the European market on or after July 1st. It names six substances of immediate concern: lead, mercury, cadmium, hexavalent chromium, PBB and PBDE. The Directive has provisions for adaptation to scientific and technical progress such as establishing, as necessary, maximum concentration values, Exempting materials and components of electrical and electronic equipment and carrying out a review of each exemption at least every 4 years [15].

The maximum concentration values for RoHS substances were established in an amendment to the Directive on 18 August 2005. The maximum tolerated value for lead, mercury, hexavalent chromium, PBB and PBDE is 0.1% by weight in homogenous materials and 0.01% by weight in homogenous materials for cadmium [16]. RoHS has number of specific exemptions declared as Annexes to the Directive. The amendments to the Directive to exempt these materials were made twice in October 2005 [17, 18], once in April 2006 [19] and thrice in October 2006 [20-22], totalling the number of exemptions to twenty nine, with majority of these concerning with use of lead in EEE.

The global impact of the European Union (EU) RoHS Directives has been enormous with companies having to make significant investments to find substitutes for banned materials. Furthermore, countries that export significant number of EEEs to EU are developing/developed RoHS type legislation. For example, in Japan an amendment to the Law for the Effective Utilisation of Resources took place on 1 July 2006 when the Japanese version of the RoHS (also known as J-Moss or JIS C 0950) was introduced. This amendment mandates that manufacturers provide material content declarations for certain categories of electronic products from sold after 1 July 2006.

Manufacturers and importers are required to label their products and provide information on the six EU RoHS substances: lead, mercury, chromium VI, cadmium, PBB and PBDE. In China, ‘Measures for the Administration of the Control of Pollution by Electronic Information Products', was promulgated by the Ministry of Information Industry and other participating agencies on 28 February 2006 and came into effect on 1 March 2007. The goal is to make companies disclose and control the use of hazardous/toxic materials through disclosure via labelling requirements and control via substance restrictions. The substances covered by this law are the same six substances covered by EU RoHS, however, with a reservation of a right to add more substances in the future. Similarly, on 2 April 2007, Korea's National Assembly passed the ‘Act Concerning the Resource Recycling of Electrical/Electronic Products and Automobiles' which has similarities to EU's RoHS. Known as Korea's RoHS this regulation goes into force on January 1, 2008. Finally, in the United States, California's Electronic Waste Recycling Act has a mandate to reduce the use of hazardous substances in electronic products sold within the State. Accordingly California RoHS (SB50) came into effect on 1 January 2007.

As seen from above, irrespective of what critics say about leaching of lead from EEE in landfills, one can expect to see more and more legislation being passed in other countries targeting the use of lead in EEE.

4. What is Lead-free?

Lead is used in electronics due to its unique properties such as malleability, low melting point, excellent conductivity and high resistance to corrosion. It is used to attach electronic components in EEE to a printed circuit board (PCB) via soldering. Soldering is the process where two metals are joined together by means of a third metal or alloy having a relatively low melting point. The process involves exposing the electronic components and the PCB to high temperatures to melt the soldering alloys which then form an acceptable solder joint. The most common processes used for such operation are reflow and wave soldering [23]. Wave soldering the electronic components are inserted or placed on the printed circuit board and is passed across a pumped wave molten solder which is held in a tank while reflow soldering attaches a surface mounted component to a circuit board, apply the solder paste, position the devices, and reflow the solder in a conveyorized oven.

Lead-based solders have been used for a time in the electronics industry with most common being 63% tin (Sn) and 37% lead (Pb) by weight referred to as Sn63Pb37. Mechanically and electrically lead-based solders make an excellent choice in the electronics industry but due to the environmental reasons described above regulators now require the manufacturers to find suitable alternatives.

The substitutes to Sn-Pb solders must satisfy various engineering and other criteria which includes similar properties to current alloys, same temperature range as Sn-Pb, same or better reliability and equal or lower cost, compatibility with standard finishes, ease of application with wetting properties similar to current Sn-Pb including fluidity and cohesive force and stability [24]. Technically, lead-free solders must have a coefficient of thermal expansion (CTE) that matches the joining components, must be able to resist thermal cycling, have sufficient creep resistance to maintain thermomechanical loading in the longer periods in the field of use [23]. In general, materials used in lead free alternatives must be readily available, be economical and should not have any negative environmental impact now or in the future.

A lead free substitute that satisfies all the above criteria is referred to as a ‘drop in' substitute for Sn-Pb solder. Unfortunately, up to date manufacturers or researchers have not been able to find such a substitute, although they have come up with near solutions. The issue here is that if all the potential metals for lead free substitute were screened even on basic requirements such as melting point, cost, availability, toxicology and chemical resistance, only very few will appear as possibilities. Sn, Cu and Ag become the leading candidates followed closely by Bi, Sb, In, Zn and Al. However, Bi and Sb are partially produced as by-products in lead manufacturing, therefore, strictly should not be considered. There are various issues for metals other than Sn, Cu and Ag. Bi and In are only produced at a rate of 3,000 and 500 tonnes per year, which is far below the 10,000 tonnes per year of lead used in conventional lead solders. Zn and Al are known to oxidise rapidly in manufacturing and use. Cost-wise, Sn is about 10 times the price of lead and Cu, Ag and In are all about 300-400 times the cost of lead [25].The Table 1 summarises some examples of the lead-free alloys developed as a result of significant amount research being undertaken by the manufacturers and researchers.

Although number of lead-free substitutes has been developed by the industry, finding a suitable substitute which satisfies all the requirements is not a simple matter. The industry is now favouring Sn-Ag-Cu (SAC) alloy for reflow and SAC and Sn-Cu alloys for wave soldering [26]. In the United States, the National Electronics Manufacturing Initiative (NEMI) launched a project to determine the most suitable alloy for a lead free substitute. Their extensive research into processing and reliability of lead free solder joints resulted in the alloy 95.5Sn/3.9Ag/0.6Cu for reflow soldering and 99.3Sn/0.7Cu for wave soldering [25]. In the European Community, a project was undertaken by Marconi Materials Technology Group under the heading 'Improved Design Life and Environmentally Aware Manufacturing of Electronics Assemblies by Lead-Free Soldering or IDEALS'. In an extensive study lasting over 3 years this group studied several candidate solders under extensive assembly trials and came out with 95.5Sn/3.8Ag/0.7Cu eutectic alloy for reflow soldering and 95.25Sn/3.8Ag/0.7Cu/0.25Sb for wave soldering [27]. Furthermore, at the European level ELFNET (European Lead Free soldering NETwork) has been developed which is a network of the national organisations, technical experts and industry bodies in micro-electronics. It provides support to European Union electronics producers comply with the EU directive to introduce lead-free soldering (http://www.europeanleadfree.net/). Even before the regulations came into force, the Japanese electronic manufacturers have attempted to adopt lead free electronic to satisfy the demand for green products in the market. The Japanese Electronic Industry Development Association (JEIDA) has developed a roadmap towards the introduction of the lead-free soldering to gradually introduce the lead free soldering in the industry [28]. JEIDA also recommended 96.5Sn/3Ag/0.5Cu for wave soldering and 96.5Sn/3Ag/0.5Cu, 99Sn/8Zn/3Bi and 48Sn/57Bi/1Ag as strong candidates for reflow soldering.

5. Issues with Lead-free Substitutes

The issues related to development and use of lead free substitutes concentrate on melting temperatures, intermetallic formation, reliability and tin whiskering [29], all to be explained in this section.

One of the key issues with lead free substitutes is the temperature and the process time required to flow the solder. The melting point of the traditional Sn-Pb solder is 183^0C, which requires a maximum reflow temperature of around 220^0C. The most preferred lead-free alloys have a melting temperature range from 217-220^0C (see Table 1), which corresponds to reflow temperature of 254^0C, an increase of 34^0C heating difference [23]. Since soldering is one of the last steps of the PCB manufacturing process, all the materials and electronic components on the board must withstand this increased thermal differential. The question is whether most of laminates that are currently used in PCBs can achieve this as they have low glass transition temperatures. Hence more expensive substrates need to be designed for this new temperature environment. Taking this into account, the design engineers are replacing the traditional substrates used in PCBs by newer materials which have higher glass transition temperatures. A further issue related to the high temperatures is increased potential for the growth of conductive anodic filament (CAF) known to be an electrochemical failure of the PCB during the use environment. CAF are by products from Cu corrosion that emanate from the anode of a circuit and grow subsurface towards the cathode most frequently along separated fiber-epoxy interfaces in the PCB. A recent study has shown that higher reflow temperatures needed for lead free solders could result in increasingly higher incidences of CAF [30].

Another problem related to high temperature soldering relates to the polymers used in the PCBs. Prior to reflow soldering most of these components are exposed to the environment and hence absorb moisture from air. As the components undergo the reflow process this moisture turns into steam and creates internal stress by trapping inside the polymers. This can result in electrical failure if the connections are broken. This process can be worsened by the increased temperatures used in lead free solders. Only solution for this is to use high water permeability polymers [29].

As with many other manufacturing processes, higher operating temperatures will increase the energy consumption and the associated CO_2 emissions which is also one of the drawbacks of lead-free soldering.

Intermetallic formation, an another issue in lead free soldering, is a diffusion driven process where solder-wettable coatings are transformed into intermetallics by solid-state reactions. During the soldering process molten solders come into contact with Cu or Ni surfaces they wet resulting in the formation of interfacial intermetallics. These grow in solid state into the solder as rods or plates. If these formations become too thick they can weaken the solder joint and may fracture under certain conditions. There is a concern that high Sn-content lead free solders could accelerate the growth of the intermetallics. However, Frear [29] found that reaction with lead free solder with Ni and Cu metals resulted in the formation of intermetallics that are not significantly thicker than with traditional Sn-Pb solder but provided a path for fracture under mechanical loading due to increased strength of lead free alloys. Furthermore, Ho et al [31] found that addition of Ni to Sn, SnCu, SnAg, and SnAgCu alloys in amounts as minute as 0.1 wt.% is able to substantially hinder the intermetallic growth hence a useful alloying additive to these solders. However, the present understanding of the behaviour of these intermetallic structures under elevated temperatures or longer term use is very low, hence needs more research [24].

As with intermetallic formation, the complete understanding of the reliability of lead free solders is still far away. The fatigue characteristics of popular lead free solders are unknown to a certain extent as they vary dependant upon the test conditions. Under some conditions lead free solders were found to have more fatigue resistance than the traditional Sn-Pb solder but in other cases they were found to be equal or worse [32].

Tin whiskers are metallic crystals that can grow out of the surface of a Sn surface very rapidly and can be very long. The problem occurs when these whiskers join across conducting contacts resulting in electric shorts. Although the potential growth of whiskers on tin and tin alloys has been a consideration in electronics in the past they have not been a major issue since alloying of Sn with a few percent of Pb was found to greatly reduce the whisker formation. However, with the advent of lead free regulations industry is moving rapidly to pure Sn and other high Sn content lead free alloys and as such formation of tin whiskers has become a major issue. A significant amount of scientific literature could be found on the topic of tin whiskers, much of recently, however, there is still no consensus on the specific growth mechanisms for whisker growth [33]. The most preferred lead free alloy – SnAgCu- has only very small amounts of Ag and Cu, hence the possibility of these elements consumed at the interface is large leaving behind a large regions of Sn available for whisker formation. Fukuda et al [34] studied the whisker growth on whisker growth on various types of specimens in terms of density and length distributions. They found high whisker densities and lengths in bright Sn plating demonstrating the unsuitability of their use in electronics. However, they found shorter whisker lengths in matte Sn finishes although they could still cause problems with fine-pitch devices. They also questioned the applicability of current durability testing times as whisker growth continues to increase over time.

Tin pest is an allotropic transformation of Sn which causes deterioration of Sn objects at low temperatures. At 13.2^0C and below, pure Sn transforms from the silvery, ductile allotrope of β-modification white tin to brittle α-modification grey tin, eventually decomposing into powder. A large volume change is associated with this transformation causing eruptions (warts), cracking and eventual disintegration. Scientific observations of tin pest formation reveal a huge inconsistency and an incomplete understanding of the process with some alloy additions promoting tin pest by reducing the incubation time, whereas others retarding or inhibiting its formation.

The factors governing the tin pest formation are unknown although elements such as Pb, Sb and Bi which are soluble in Sn seem to inhibit tin pest appearance while insoluble metals such as Zn, Al and Mg promote its formation [35]. The major issue is to what extend the proposed lead free alloys are vulnerable to the tin pest phenomenon. Plumbridge [35] studied the behaviour of several lead-free solder alloys (Sn–3.5Ag, Sn–0.5Cu, Sn–3.8Ag–0.7Cu, Sn–8Zn–3Bi) and found that only the Sn–0.5Cu solder is vulnerable to the appearance of tin pest. He also found that impurities may inhibit the formation of tin pest, but for long term applications there is no certainty that tin pest and joint deterioration will never occur.

6 Concluding Remarks

End-of-life management of used EEE is becoming a major issue in many countries around the world today. Rapid uptake of information and communication technologies and diminishing life span of EEE due to constant availability of newer designs has led to this major e-waste problem. To combat this problem several countries are in the process of developing legislation to remove certain toxic substances from EEE manufacture. EU's RoHS has led the way in this regard and has also triggered legislation similar to that in other countries such as China, Korea, Japan and some states in the US. Of the substances targeted by this legislation, lead stands out, end-of-life disposal being the major driving force. TCLP tests conducted on used EEE by many researchers have found that lead from EEE has enough leachability to be considered as a hazardous waste. However, there are many doubts whether the

TCLP tests represent the actual scenario when the used EEE are disposed in landfills. Research is still underway to address this issue. Earlier in the paper it was reported that 40% of lead found in US landfills come from EEE [2]. However, it is interesting to note the contribution made by individual components of used EEE in this percentage. Turbini et al [36] reports of a US EPA commissioned study of municipal solid waste (MSW) to determine whether the leaching of lead from landfills presents a problem. This study found that 40.2% of lead in MSW comes from consumer electronic devices of which television picture accounts for 35.8% with the remaining 4.4% from other sources. According to this study majority of the lead (48.1%) in MSW comes from lead acid batteries. The findings of this study and the doubts about TCLP results have significant implications to legislation being developed around the world to ban lead from EEE.

The current legislation requires that traditional Sn-Pb solder be replaced by lead free solders to eliminate the risks posed by end-of-life management of EEE, thus moving towards green electronics. To fully demonstrate the environmental gains of this transformation it's necessary to look at the issue in a holistic, life cycle way so that aspects from extraction to final disposal could be taken into account of the substitutes proposed for the traditional Sn-Pb solder. Life Cycle Assessment (LCA) is a well-known and accepted method for evaluating the life-cycle environmental impacts of raw material extraction, material processing, product manufacture, product use and final disposal. Such assessment conducted by the United States Environmental Protection Agency has evaluated the life-cycle impacts of various lead-free alternatives. However there findings are overshadowed by several uncertainties including missing individual inventory items, missing processes or sets of data, measurement and estimation uncertainty and unspeciated chemical data [37].

Usage wise electronic solders only account for 1% of the total usage with majority (80.8%) being used by the storage battery industry [36]. Hence moving from Sn-Pb solder to lead free alternatives will have little or no impact on the environmental issues related to resource extraction. However, the major impact of lead free transformation is in the area of manufacture and use. This paper has identified several unresolved issues related to lead free solders such as high temperature use in production of PCBs, enhanced formation of intermetallic compounds and little known issues such as tin whiskering and tin pest. As a result of these issues non one has found a 'drop-in' substitute for the traditional Sn-Pb solder where an easy substitute could be made. Instead, conversion to lead free soldering has resulted in design and material changes in other components of the electronics. Given that fact that failure of a solder also leads to the failure of EEE, the reliability of the solder becomes a high priority. This is an area where several unresolved issues exist hence the need for more research.

Despite the doubts about the impact of lead in landfills and some unresolved issues related all the substitutes found so far to replace the leaded solder, manufacturers around the world are rapidly converting their products to lead free alternatives. This has come about due to legislation pressure as well as to avoid any market losses. If the manufacturers decide not to convert their products to lead free they would have problems exporting to countries where lead free legislation exists (e.g. EU) and also they will loose competition with manufacturers who have adopted lead free products.

Hence it can be argued the urgent transformation to lead free by manufacturers is more do with fear than environmental reasons.

As for the consumers, it is a difficult decision to make. It is now known that the longer term solution to the e-waste problem relies upon the adoption of practices such as design for environment (DfE), cleaner production and sustainable consumption leading to greener electronics [38]. However, there is some uncertainty among the scientific community about how greener electronics could be achieved through lead free soldering.

The paper attempted to investigate the contribution of lead free soldering to green electronics in a holistic way. As for the global lead free transformation it has reached a point of no return as the regulators and leading manufacturers have invested significant amount of resources to make sure lead free products are developed without any delay. Therefore, for many electronic manufacturers it's not a matter of 'if' but it's a matter of 'when'. The most important issue as far as the environment is concerned (for which the lead free legislation was initially targeted) is to make sure that life span of the EEE using the lead free products is not shortened thereby resulting in unforeseen increase in e-waste.

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Table 1 Some examples of lead-free alloys, their composition and melting points

Alloy System	Composition (wt%)	Melting range (^{0}C)
In-Bi-Sn	51In/32.5Bi/16.5Sn	60 (eutectic)
In-Bi	66.3In/33Bi	72 (eutectic)
Bi-In-Sn	57Bi/26In/17Sn	79 (eutectic)
Bi-In-Sn	54.02Bi/29.68In/16.3Sn	81 (eutectic)
Bi-In	67Bi/33In	109 (eutectic)
In-Sn	52In/48Sn	118 (eutectic)
In-Sn	50In/50Sn	118
Bi-Sn	58Bi/42Sn	138 (eutectic)
Sn-Bi-In	70Sn/20Bi/10In	143
Sn-Zn-In-Bi	86.5Sn/5.5Zn/4.5In/3.5Bi	174
Sn-In-Ag	77.2Sn/20In/2.8Ag	175
Sn-In--Zn	83.6Sn/8.8In/7.6Zn	181
Sn-Zn-Bi	89Sn-8Zn-3Bi	189
Sn-Zn	91Sn/9Zn	199 (eutectic)
Sn-In-Ag	86.9Sn/10In/3.1Ag	204
Sn-Ag-Bi	93.5Sn/3.5Ag/3Bi	206
Sn-Bi-Ag	95Sn/2Bi/3Ag	210
Sn-Ag-Cu	91.8Sn/3.4Ag/4.8Bi	211
Sn-Bi-Ag	91Sn/7.5Bi/2Ag	212
Sn-Ag-Cu-Sb	96.7Sn/2Ag/0.8Cu/0.5Sb	216
Sn-Ag-Zn	95.5Sn/3.5Ag/1Zn	217
Sn-Ag-Cu	95.5Sn/3.8Ag/0.7Cu	217
Sn-Ag-Cu	95.5Sn/4Ag/0.5Cu	217
Sn-Ag-Cu	95.5Sn/3.9Ag/0.6Cu	217
Sn-Ag-Cu	96.5Sn/3Ag/0.5Cu	217
Sn-Ag-Cu	93.6Sn/4.7Ag/1.7Cu	217
Sn-Ag	96.5Sn/3.5Ag	221 (eutectic)
Sn-Ag	98Sn/2Ag	221
Sn-Cu	99.3Sn/0.7Cu	227 (eutectic)
Sn-Sb	99Sn/1Sb	232
Sn-Sb	97Sn/3Sb	232
Sn-Ag-Sb	65Sn/25Ag/10Sb	233
Sn-Sb	95Sn/5Sb	235
Au-Sn	80Au/20Sn	280 (eutectic)

Sources: http://www.pb-free.com & http://www.soldertec.com