Contamination of Solid Waste from Toxic Materials in Electronic Waste (e-Waste)

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Abstract

Electronic waste or e-waste is the fastest growing and the latest waste stream in global waste sector. Ever increasing demand for electrical and electronic equipment (EEE) such as computers, mobile phones, televisions, washing machines, refrigerators in our modern society coupled with wide availability of latest designs in the electronics industry lead to rapid obsolescence of EEE well before their end-of-life use. Apart from the significant number of EEEs entering the global stream, the toxicity of certain materials contained in them is major concern to waste managers. E-waste contains more than 1000 different substances out of elements such as lead, mercury, cadmium, hexavalent chromium and brominated flame retardants are of major threat to human health and the environment. Regulations are being developed or implemented in many countries around the world to ban or restrict above materials from EEE. This paper investigates the use and toxicity of materials used in the manufacture of EEE that could contaminate the solid waste streams.

Keywords: Electronic waste; E-waste; Lead; Brominated flame retardants, Hexavalent chromium

Introduction

Electronic waste or E-waste is one of the fastest growing and newest international waste streams growing at a rate of 3-5% per annum or around three times faster than other normal municipal solid waste (Schwarzer et al., 2005). A continual development in the electronic sector resulting in rapid obsolescence of many electronic and electrical items is causing the growth of this waste stream. For example the average lifespan of a new model computer has decreased from 4.5 years in 1992 to an estimated 2 years in 2005 (Widmer et al., 2005). Studies have revealed that around 500 million computers will have become obsolete in the United States alone between 1997 and 2007 (Yu et al., 2006). The same scenario applies to mobile phones and other hand held electronic items used in the present society. Each 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 (Canning, 2006). As a result used electronic and electrical items, commonly known as e-waste, have become a serious social

problem and an environmental threat to many countries worldwide. United Nations estimate that collectively the world generates 20 to 50 million tonnes of e-waste every year (Schwarzer et al., 2005).

In addition to the amount of e-waste generated the composition of it is also creating a major problem to the waste managers around the world. E-waste contains more than 1000 different substances, many of which are toxic metals such as lead, arsenic, cadmium, hexavalent chromium and flame retardants used in the plastics (Widmer et al., 2005). Although the regulations being developed around the world are demanding the replacement of many of these materials including lead, cadmium, mercury, hexavalent chromium and polybrominated biphenyls, they will still remain in the waste stream for some time. The aim of this paper is to investigate the toxicity of some of the materials in the e-waste stream and to determine the materials which are of most concern to the humans and the environment.

Lead

Lead is naturally occurring metal in the earth's crust. It can be found in our environment due to human activities such as manufacturing, mining of course due to fossil fuel burning. Lead is used in variety of uses including the production of batteries, paints and ceramic products and in metal products such as solders. Lead itself does not break down but the characteristics of lead compounds could change due to 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.

Exposure to lead can happen by breathing the contaminated air or eating contaminated food or drinking contaminated water. 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 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 (ATSDR, 2005b).

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 (Five Winds International, 2001). In a typical desktop personal computer lead amounts to 6.3% by weight (MCC, 1996). 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 (Five Winds International, 2001).

The main environmental effect of lead is the leaching of lead ions from 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 comes from EEE (Widmer et al., 2005). 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 by Greenpeace International 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 EEE recycling workplaces in other parts of the world (Brigden et al., 2005).

Wide awareness of health and environmental hazards associated with lead has forced different policies among the decision makers on e-waste worldwide. The European Union (EU) has adopted directives banning lead (with some exemptions) followed by countries like China and Taiwan and most of the original equipment manufacturers (OEMs) in Japan, embracing lead-free EEEs for environmental as well as for marketing benefits. However sustainable lead-free electronics is not easy to achieve as it

depends on several factors. These include design, use and end-of-life management issues of the alternatives, ability to meet similar functionality and safeguard the reliability and the availability of the resources to meet the demand. Although several lead-free alternatives have been developed, the long term environmental and health impacts of such alternatives are relatively unknown at this stage. Life cycle assessment of the lead-free alternatives is the key as the lead-free alternatives must be environmentally preferable to lead throughout the product design, use and disposal. Although the above mentioned issues are real, the electronic manufacturers are very sensitive to public opinion about much published health and environmental impacts of lead use thus striving to reduce or eliminate lead from their product.

Mercury

Mercury is a naturally occurring metal which in pure form is a shiny silver white liquid. It is most common in thermometers, batteries and dental fillings. Mercury also combines with other elements to produce organic and inorganic compounds. The most common is the combination of mercury and carbon which results in methyl mercury and produced by microscopic organisms in the water and soil.

Metallic mercury and its compounds enter the environment from manufacturing plants and through the burning of coal and waste. Exposure of mercury could happen through eating fish contaminated with methyl mercury or breathing vapours from incinerators and industries that burn mercury containing fuel. Exposure of high level of mercury can severely damage the brain, kidneys and developing fetus. Short term exposure to high levels of mercury could cause lung damage, nausea, diarrhoea, skin rashes and eye irritation (ATSDR, 1999b).

Mercury is a concern in managing EEEs as they are used in backlight lamps that illuminate laptop computers and other flat panel displays. Given the rapid uptake of laptops and flat panel displays replacing traditional cathode ray tubes worldwide, mercury is becoming a major issue for e-waste managers although the amount of mercury per screen is small averaging between 0.12mg – 5 mg (Five

Winds International, 2001). In a typical desktop personal computer mercury averages only around 0.0022% by weight (MCC, 1996) and mainly used in sensors and switches on printed circuit boards, batteries and in tubes in flat panel screens. Mercury is also used in fluorescent lamps averaging 20-50 mg/tube depending on size of tube (Poulios et al., 2006). It is estimated that EEEs use 22% of the annual worldwide consumption of mercury (Department of Environment Food and Rural Affairs, 2006).

Mercury contained in EEE could be released to the environment during its end-of-life management processes such as recycling, incineration and landfilling. The main concern is the emission of mercury into air during the recycling processes causing immediate health hazard to workers.

Cadmium

Cadmium is a natural element occurring in the earth's crust in forms such as cadmium oxide, cadmium chloride and cadmium sulphate/sulphide. Due to its non-corrosive nature, cadmium is used in many applications such as batteries, metal coating and plastics.

Cadmium mainly enters the environment from mining activities, industrial operations and from incinerators burning coal or household wastes. Exposure to cadmium could occur via breathing contaminated workplace air especially from battery manufacturing, metal soldering and welding, drinking cadmium contaminated water, breathing contaminated air near incinerators and breathing cadmium in cigarette smoke. Breathing high levels of cadmium could severely damage the lungs while eating food or drinking water contaminated with cadmium could cause vomiting and diarrhoea diarrhea. Long-term exposure to lower levels of cadmium could lead to build up of cadmium in the kidney leading to kidney failure (ATSDR, 1999a).

Cadmium is used in variety of components in EEEs due to its excellent corrosion resistance, low electrical resistance and sound soldering characteristics and its solubility in strong acids. The most

common use of cadmium is in nickel-cadmium (Ni-Cd) batteries extensively used in older laptops and mobile phones. Although the newer laptops are likely to contain batteries made from Lithium (Li) ion or nickel metal hydride (NiMH), disposal of older laptops could still cause transfer of cadmium to the environment. In addition cadmium in EEEs could be found in plating applications in contacts and switches in computers, phosphorescent coatings on inside of cathode ray tubes, as a platicizer, stabilizer, flame retardant and colouring in PVC cabling and plastic computer housings and as surface finishers, chip resistors and semiconductors in printed circuit boards (Five Winds International, 2001). A typical desktop computer contains around 0.0094% of cadmium by weight in its components (MCC, 1996).

Cadmium from EEE could enter the environment when plastics containing cadmium are burned and when printed circuit boards are shredded during the metal recovery processes. Furthermore, cadmium could also leach into groundwater when plastic containing cadmium is landfilled.

Hexavalent Chromium

Chromium is present in the environment in several different forms out of which Chromium (III), Chromium (VI) and Chromium (0) are the most common ones. Chromium (III) occurs naturally while the other two forms are produced by industrial processes. Chromium (0), which is the metal chromium is used for making steel while Chromium (III & VI) are used in processes such as leather tanning, wood preserving, dyes and pigments and chrome plating.

Chromium enters the environment mainly in the Chromium (III) and Chromium (VI) forms. Exposure can occur as a result of breathing contaminated workplace air, drinking contaminated water and breathing emissions from uncontrolled hazardous waste sites containing chromium or industries that use chromium in their manufacturing processes. Out of all forms, Chromium (VI) is the most dangerous as breathing high levels of it can cause irritation to nasal system, nosebleeds and can cause cancer. Ingesting large amounts of Chromium (VI) could cause stomach upsets and kidney and liver

damage. Skin contact with these compounds could also cause skin ulcers in some people (ATSDR, 2001a).

Chromium in EEE is mostly phased out but is still being used as a hardener for plastic housings and as decorative in pigments in components such as housings, printed circuit boards, hard disks and cabling. In a typical desktop computer there is about 0.0063% by weight (MCC, 1996). Landfilling the incineration residues of EEE could cause it to leach into groundwater.

Beryllium

Beryllium is naturally found in earth's crust and its ore is mined and purified to use applications such as nuclear weapons, aircraft and space vehicle structures, x-ray machines and in various instruments. Beryllium oxide is used in to produce special ceramics which are used in electrical and high technology applications while beryllium alloys are used widely in automobiles, computers, sport equipment and dental bridges.

Exposure to beryllium occurs in people working in industries where beryllium is processed into metal and alloys and people living near these industries. Also people living near uncontrolled hazardous waste sites could be exposed to much higher than normal levels of beryllium. The effect of breathing beryllium will depend on the nature and duration of the exposure. Lung damage has been observed in people exposed to very high levels of beryllium. According to the United States Department of Health and Human Services, about 1-15% of all people occupationally exposed to beryllium in air may develop the condition called 'chronic beryllium disease (CBD)' which could cause fatal scarring of the lungs resulting in weakness, tiredness and difficulties in breathing (ATSDR, 2002).

Use of beryllium as copper-beryllium alloy is becoming very popular in EEE. Around 2-4% beryllium is used in this copper alloys to improve the properties of copper contact springs due to the high strength, high conductivity and high elastic quality of beryllium (Five Winds International, 2001). It is

estimated that beryllium exists in EEE as 0.08kg/tonne of printed circuit board, 0.05 g per cathode ray tube and 0.0157% by weight in a typical desktop computer (Poulios et al., 2006).

Brominated Flame Retardants

Brominated flame retardants (BFRs) are synthetically produced with several variants of different chemical properties. Polybrominated diphenyl ethers (PBDEs) which include penta-brominated diphenyl ethers (penta-BDE), octa-brominated diphenyl ethers (octa-BDE), and deca-brominated diphenyl ethers (deca-BDE), polybrominated biphenyls (PBBs), Tetrabromobisphenol-A (TBBPA) are the major types of BFRs which have replaced polychlorinated biphenyls (PCBs) as an effective flame retardant.

Worldwide production of BFRs has increased rapidly in the recent past and doubling between 1990 and 2000 with an annual growth rate of 4-8%. It is estimated that about 40% of all bromine consumed worldwide is consumed for BFR manufacture (Morf et al., 2005).

PBBs have been found to be persistent, bioaccumulative toxins and are classified as possible carcinogens. Since most production of PBBs ceased in the 1970s major EEE manufacturers now prohibit their use, and, as a result, PBBs are rarely found in electronic equipment manufactured today.

PBDEs are chemically manufactured flame retardant compounds that are added to plastics and foam products to safe guard them from burning. There are several kinds of PBDEs defined according to the number of bromine atoms attached to the central molecule. PBDEs are mixed into plastics and foams hence they can leave the products and enter the environment because they are not bound to the product.

Exposure of PBDEs can occur in workers in PBDE manufacturing plants as well as in people who work in enclosed areas where PBDE containing products are dismantled or recycled. Very little is

known about the health effects of PBDEs in humans but there is evidence that high concentrations of PBDE could cause neurobehavioral alterations and affect the immune system in animals (ATSDR, 2004b).

In EEE BFRs are used in variety of areas including printed circuit boards, plastic computer housings, motherboards, keyboards and cabling to prevent and safeguard the equipment from fire. It is estimated that plastic housings in computers could contain around 25% PBDE (Five Winds International, 2001). Some BFRs are considered to be persistent organic pollutants and known to bioaccumulate in the environment. Due to this reason many countries are now phasing out the use of PBDEs and PBBs and replace TBBPA which is regarded as less hairdos. However, PBDEs and PBBs still could enter the environment through end-of-life management activities of existing EEE.

Substitution of halogenated flame retardants are being initiated in many jurisdictions worldwide. The Restriction of use of Hazardous Substances (RoHS) directive which came into effect in July 2006 in the European Union bans the use of PBB, octa-PBDE and penta-PBDE and calls for a risk assessment of deca-PBDE. No restriction is made in this directive regarding TBBPA. The use of TBBPA is not restricted in any country. As with lead-free electronics finding sustainable halogenated flame retardants is a challenging task as it involves life cycle impacts of the replacement, its ability to meet the technical and functional requirements and be compatible with lead-free alternatives.

Polyvinyl Chloride

Polyvinyl chloride (PVC) is produced from a colourless gas called vinyl chloride which is a manufactured substance. Vinyl chloride can be formed by breaking down substances such as trichloroethane and trichloroethylene. PVC is used widely in variety of plastic products including pipes, wire and cable coatings and packaging materials.

Exposure could occur by breathing vinyl chloride released from plastic manufacturing industries and hazardous waste disposal sites. Breathing high levels of vinyl chloride gas for short period can cause symptoms such as dizziness and sleepiness and at extremely high levels could even cause death. Some people who have breathed vinyl chloride for longer periods have structural changes in their livers and could result in permanent liver damage and liver cancer (ATSDR, 2006).

PVC is the main plastic used in the manufacture of EEE. It is mainly found in keyboards, cabling and computer housings although many computer mouldings are now made of more benign ABS plastics.

The estimated amount of PVC used in different EEE range from 37.1g in keyboards to a total of 314g in cabling (Five Winds International, 2001).

The potential of dioxin formation from PVC contained in EEE during the incineration process is well known. PVC may also produce hazardous dusts and fumes during the heating and shredding processes causing danger to workers.

Antimony

Antimony is a metal found in the earth's crust and is mixed with other metals to form antimony alloys which are then used in applications such as solders, lead storage batteries, sheet metals, bearings and metal castings. Antimony is also combined with oxygen to form antimony oxide which is then used in textiles and plastics as fire retardants, fireworks, paints, ceramics and as enamels for plastics, metal and glass.

Antimony is released to the environment via natural processes and manufacturing industries. Exposure occurs by breathing air near industries such as smelters and coal fired plants that process antimony and also near waste incinerators. Workers in industries that process antimony could be exposed to much higher levels of the metal. Breathing high levels of antimony for longer period of time could irritate

the eyes and lungs and could cause problems with stomach leading to stomach pain, vomiting, diarrhoea and stomach ulcers (ATSDR, 1995).

In EEE antimony is used as a flame retardant, as a melting agent in cathode ray tubes, and as a solder alloy in cabling. In monitors it is estimated that antimony contributes around 0.2% by weight in the funnel and 0. 24% by weight in the panel (Five Winds International, 2001). Little is known about the release of antimony from EEE end-of-life management processes but it is now known as a carcinogen hence a concern for the electronic industry.

Polychlorinated biphenyls

Polychlorinated biphenyls (PCBs) are a mixture of several individual chlorinated compounds commonly known as congeners which are no longer manufactured but are still found in the environment. PCBs have been used as coolants and lubricants in transformers, capacitors and other electrical appliances due to their stable properties as sound insulators.

PCBs enter the environment from hazardous waste sites, leaks from stockpiled transformers containing PCBs and from some waste incinerators. PCBs do not break down readily hence may remain in the environment for a long time. Exposure to PCBs still could occur using old fluorescent bulb fixtures and from old electrical devices such as televisions and refrigerators manufactured few decades ago. Exposure could also occur by breathing air near hazardous waste sites and in workplaces where repair and maintenance of PCB transformers are taking place. Studies in exposed workers have shown symptoms that indicate liver damage but most commonly observed health effects of people exposed to large amounts of PCBs are skin conditions such as acne and rashes. Experiments have shown that PCBs can cause in animals (ATSDR, 2001b).

There is some disagreement in the literature about the use of PCB in EEE. While some sources confirm that PVC was never used, other sources refer to PCB use in old capacitors and as a possible

flame retardant in PVC plastic cables but only found in older equipment (Five Winds International, 2001).

Copper

Copper occurs naturally in the environment and is an essential element in plants and animals. It is used to manufacture several products such as wires, pipes and sheet metals. Copper is combined with other metals to make brass and bronze pipes.

Copper is released to the environment by manufacturing processes and also by mining and farming activities. Exposure could occur by breathing air containing copper particles or by drinking copper contaminated water. Although low levels of copper are essential to maintaining good human health, high levels can be harmful. Uptake of high levels of copper could cause irritation of the nose, mouth and eyes and can also cause nausea, vomiting and diarrhoea leading to liver and kidney damage (ATSDR, 2004a).

Arsenic

Arsenic is a naturally occurring element in earth's crust. In the environment arsenic is combined with other elements to form organic and inorganic arsenic compounds. Inorganic compounds are used to preserve wood and the most common is copper chromated arsenic (CCA) mainly used in only industrial applications these days. Organic arsenic is used in some pesticide applications.

Exposure to arsenic could occur in workers involved in arsenic production or use such as copper or lead smelting, wood treating and pesticide production or breathing sawdust or burning smoke from wood treated with arsenic and by also breathing air near hazardous waste sites. Very high uptake of arsenic could potentially lead to death while exposure to lower levels for a long time could cause a darkening of the skin and the appearance of small warts in the skin. Contact with inorganic arsenic

could also cause redness and swelling. Several studies have reported that uptake of inorganic arsenic could increase the risk of skin cancer and cancer in the bladder, lung, liver, kidney and prostate (ATSDR, 2005a).

A typical desktop computer contains 0.0013% by weight of arsenic mainly used as a doping agent in transistors or printed wire boards (MCC, 1996).

Nickel

Nickel is a naturally occurring element. Nickel can be combined with other metals to form alloys to produce coins and items such as valves and heat exchangers. By far the major use of nickel is in the production of stainless steel. Nickel can also combine with elements such as chlorine, sulphur and oxygen to form compounds that are used to make some batteries and for nickel plating.

Nickel is released to the environment through industries that use or produce nickel and its alloys and compounds. It is also released to the atmosphere by coal and oil powered power stations and waste incinerators. Exposure to nickel by eating food contaminated with nickel or by breathing air in manufacturing workplaces that deal with nickel. The most common effect of nickel in humans is an allergic reaction. People working in nickel processing industries have experienced severe bronchitis and reduced lung function and lung and nasal sinus cancers (ATSDR, 2005c).

A typical desktop computer contains 0.8503% by weight of nickel mainly used in the computer housing, cathode ray tube and the printed circuit boards (MCC, 1996).

Conclusions

There is a growing concern in the society about the potential environmental and health impacts posed by the end-of-life management processes of EEE. This concern has grown due to rapid uptake of information technology worldwide, rapid obsolescence of EEE, presence of certain substances in them and less than sound practices adopted recycling operations in certain countries. This paper investigated some substances in EEE to find which substances are of most concern to the public. Accordingly the paper found that substances such as lead, mercury, cadmium, hexavalent chromium and brominated flame retardants are of major threat to human health and the environment.

The RoHS Directive of European Union which came into effect on July 2006 bans the placing on the EU market of new EEE containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants. Many other countries around the world are now investigating or developing laws and regulations similar to RoHS to cope with health and environmental threats posed by these materials.

Although RoHS type regulations are favoured by many governments around the world (mainly to address the public concerns) and by many original equipment manufacturers (mainly to address environmental issues and to gain market advantage), much research is needed to find sustainable alternatives to materials banned from these regulations. It is very important to undertake a detailed life cycle assessment of the alternative materials from design stage to disposal stage to make sure that these materials are superior to the ones which were replaced. Unless this is done there is a possibility that although the public concerns regarding the current materials used in EEE are addressed, the society might end up with more e-waste to deal with from non-functional EEE.

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