Impact of environmental regulations on green electronics manufacture

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Abstract
Purpose – The purpose of this paper is to investigate the electronic industry's reaction to environmental regulations specifically in terms of lead-free solders and halogen-free flame-retardants (FRs).
Design/methodology/approach – This work achieves its objective by discussing the various international regulations pertaining to electronics manufacturing and relating the industry reactions to those regulations. The electronics industry is pursuing lead-free solders and halogen-free FRs, in part due to regulations. However, the paper includes examples of how the industry is successful in implementing environmentally friendly changes.
Findings – The authors compared regulations from Japan, the European Union, and the US. While the regulations themselves vary in scope, industry actions to find alternatives do have common purposes. Electronics manufacturers recognize that environmentally motivated changes are beneficial in terms of waste minimization. Regardless of the regulatory motivation, minimization does lead to energy and economic efficiency.
Practical implications – Electronics manufacturers that are interested in green design will benefit from understanding present regulations. They will also benefit from the included examples of product and process improvement for the purpose of environmental compatibility. The paper includes specific examples of material alternatives to banned substances.
Originality/value – This paper derives its perspective from a similar review of literature and company findings that the authors completed in 2001. As refinement of the regulations has continued, the electronics industry has developed improvements in basic materials and processes.

Keywords Environmental management, Electronics industry

Paper type Conceptual paper

Preface

It is crucial for manufacturers to understand recently enacted environmental legislation and directives in the US, the European Union (EU), and Japan, and to assess their effects on the electronics industry. However, heightened consumer awareness has also become an important consideration for electronics manufacturers. In fact, examination of electrical and electronic products shows that companies are already using lead-free solders and halogen-free FRs. Regulations banning toxic materials in electronics manufacturing have received deserved attention; however, they do not stand alone in guiding fundamental changes in the industry.

Introduction to green electronics

Green engineering requires environmental consideration at the design phase of a product. This consideration includes all material and energy requirements and their effects over the lifetime of the product. Material requirements include those for both products and processes. The focus on energy must include the energy to make, use, and dispose of the product. Green design and manufacture leads to the understanding of the interplay among processes and flows and the optimization of the various considerations that are present.

Green electronics is the application of environmentally considerate design and manufacture to electronic products. Environmentally considerate electronic products include those made with recycled and recyclable materials and energy efficient processes. Green electronic products do not become part of the solid waste stream, and their processes do not contribute liquid and gaseous emissions to the environment.

What is lead free?

Lead is the most abundant heavy metal in Earth's crust, occurring principally as the sulfide ore, galena. Lead's malleability, low melting point, excellent conductivity, high resistance to corrosion, and abundant supply have made it a useful material in electronics (Pecht *et al.*, 1995, 1999). The main applications of lead in electrical and electronic equipment (EEE) include solder joints of printed circuit boards, board finishes, and glass of cathode ray tubes. EEE is responsible for between 1.5 and 2.5 percent of all worldwide lead applications (Turbini, 2000).

After decades of experience using lead-based solder, the industry has a wealth of knowledge concerning its performance characteristics, reliability, and durability, as well as the safety of its use in manufacturing, and its environmental impact throughout the product life cycle. The lead-free movement has made the electronics industry both exited and apprehensive.

Typically, electronic components in an assembly attach to a printed circuit board via soldering. The most common

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processes used in electronic assembly are reflow and wave soldering. Both processes involve exposing the components and circuit boards to processing conditions sufficiently hot to melt the soldering alloys, which then form acceptable solder joints. Unfortunately, lead-based solder is toxic. Environmental threats arise from lead because of the improper disposal of old and obsolete electronics. Lead oxides from the solder can potentially become soluble, then leach into and contaminate groundwater. Even though electronic solder accounts for a small percentage of the worldwide use of lead; litigation, legislation, and environmental mandates have increasingly sought to eliminate lead-based solder.

Electrical and electronic products and components are lead free if their assembly does not intentionally use lead in the raw materials or the manufacturing processes. Even when processing does not intentionally add lead, the material may exist as an impurity in the final product. One standard for an acceptable level of incidental lead impurities is 1,000 parts/million (Japan Electronic Industry Development Association, 2000).

What is halogen free?

Manufacturers add flame-retardant (FR) chemicals to their materials during or after manufacture to inhibit or suppress combustion. FRs interfere with combustion at various stages of the process, such as during heating, decomposition, ignition, or flame spread. Designs include them to prevent the spread of fires or delay the time of flashover. Studies show that the use of FRs in the manufacture of electronic equipment, upholstered furniture, construction materials, and textiles save lives from fire (European Flame Retardants Association, 2005).

There are various kinds of FRs, such as halogenated, chlorinated, phosphorous-containing, nitrogen-containing, and inorganic. Different types of FRs are better suited for different applications. Their suitability depends on compatibility with the material to be flame-retarded, the fire safety standards with which the product must comply, and cost considerations.

The halogens are the chemical elements fluorine, chlorine, bromine, iodine, and astatine. Manufacturers do not use fluorine and iodine-based FRs in practice because neither type interferes with the combustion process: fluorine has too strong a bond and iodine too loose a bond to carbon. In plastics, brominated FRs (BFRs) are the most effective FR when both performance and cost are considered.

Bromine in its elemental form is a highly volatile reddish-brown liquid at room temperature. However, bromine never occurs in its elemental form naturally, but in compounds with other substances, known as bromides. The recoverable form of bromine is from soluble salts found in seawater, salt lakes, inland seas, and brine wells. It is these bromides, which become the raw material to produce commercial brominated products. Today, bromine production exceeds 470,000 tons annually (European Flame Retardants Association, 2005).

Halogenated FRs primarily consist of chlorine and bromine. Through BFRs' unique chemical interaction with the combustion process, bromine is more effective than most of the alternatives, meaning that a much lower quantity of FR achieves the highest fire resistance. As a result, designers require BFRs to protect a wide variety of products: EEE including televisions, computers, radios and stereo systems, and also textiles and foam in upholstered furniture, and even carpets.

BFRs (39 percent) and chlorinated FRs accounted for 45 percent of the FR worldwide market in 1998 (European Flame Retardants Association, 2005). Electrical and electronic components accounted for 56 percent of the BFR market.

There are different types of BFRs (O'Connell *et al.*, 2004), such as polybrominated biphenyls (PBB), polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol – A (TBBPA), and hexabromocyclododecne (HBCD). Each of these BFRs has very different properties. However, "halogen-free" is misused to describe the movement of eliminating some of the BFRs (PBBs and PBDEs) from the electrical and electronic products. IPC Association Connecting Electronics Industries (2003):

> … recognizes the term halogen-free as a marketing term only and does not support it as an industry standard for materials and final products containing any level of halogenated flame retardants.

Regulation in the European Union

On January 27, 2003, the European Parliament and the Council of the EU passed a pair of directives aimed at reducing the effects of the production, use, treatment, and disposal of waste EEE (WEEE) on human health and the environment. EU constituencies had considered and debated Directive 2002/95/EC on the restriction of the use of certain hazardous substances in EEE (ROHS) (EU, 2003a) and Directive 2002/96/EC on WEEE (EU, 2003b) for years. Together, they identify lead as a material manufacturer must not include in EEE after July 1, 2006. Other materials facing similar restrictions are mercury, cadmium, hexavalent chromium, PBB, and PBDEs. Besides new restrictions on industry, the directives propose new policies and practices to help manufacturers meet the objectives. The goal is to improve the environmental performance of all operating companies that are directly involved in the handling of WEEE particularly those companies that are involved in the treatment of the waste.

The directives place EEE into categories such as household appliances, telecommunications equipment, lighting equipment, toys, tools, and other consumer products. WEEE includes all components and subassemblies that are part of the product at the time the user discards it (EU, 2003a, b). Prior to the July 1, 2006 ban on lead and other materials, producers must establish systems to recover electronic waste (Schmidt, 2004).

Regulation in Japan

The twentieth century saw the progression from mass production and mass consumption to mass disposal and led Japan to improve the handling end-of-life products. The gross domestic product (GDP) of Japan grew from ¥75.3 million in fiscal year 1970 to ¥497.3 million in 1988. With that seven-fold increase, product consumption saw similar growth. The number of color televisions per 100 households rose from 26.9 to 224.0 over the same time span (Environment Agency, 2000).

In Japan, there is indirect pressure for lead-free products from Japanese legislation. Only certain landfill sites permit dumping of lead, which carries a cost premium, and there is a Home Electronics Recycling Law requiring companies to take back end-of-life electronics. Japan has begun its own version of take-back legislation effective in 2001 for a variety of its domestic products. The Electric Household Appliance Recycling Law passed the obligation for collection and recycling of waste appliances to the producers of those appliances. The appliance law is part of "The Basic Law" for establishing the Recycling-based Society in Japan. This law is part of are seven laws, which include the Waste Management and Public Cleansing Law and enacting the Law on Promoting Green Purchasing (Ministry of the Environment, 2000).

Japan's motivations for change are the increasing use of electronic products, the physical limitations the country has to house waste products of all kinds, and the recognition that these waste appliances contain valuable materials. The approach is to phase-in the law by adding a specific number of products that must return to the producer each year. In 2001, color televisions were included, thus directly affecting the electronic industry. The other products included during the first year of the law's jurisdiction were air conditioners, refrigerators, and washing machines (Environment Agency, 2000). Japan established an industry target of 6 million units collected for the first year of the program. Manufacturers actually collected over 8.55 million units. Another target for color televisions was for material recovery from recycling at a rate of 55 percent; actual recovery was 73 percent (Mayers, 2002). During fiscal year 2003, one recycling plant collected 700,000 appliances from six of the seven prefectures in its region. Since, the law's inception, recycling plants across the country have collected over 10 million appliances (Anonymous, 2004; Schneiderman, 2004).

Recycling materials will be a large part of the action upon receipt of the waste products, but disposing toxic wastes due to lead content will also require manufacturers' attention. Although the take-back legislation does not specifically target lead-based solder, electronic manufacturers will ultimately be responsible for the proper disposal of the lead used in their post-consumer products. Elimination of lead from electronic manufacture alleviates the need for controlling lead disposal.

In Japan, there is no pending legislation for halogenated FRs. However, Japanese manufacturers have indicated activities planned or underway to reduce or remove halogenated FRs from their products. For example, Sony has indicated it will provide globally halogen-free products by 2002. Fujitsu is producing halogen-free plastic cover computers. In March 2000, JVC certified a PCB that eliminated the use of halogenated materials from base materials and insulation layers. Japan Printed Circuit Association (JPCA) uses 900 ppm bromine or chlorine to describe a product as "halogen-free" (Anonymous, 2000a), provided it is not an intentional additive to the product.

Regulation in the US

In the early 1990s, US legislators proposed the Lead Exposure Reduction Act, which would control lead. A successful lobbying effort by the electronics industry at the time saved lead-based solder from restrictions. However, the US Environmental Protection Agency (EPA) did inventory lead-containing products and list those products that would present unreasonable risks of injury to human health. The 1993 Lead Tax Act was enacted to place a per pound charge on all lead smelted in the US and on the lead content of imported products. Neither has had a measurable effect on the electronics industry. In 2001, the US EPA, which was acting under two presidential administrations, adjusted the lead reporting level in an effort to reduce lead use. The Clinton Administration proposed and the Bush Administration affirmed the change. The threshold for lead reporting accountability had been £25,000 annually for manufacturers and processors and £10,000 for users. EPA now requires manufacturers, processors, and users of £100 or more of lead to report that use to the toxic release inventory. EPA first collected chemical emissions data reports under the Emergency Planning and Community Right-to-Know Act of 1986 (Hester, 2001). Subsequently, the agency has witnessed substantial decreases intoxic releases, and it expects the new reporting threshold to show similar results (Erdmann, 2005).

In 2003, California was the first of the US to pass legislation to eliminate stockpiles of electronic waste. Recycling whenever possible comprised a significant portion of the legislative initiative (Erdmann, 2005). The Electronics Recycling Act of 2003 requires retailers to collect fees on sales of video display devices. The state uses the fees to run a cathode ray tube collection-recycling program (Reisch, 2004).

In the US, there is no current production or use of PBB. Companies intending to resume manufacture must notify Environmental Protection Agency 90 days in advance for approval. There is no pending legislation on the use of PBDEs (Anonymous, 2000a).

Issues with lead free

The temperature and process time required to flow the lead-free solders pose a significant issue in tin-lead replacement. The melting point of tin-lead solder is 183°C, which corresponds to a maximum reflow temperature of 220°C. The primary lead-free alloys have melting points in the 217-220°C range with corresponding processing temperatures of approximately 254°C (Parker, 2000). Such an increase in processing temperature raises the concern for boards and components initially designed for the tin-lead processing and now must withstand a 34°C heating differential.

Reflow ovens need to be set 30-40°C higher than they were for tin-lead solder, and the industry expects this increase affect boards and components adversely. The amount of time at the reflow temperature as well as the pre-heating and heating ramp rates will be further contributing factors to the concern for the reflow temperature's effects. Manufacturers and inspectors use the specifications of JEDEC Solid State Technology Association of the Electronic Industries Alliance to rate plastic packages, which are susceptible to moisture ingress (JEDEC, 2002). Especially a concern is the reaction of plastic encapsulated microelectronic parts that may crack or "popcorn" due to trapped moisture. Significant deformation of moisture-laden packages versus dry packages starts to increase around 90°C. An increased rate of deformation occurs beyond 138°C (Pecht *et al.*, 1995; Pecht and Govind, 1997). Resulting conditions can be as simple as discoloration, or as severe as the complete meltdown of the packaging material.

Lead-free alternative solders have the extensive history of their tin-lead counterparts to overcome before those associated with the electronics industry become comfortable

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with their use. The main problem with finding a lead-free solder alloy is that no obvious substitute is available. An evaluation of 79 lead-free alloys identified seven potential alternatives, although there was not one simple replacement. The new solder alloy must have a coefficient of thermal expansion (CTE) that matches the joining components and/or substrates, and the alloy must be able to withstand thermal cycling and thermomechanical loading. In addition, the solder must have creep resistance to sustain such thermomechanical loading over long periods in the field, must be harmless to the environment, must have good wettability properties so there is ease of manufacture, and must be economically viable (National Center for Manufacturing Sciences, 1998). The National Electronics Manufacturing Initiative's (NEMI) Lead-free Assembly Project recommended standardization on a lead-free solder, and identified un-patented alloys that could meet the requirements set by the industry (Parker, 2000).

In order to keep process transition costs down, the replacement alloy should provide sufficient wettability to work with conventional systems. An inert atmosphere may help processing, and in a wave-soldering process, that is acceptable since making the wave inert is not too costly. However, for surface mount technology (SMT) reflow, it is desirable for the alloy to reflow in air, due to the high cost of adding an inert atmosphere to a reflow oven.

Adequate electrical conductivity is a basic requirement of an electrical connection. Experimentation continues to characterize the electrical properties of lead-free alternatives. Thermal conductivity is required to transfer heat rapidly to dissipate the thermal energy as needed. The selected lead-free alternative alloying elements must be non-toxic, thereby eliminating cadmium, thallium, and mercury. Environmental consideration also suggests that the alternative elements should not be by-products of refining processes of a toxic material. For example, bismuth is the by-product of lead mining.

The goal of finding a lead-free replacement, which costs no more than tin-lead solder, cannot be met as there is no alternative within 35 percent of the cost of tin-lead. The form of the lead-free solder will affect cost, as required metal volume is relatively small for making solder paste, but is greater for wire and bar solder (Bastecki, 1999).

The availability of materials is a factor in the switch from tin-lead solder. Indium is an alloying element with unique properties, but is not highly available. Other elements such as tin, copper, silver, and antimony exist in large enough supply to produce the solder required globally; whereas expense might be a limiting factor for silver. Storage of certain alloys will be an issue as tin-zinc powder has a short shelf life due to its oxidation potential. Other key issues in materials supply are the materials' recyclability and their manufacturability into bar, wire, powder, and preform shapes (Anonymous, 2000b). If the electronics industry changed completely to tin-bismuth eutectic solder, then they would deplete the existing resources of bismuth in fewer than 20 years (Raby and Johnson, 1999). A patented alloy might be limited in supply and will likely increase the price of the material (Bastecki, 1999).

The electronics industry faces challenges to its readiness for the change to lead-free technologies. Supply chain availability due to the conversion to a higher reflow temperature and time must be determined. Industry-wide coordination and convergence of effort on such products as transistors, capacitors, mold compounds, die attach epoxies, underfill, substrates, flame retardant-4 (FR4) printed circuit board materials, is needed. Requisite transitioning established manufacturing lines to new processes and materials will take time. Managing product transitions from lead-based to lead-free materials will likely produce dual inventories (Huber *et al.*, 2001).

NEMI recommended Sn3.9Ag0.6Cu as a replacement for lead-based solder in reflow applications. Use of this alloy will raise the melting point by as much as 40°C; that will influence the materials selection and the assembly process (Anonymous, 2000c). For wave solder production, requiring more solder than reflow, the group is recommending the less expensive tin-copper eutectic alloy, Sn0.7Cu, or, as an alternative, the tin-silver eutectic, Sn3.5Ag. The higher melting point of the tin-silver-copper alloy family would raise a number of issues and concerns for component and board manufacturers. The European Community has done a study of lead-free alloy alternatives and found that optimum solder replacements include tin-silver-copper. They recommended Sn3.8Ag0.7Cu for reflow soldering, Sn3.8Ag0.7Cu0.25Sb for general-purpose wave soldering and Sn5Bi2Sb1Ag for single-sided wave assembly (Marconi Materials Technology, 1999). Japanese Electronic Industry Development Association (JEIDA) recommends Sn3.0Ag0.5Cu as a good choice taking into consideration the price of silver and the limitation of the related patents (Suga, 2000). The tin-silver-copper family is sufficient for higher-temperature applications, while tin-zinc-bismuth alloys are better for lower-temperature consumer-product applications (Fryer, 2001).

Issues with halogen free

Human and environmental exposure can occur in connection with the use of products, in the recycling of plastics containing PBBs and after disposal to landfills. Emission is probably slow, but degrading PBB-bearing materials can release PBBs. In conventional sub-chronic animal experiments, the liver is the organ most sensitive to pentaBDE. Both morphology and function effects occur when pentaBDE exposure through food exceeds 1 mg/kg. Skin injuries and effects on thyroxin hormone levels can occur at high exposures. A Swedish study gave young mice a low single dose of tetraBDE or pentaBDE (0.7-12 mg/kg). The study monitored the effects on their behavior once they reached adulthood. The results showed that exposure during the critical period when the brain is growing and maturing fastest leads to effects on the behavior of the adult animals. Researchers observed effects on motor activity, reproduction, and memory and learning (Anonymous, 1999).

One of the main reasons for the current controversy surrounding BFRs in particular PBBs and PBDEs, is the possible formation of polybrominated dibenzo-dioxins and furans (PBDD/F) during combustion of both the BFRs themselves and flame-retarded materials. Incineration of flame-retarded plastics present in municipal solid waste is of particular concern. There is also concern about what happens when products made with BFRs burn in accidental fires, such as the catastrophic fire at the Düsseldorf Airport in April 1996. However, the official fire report stated that investigators did not detect dioxins and furans at levels approaching the

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5 parts/billion limit of the German Chemicals Banning Ordinance (Anonymous, 1997).

Analyses of the principal halogen-containing components of printed circuit boards, TBBPA, found it not to be a source of potential human dioxin exposure (IPC Association Connecting Electronics Industries, 2003). According to an IPC White Paper, the studies involving TBBPA and TBBPA-containing polymers support the conclusion that the manufacture, use, and disposal of information technology devices containing TBBPA flame-retarded printed circuit boards do not increase human dioxin exposure. IPC indicated that a major driver for halogen-free flame substitutes for TBBPA in printed circuit boards is marketing and is not significant health concerns.

Lead-free and halogen-free products

Lead-free consumer products, components, and assemblies are available, and manufacturers have marketed them successfully. Some of the early successes with consumer products in Japan have involved lead-free solders, while board and component finishes may have contained lead. Japanese manufacturers have been careful to designate which lead-free materials they used to make a particular product. For example, in the mini-disc player sold by Panasonic, Matsushita uses a tin-silver-bismuth solder alloy for its portable mini-discs, which they label with a green leaf sticker. Initial sales data indicated an increase in market share of this product in Japan from 4.7 to 15 percent (Krsmanovic, 2000). Manufacturers have accomplished successful applications of lead-free technologies, and those applications include components and assemblies.

Reacting to pending legislation is not the only driving force behind the lead-free movement in Japan. Since, consumer preference for environmentally friendly products has given manufacturers market share gains for products that use lead-free alternatives, Japan's motivation comes partly from product differentiation. Japanese companies have voluntarily set goals for achieving lead-free production. The JEIDA released a roadmap for lead-free soldering in cooperation with the lead-free soldering committee of the Japanese Institute of Electronic Packaging Association (JIEPA) (Robins, 2000).

There are halogen-free alternatives including red phosphorous, organo-phosphorous materials, nanoclays, metal hydroxides and trioxides, and phosphates. Some alternatives tend to be toxic in certain forms, so material researches continue to test toxicity levels of all viable alternatives (Markarian, 2005).

Conclusions

Neither the proposed EU ban nor the enacted Japanese take-back legislation is the only driving force behind lead-free solder or halogen-free FR adoption. Manufacturers are voluntarily changing prior to a ban. Consumers have increased expectations of corporations and hold those corporations responsible for a quality of life that goes beyond the value of their product or service. Consumer awareness and activism are also driving market share opportunities.

Consumers have reacted positively to environmentally considerate products. Product, subassembly, component, and board manufacturers want their products labeled lead and halogen free for market share opportunities, so they are voluntarily changing prior to legislation becoming effective. Japan commerce uses green labels for market differentiation as they designate that a manufacturer made a product with environmentally friendly materials. Web page advertisements, as well as traditional print ads, portray the benefits of such applications.

Consumers are willing to pay a higher price for environmentally friendly features on some products, but sustaining the move to those technologies requires more than changes considered differentiable by only some consumers. The assumption that all consumers view environmental material changes as differentiable improvements is incorrect.

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