Environmental and Human Health Concerns in the Processing of Electrical and Electronic Waste

Allsopp, M., Santillo, D. & Johnston, P.

Greenpeace Research Laboratories, Department of Biological Sciences,
University of Exeter, Exeter EX4 4PS, UK

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Executive Summary

There is currently a rapidly growing waste stream of electrical and electronic equipment in the world. This waste is of great concern because many of the components that make up electrical/electronic products are hazardous. The hazardous materials include many heavy metals, including lead, cadmium, mercury and beryllium, as well as hazardous chemicals in the plastic casings and printed circuit boards, including brominated flame retardants.

The quantities of electrical/electronic waste being produced are vast. Presently, some of this waste goes into the normal municipal waste stream to be landfilled or incinerated. Both these methods of disposal are problematic because they can result in environmental contamination with hazardous substances. In some cases, waste products such as mobile phones and computers are reused. In cases where they are not reused, these products and other electrical/electronic waste are being treated to reclaim metals and, sometimes, recycle the plastics. In some countries in Asia, including India and China, metals are being recovered from the waste often in small workshops using a wide range of techniques. In some more developed countries , metals are reclaimed at smelters/metal refineries or using mechanical separation techniques. With regard to smelters, there are four designated as "integrated smelters", located in Sweden, Belgium, Germany and Canada, which deal with large quantities of electrical/electronic waste.

There are many environmental and human health problems that are associated with current methods of recycling electrical/electronic waste. These can be mostly divided into two categories, namely the reclaiming of metals and the burning of plastics.

Reclaiming Metals

- In workshops in India and China, a number of methods are being used to recover metals. Solder is recovered from printed circuit boards using open flames or hot plates, and subsequently the electronic components are removed, either for re-use, or to be ground down to recover metals. Another technique includes burning of electrical/electronic wastes in fires to burn off plastics and recover metals. Also, in China, printed circuit boards are shredded and the metals separated by vibration. The processes being used that involve grinding or shredding may result in environmental contamination and human exposure from metal dusts. The burning/heating processes may result in emission to air of metals and possible human exposure. Of particular concern with regard to health is exposure to lead, cadmium, mercury and beryllium. From current practices to reclaim metals, there is also likely to be considerable contamination of the local environment with heavy metals. For instance, wastes generated from some of the processes are known to be dumped in local rivers. Furthermore, acid solutions containing high concentrations of hazardous metals are dumped onto ground and into rivers. Presently, there is a lack of scientific data on environmental contamination and human exposure from these practices. One study on health impacts to workers and local residents in a town in China indicated a negative impact on health to these people.

- In more developed countries, where smelters and metal refineries are used to reclaim metals from electrical/electronic waste, there is also the potential for exposure of workers, local communities and the wider environment to heavy metal fumes and dusts again including lead, cadmium, mercury and beryllium. There is a lack of occupational health data on exposure and health impacts in workers involved in reclaiming metals from waste electrical/electronic goods in smelters and refineries. However, one study at a precious metals refinery in the late 1980s did identify beryllium in fumes from the process and found chronic beryllium disease in some workers. Exposure to beryllium is of great concern even for workers in industrial smelters and refineries because chronic beryllium disease has been found in people whose exposure was much lower than permissible limits. Environmental contamination with heavy metals is also a concern. One study on an integrated smelter in Canada reported that hazardous metals, including copper, lead, cadmium, zinc, nickel and beryllium were found to be deposited on the surrounding landscape up to a distance of 50 km away.

- Mechanical separation techniques to recover metals from electrical/electronic waste can result in exposure of workers to dusts containing brominated flame retardants and heavy metals. Brominated flame retardants are generally persistent, bioaccumulative chemicals that have been shown to exert adverse impacts on health in animals.

Burning of Plastics

Plastic casing of electrical/electronic products such as computers and mobile phones, and plastic in printed circuit boards from such equipment, may all contain brominated flame retardants. Studies have shown that when brominated flame retardants are burned at 400-800 °C, other chemicals, called polybrominated dibenzo dioxins and furans (PBDD/Fs) and mixed chlorinated-brominated dioxins and furans are produced as a result. PBDD/Fs and mixed chlorinated-brominated dioxins and furans, like the well known environmental pollutants chlorinated dioxins and furans, are persistent, bioaccumulative and have a wide range of adverse impacts on health. For example, animal studies have shown that exposure to PBDD/Fs and mixed chlorinated-brominated dioxins and furans can result in toxicity to the immune system, the reproductive system and the developing foetus during pregnancy and that they should be considered as being capable of causing cancer in humans.

- In small workshops in India and China where open flames/hot plates are used for recovering solder from printed circuit boards, and open burning of electrical/electronic wastes is conducted, it is highly likely that PBDD/Fs and mixed chlorinated-brominated dibenzo dioxins and furans will be produced. This will inevitably result in exposure of workers and the surrounding environment to these toxic chemicals.

- It is possible that PBDD/Fs and mixed chlorinated-brominated dibenzo dioxins and furans are produced by smelters and metal refineries that burn plastics from electrical/electronic waste. There appears to be no published scientific literature on the burning of plastics containing brominated flame retardants in smelters/metal refineries, but there are data from burning of these chemicals in other high temperature facilities, i.e. in incinerators and in test incinerators. Some, but not all of this research has shown that PBDD/Fs and mixed chlorinated-brominated dioxins and furans can be emitted in the flue gas on burning of brominated flame retardants. It is, therefore, probable that these chemicals would also be released from smelters/metal refineries, albeit in quantities dependent on the design and operating conditions of the plant. The integrated smelters use very high temperature burning (1200 to 1300 °C) and rapid gas cooling, a method which reduces the production of chlorinated dioxins and should also decrease the production of brominated dioxins and furans. Information supplied by one company operating an integrated smelter reported that one test had shown that no PBDD/Fs were detected at detection limits in the range of <0.02 to <0.09 ng/m^3. However, since the brominated flame retardant content in the waste was described as rather moderate, further testing during routine operations would be necessary to confirm whether brominated or mixed brominated-chlorinated dioxins and furans are produced as a result of smelting electrical/electronic waste.

- Some plastics from mobile phones and computer cases are being separated and sent for recycling to be made into other plastic products. However, others are not separated and go straight to a smelter. Furthermore, plastics from mechanical recycling may also go to a smelter or to an incinerator. In smelters, the plastics act as a fuel and as a substitute for coke that is normally used as a reducing agent in the smelting process. In addition to the potential problem of formation of PBDD/Fs and mixed chlorinated-brominated dibenzo dioxins from the burning of plastics, this method of plastic disposal is not in keeping with responsible waste management. Material recovery, and thus in this case recycling of plastic, is higher in the waste management hierarchy and, therefore, preferable to combustion even if combined with energy recovery.

Solutions

Electrical/electronic waste contains hazardous substances. This means that there are currently no completely safe disposal methods to deal with this waste when considered from a health and an environmental perspective. This is the legacy of producing products that contain hazardous substances. Dismantling and processing of waste electrical and electronic equipment (“e-waste”) in small workshops in India and China without appropriate protective clothing, equipment or emission controls is clearly not safe for workers, local communities or the environment. Preferable to this is to undertake the operation in a proper recycling plant, to separate out hazardous components of the waste and use mechanical separation techniques (eg. magnetic and electric conductivity-based separation techniques) and/or smelting/metal refining. However, these methods also present significant problems. Firstly, there is the problem of possible human exposure to hazardous substances and consequently risks to health. Secondly, from smelting, there is the problem of possible contamination of the environment with hazardous metals and PBDD/Fs and mixed chlorinated-brominated dibenzo dioxins and furans.

The only sustainable solution to these problems is to produce a clean electrical/electronic product, free from hazardous substances from the outset, and that is designed to be recyclable. Therefore, no hazardous substances should be used in the production of electrical/electronic goods, including no hazardous metals and no brominated flame retardants. Products should also be easy to dismantle with recyclable parts and recoverable metals.

The European Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) is due to be implemented by Member States in July 2006. While the removal of certain hazardous substances necessitated by RoHS is an important step, it is also important that additional measures are taken to address other hazardous chemical constitutents. In this regard, the electronics industry must work towards the elimination of all hazardous substances from their products, not only those currently covered by the RoHS Directive. This must be conducted on a global basis. Only then will it be possible to produce non-hazardous goods that are completely recyclable using only mechanical means. These measures are essential to protect human health and the environment.

1. Introduction

The production of electrical and electronic equipment is increasing worldwide (Cui and Forssberg 2003) and the lifespan of some of the equipment is very short. For example, computers in the early 1980s were used on average for about ten years but their lifespan has since reduced to an average of about three years. This is due to the rapid and continual improvements in technology which quickly outdate older models . Mobile phones too become outdated and are replaced on average after about two years (Boghe 2001). As a consequence of the increasing market expansion in electrical and electronic goods and their short lifespan, the waste stream of these products is fast growing. This is a significant problem because some of the products, including computers and mobile phones, contain heavy metals and other chemicals which are hazardous, and are consequently a threat to the environment and to human health. Indeed, electrical and electronic waste has been identified as one of the largest sources of heavy metals and organic pollutants in municipal waste (Boghe 2001), and is identified as the fastest growing waste stream (Betram *et al.* 2002).

Waste electrical/electronic equipment often ends up in landfills or incinerators (UNEP 2004). Such disposal of electrical and electronic waste via the usual municipal waste stream routes of landfill or municipal waste incineration is problematic because hazardous components in the waste may get into the environment. These include brominated flame retardants and heavy metals such as cadmium, lead and mercury (Richter *et al.* 1997). Incineration of electrical/electronic waste in municipal waste incinerators, for example, can lead to the concentration of metals in the fly ash (Connecticut Department of Environmental Protection 2003) and possibly metal emissions to air. In an attempt to overcome the waste disposal problems, recycling schemes are being set up to recover some of the metals and plastics in the waste. Legislation is being implemented to control the disposal. For example, in Germany (Zhang and Forssberg 1998), Switzerland (Künzler Bossart & Partner GmbH 2001) and Taiwan (Shih 2001), legislation has been implemented which requires that manufacturers take back domestic electrical/electronic goods at the end of their lifespan. Within the European Community, two directives have been adopted, namely the directive of the European Parliament and the European Council on Waste Electrical and Electronic Equipment (WEEE) and the directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS). These directives necessitate, among other requirements, that Member States are responsible for ensuring that the producers set up systems for treatment and recovery of electrical and electronic waste (Feszty *et al.* 2003), as well as placing prohibitions on the use of certain hazardous substances in the manufacture of electrical/electronic goods at the outset. The United Nations Environment Program (UNEP) has proposed establishing a network of policy makers and experts to help deal with the problem of electrical/electronic waste in Asia and the Pacific (UNEP 2004).

The amount of electrical/electronic waste to deal with is vast. For example, in Europe it has been estimated that waste electrical/electronic equipment constitutes about 4% of municipal waste (Boghe 2001), and in the USA about 1% (UNEP 2004). Figures for west Europe show that 6 million tonnes of waste electrical/electronic equipment was generated in 1998 and the amount is expected to increase by at least 3-5% per annum (Cui and Forssberg 2003). In the UK alone, a study in 2000 estimated that 1 million tonnes of waste would be discarded in a year (see Feszty *et al.* 2003). Other research in the UK estimated that IT and telecoms waste equipment, which includes mobile phones and computers, represented 23% of the number of items in domestic waste electrical/electronic equipment discarded in 2003 (see ICER 2005). In China, an estimated 4 million PCs are discarded every year (UNEP 2004).

This report was undertaken to investigate the current methods that are being used to recycle/dispose of electrical/electronic equipment, particularly mobile phones and computers.

2. Contents of Waste Electrical/Electronic Equipment

Many of the components in electronic wastes are hazardous. Table 1 lists the major hazardous components in waste electric and electronic equipment, including computers and mobile phones. Mobile phones consist of a plastic outer case, a flat screen display and inside, a circuit board and batteries. Typically, computers consist of an outer plastic or steel casing while the internal workings include both plastic and metal containing devices such as printed circuit boards. Standard monitors include cathode ray tubes, although these are increasingly being replaced with flat screens which operate by liquid crystal displays (LCDs). Due to the potential toxicity and carcinogenicity of some of the substances in LCDs, they have been under suspicion of being a health hazard (OECD 2000). They may also contain mercury (Basel Action Network and Silicon Valley Toxics Coalition (2002).

Table 1. Major Hazardous Components in Waste Electrical and Electronic Equipment

Materials and components	**Description**
Batteries	Heavy metals such as lead, mercury and cadmium are present in batteries.
Cathode ray tubes (CRTs)	Lead in the cone glass and cadmium/zinc/yttrium sulphide in the fluorescent coating
Mercury containing components, such as switches	Mercury is used in thermostats, sensors, relays and switiches, for example, on printed circuit boards.
Liquid crystal displays (LCDs)	LCDs of greater than 100 cm^2 have to be removed from electric/electronic waste. LCDs are used in mobile phones and flat screen computer monitors and may contain mercury.
Printed circuit boards	In printed circuit boards, cadmium occurs in certain components. Other hazardous metals are also present (see text)
Plastics containing halogenated flame retardants	During incineration/combustion of the plastics, halogenated flame retardants can produce toxic components.
Solder	Lead/tin and other trace metals

Source: Adapted from Cui and Forssberg (2003).

The plastic casing of computers and mobile phones and the printed circuit boards within them contain hazardous chemicals, commonly including brominated flame retardants. Brominated flame retardants are generally environmentally persistent chemicals, some of which are known to bioaccumulate and to cause a wide range of adverse health impacts in laboratory animals. Where they are used, treated plastics contain typically 5-10% by weight of brominated flame retardants (Australian Government, Department of the Environment and Chemicals Management 2004). Veit *et al.* (2005) gives the bromine content of the plastics, especially as flame retardants, as 19%. It has been estimated that a single personal computer may contain about 1.7kg of flame retardants, of which 70% is in the cabinet and the remainder in the printed circuit board (Menad *et al.* 1998). An experimental study to determine the quantities of substances in printed circuit boards, including brominated flame retardants, found that the average concentration of polybrominated diphenyl ethers (PBDEs) was 40.5 mg/kg and the average concentration of tetrabromobisphenol-A (TBBP-A) was 14.4 mg/kg (Richter *et al.* 1997) .

Printed circuit boards also contain antimony trioxide as a flame retardant (typically 1-2% by weight) (Australian Government, Department of the Environment and Chemicals). Antinomy trioxide is suspected to be carcinogenic (Veit *et al.* 2005).

Some waste electrical/electronic equipment, including mobile phones and computers, contain printed circuit boards. In general, printed circuit board scrap from electrical/electronic products contains approximately 40% metals, 30% plastics and 30% ceramics (Cui and Forssberg 2003). The metals in printed circuit boards consist of a large amount of base metals such as copper, iron, aluminium and tin as well as rare metals like tantalum, gallium (and other rare platinum group metals) and so-called noble metals such as gold, silver and palladium. Hazardous metals that are present in printed circuit boards include chromium, lead, mercury, cadmium, zinc and nickel (Li *et al.* 2004). Lead is present in solder. Cadmium and americium may also be used for solder joints (Li *et al.* 2004). Significant levels of another hazardous metal, beryllium may be present (Australian Government, Department of the Environment and Chemicals Management 2004). Beryllium is present as copper-beryllium alloys, which typically contain around 2% beryllium. These alloys are used in springs, relays and connections and, historically, in computer motherboards (OECD 2003, Taylor *et al.* 2003).

With regard to quantities of metals, copper typically makes up around 10-20% by weight, lead 1-5% and nickel 1-3%. Precious metals including silver, gold, platinum and palladium, generally total around 0.3 to 0.4 % (Veit *et al.* 2005).

3. Recycling of Computers and Mobile Phones in More Developed Countries

There are many companies who deal with the recycling of mobile phones and computers. A search of websites of such companies in the UK revealed that both mobiles and computers are being re-used where possible. Mobile phones are being refurbished and sent to less developed countries for reuse. Similarly, computers are being re-used and sent, for instance, to charities and schools.

Phones and computers that cannot be re-used are disposed of in a manner similar to each other . For the casing of mobile phones, a number of companies that were personally contacted as part of this study had the plastic ground down and subsequently re-used for making low-grade products such as traffic cones. Plastic computer cases may also be granulated for recycling into other products, such as plastic posts and benches. In some cases, the plastic was not being re-used but sent for landfill.

According to the companies contacted, steel computer cases are sent for metal recycling. The printed circuit boards inside mobile phones and computers are sent for processing to recover metals. For about 10 companies that were contacted in the UK, the process being used for metal recovery was smelting; this is discussed further below. In some cases, however, the plastic case of mobile phones is not routinely separated for recycling such that whole phones, minus the batteries, are being sent for smelting. The plastic is then used as ‘fuel’ and also serves as a reducing agent to replace coke in the smelter (see section 3.1.4) (personal communication from the Umicore smelter, Belguim).

3.1 Processes to Recover Metals and Plastics from Electrical/Electronic Waste

Methods are in place for recovering metals such as silver, gold, palladium, platinum, copper and aluminium from electrical/electronic scrap of computers and mobile phones. However, it has been reported that the efficiency with which metals are recovered from printed circuit boards is not high. For instance, most recycling approaches that are practiced can only recover metal contents of printed circuit board scraps to an extent of 28% of the total weight. More than 70% of printed circuit board scraps cannot be efficiently recovered and have to be incinerated or land filled (Li *et al.* 2004). It was noted that it is therefore important to develop recycling techniques that have higher recycling efficiencies.

Recycling processes commonly employed involve a number of separate stages which are discussed below.

3.1.1 Dismantling

The first stage of the process for recovering metals and plastic from electrical/electronic scrap involves dismantling obsolete equipment. In this step, equipment is dismantled and some hazardous components may be removed, such as cathode ray tubes, mercury components and batteries (Zhang and Forssberg 1998). For instance, batteries are generally removed from mobile phones and sent for processing to recover lithium, cadmium and nickel (personal communication from Fonebak). Presently, the next step can involve either mechanical separation techniques or alternatively smelting.

3.1.2 Smelting

One method of recycling printed circuit boards that have been manually separated from electrical/electronic waste is smelting. Copper and lead smelting processes have been used (Legarth 1997). There are a few large smelting operations which are dealing with a lot of electrical/electronic waste. These so called integrated smelters include Boliden in Sweden, Umicore in Belgium, Noranda in Canada and Norddeutsche Affinerie AG in Germany.

Following smelting, further separation and recovery of metals may be carried out using metal refining or hydrometallurgical techniques. Quinet (2005) reports on the experimental development of a hydrometallurgical technique without smelting for the recovery of metal from printed circuit boards in mobile phones.

With regard to pollution from these methods of metal recovery, the smelting process generates atmospheric pollution, whilst hydrometallurgical processes generate great amounts of effluent (Veit *et al.* 2005). Possible hazardous emissions from smelting include certain hazardous metals and brominated dioxins from burning plastics in the printed circuit boards (see sections 4 and 6).

Hazardous wastes from the smelting process include mercury. At Boliden, Sweden, these wastes are currently stockpiled and stored (personal communication).

3.1.3 Mechanical Separation

Following the dismantling stage, an alternative method of metal recovery to smelting/refining is by mechanical separation (Cui and Forssberg 2003, Zhang *et al.* 1998, Veit *et al.* 2005). In more developed countries, mechanical separation processes are far more sophisticated than those used in small workshops in other countries such as China and India. The printed circuit boards are ground up into small particles and then separated magnetically, a process for the recovery of ferromagnetic metals from non-ferromagnetic metals. Further separation may then be achieved by electric conductivity-based separation techniques such as eddy current separation or corona electrostatic separation, the latter process being in its infancy for electronic scrap (Cui and Forsssberg 2003). Electrostatic separation has been used for the recovery of aluminium from chopped electric wires and cables, and the recovery of copper and precious metals from printed circuit boards (Veit *et al.* 2005).

Zhang and Forssberg (1998) reported that, following mechanical separation, the various metal concentrates obtained may then be sent to a smelter for separation of the metals. In an experimental study, Veit et al (2005) reported that, following electrostatic separation of printed circuit board scrap, the metal concentrates obtained could be further treated by a process known as electrowinning which can separate most metals from each other.

During shredding and grinding of electrical/electronic wastes used for mechanical separation techniques, there will be an inevitable formation of dusts containing hazardous metals such as lead, cadmium and beryllium. Workers can potentially exposed via inhalation of the dusts.

In Switzerland, the company Immark, uses mechanical separation techniques for large amounts (25,000 tonnes/year) of electrical/electronic waste. The various metallic fractions go to smelters for further separation. Currently, plastics containing brominated flame retardants are generally not recycled in Switzerland . Instead, at Immark, the separated plastic fraction from the waste goes to a smelter in Belgium (Umicore) to be used as fuel, or to high temperature incineration. At Immark, work is being conducted on separation techniques so that in the future it may be possible to separate plastics that contain brominated flame retardants and plastics that do not.

It is interesting to note that recycling of plastics from waste mobile phones and computers is occurring in the UK according to the few companies involved in the work which were contacted as part of this study. According to another Greenpeace study, plastic recycling from waste electrical/electronic equipment is also known to be occurring in India and China. It is possible that hazardous compounds, namely, brominated dibenzo dioxins and furans, may be formed during the recycling of plastics due to the presence of brominated flame retardants. The amount of brominated dibenzo dioxins and furans produced depends on the processing temperature and the purity of the flame retardant (Hamm *et al.* 2001). A study by Tange and Drohmann (2004) reported that several recycling studies have shown that recycling of plastics containing brominated flame retardants can meet the German regulatory limits on emissions of brominated dibenzo dioxins and furans if proper techniques and controls are used.

3.1.4 Burning of Plastics

According to UK companies that were contacted, some of the plastics that are separated manually from electrical/electronic waste are being recycled. However, Zhang and Forssberg (1998) reported that the mechanically separated non-metal fraction of the printed circuit boards is rich in heating power and can be used for combustion purposes. This may be so but there are environmental concerns with such an approach. The plastics contain brominated flame retardants such that, if used as a fuel for combustion processes, it could result in emissions of hazardous compounds including brominated dibenzo dioxins and furans.

On a similar note, big smelters such as Umicore in Belgium accept mobile phones for smelting which have not had the casing manually separated (personal communication). The casing is burned in the smelter and is said to act as a 'fuel' and also as a substitute for coke that is normally used as a reducing agent in the smelting process.

A report which was commissioned by the Swedish take-back system for electronic products (El-Kretsen) studied whether the 'direct smelter route' for mobile phones was environmentally and economically better or worse than the 'disassembly route' where the casing was manually removed for recycling (Huisman 2004). The calculations in the report were based around sending the phones to the Boliden smelter for processing. The calculations considered transport costs and the costs of recycling. The report concluded that the 'direct smelter route' was the most eco-efficient process. However, the report has been criticised on a number of points by Ökopol, Institute for Environmental Strategies (Sander 2004). This critique noted that the environmental effects of emissions from burning brominated flame retardants in the plastics were not considered in the El-Kretsen report. Also, there were uncertainties with regard to the economic calculation because of a lack of transparency. In addition, it was questioned whether the calculations would be transferable to other smelters and whether the transport costs would be transferable to other countries.

The burning of complete mobile phones in smelters without any pre-processing appears to contravene the current WEEE Directive of the EU, which stipulates the requirement of dismantling before smelting. Furthermore, the possible production of emissions of brominated dibenzo dioxins and furans is a concern for the environment and human health (see section 4). Furthermore, if considered from a waste management perspective, responsible waste management would always lead to selection of materials recovery as the preferred option to combustion or landfilling. Utilization of combustion as the disposal option for mobile phone plastics acts directly against incentives for take-back and greener designs.

3.1.5 Cathode Ray Tubes

Cathode ray tubes (CRTs) are used in television sets and in computer monitors. They consist of a glass funnel, which contains lead oxide in the glass, and on the front of the funnel, a glass plate which contains a high level of barium oxide (but no lead oxide). The funnel section contains up to 25% lead oxide, the neck of the funnel up to 40% lead oxide. Solder glass containing up to 60% lead oxide is used to join the different parts of the funnel together (ICER 2003). Each CRT monitor and TV therefore contains about 0.4 kg and 1 kg of lead respectively in the form of lead oxide (Menad 1999). Research has shown that when CRTs are disposed of in landfill sites, lead can leach from the crushed glass and contaminate ground water (see ICER 2003). This has been one of the major reasons for trying to recycle CRTs. Lead is toxic to plant and animal cells and long-term exposure can be harmful or even fatal (Menad 1999). Cathode ray tubes also contain a fluorescent coating which contains cadmium sulphide and to a lesser extent yttrium and zinc sulphides.

The WEEE directive of the EU sets targets for the recycling of CRTs and in August 2005 will require that producers pay for recycling of waste electrical and electronic equipment from households. Currently, The European Hazardous Waste Catalogue classifies CRTs as hazardous waste and the Landfill Directive requires CRTs to go to specially designated hazardous waste landfills.

The amount of waste CRTs in the UK in 2002 was estimated to be 105,000 tonnes. Estimations for 2012 put the amount of waste CRTs at 100,000 tonnes, which included a lower input from computer monitors due to the shift to flat screen display technology but an increase from TVs because of larger screen sizes (ICER 2003).

The recycling of CRTs is problematic because there is a lack of applications for glass which contains high levels of lead oxide. ICER (2003) noted that some CRTs from end of life computer monitors are sent to a copper-lead smelter in Europe where the glass acts as a substitute for sand in the smelting process. However, experiments by ICER (2003) showed that glass smelting resulted only in a 50 % reduction of lead oxide from the CRT waste and barium and strontium were reduced by 30% and 35% respectively. It was concluded that, under experimental conditions, the removal of lead, barium and strontium to acceptably low levels was not practical. It was noted that smelted waste glass should not be used in applications such as food and drink containers where there are limits on lead, barium and strontium oxides. Another report by ICER (2004) noted that it if CRT glass is used in smelting operations, it is necessary that the lead in the glass can be recovered and that the resulting slag is sufficiently non-toxic to use in secondary applications such as road aggregate. Menad (1999) reported that recycling of CRTs on an industrial scale has been achieved by some companies in Germany and USA. One process used waste CRT glass in the manufacture of new CRTs. Another extracted the lead from CRT glass using a chemical process.

3.2 Processes to Recover Metals, Components and Plastics in Less Developed Countries

A study conducted by Greenpeace at recycling workshops in New Delhi, India and GuiYu, China, has revealed that there are a broad range of processes being widely used in small, back street operations to recover materials from electrical/electronic waste. These small workshops operate with only rudimentary equipment. In India, one technique to recover solder from printed circuit boards involved heating over an open flame, whilst in China, this process was typically conducted by heating on hot plates. Both techniques may cause emissions of metals to air and possible human exposure and likely emissions of brominated dibenzo dioxins and furans from heating the plastics. Following removal of the solder, some of the components of the printed circuit boards were removed for re-use. Other components were ground down mechanically to further recover metals. This process would result in production of dusts containing metals and possible human exposure via inhalation of dusts. In some cases, mechanical shredding of printed circuit boards was carried out to recover metals and plastic was ground down for recycling. Wastes were also burned in open fires to burn off the plastics and recover metals. This process would possibly result in emissions of metals and brominated dibenzo dioxins and furans.

Another technique used in both India and China was acid processing of electrical/electronic waste to recover metals. Waste acids from this process, which contained high concentrations of metals, were dumped directly on the ground or in rivers. This would inevitably result in environmental contamination with acids and metals.

A technique found in China was the shredding of electronic waste followed by vibration to separate out different fractions. Waste fractions from this process were dumped into rivers. This would result in environmental contamination with metals and plastics containing brominated flame retardants.

4. Formation of Brominated and Brominated-Chlorinated Dibenzodioxins and Dibenzofurans from Brominated Flame Retardants

Polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), also known respectively as dioxins and furans, are perhaps one of the most well known classes of environmental pollutants. They are persistent, (resist natural breakdown processes), bioaccumulative, (build up in tissues of animals and humans), and exert a wide range of toxic effects. They are formed unintentionally as by-products of various industrial processes, usually involving chlorine or chlorinated chemicals. One way that dioxins and furans can be formed is by incomplete combustion processes (d'Silva *et al.* 2004) and consequently one of the sources of these chemicals over recent decades has been from incinerators (Stringer and Johnston 2001, Allsopp *et al*. 2001). Although these chlorinated dioxins and furans have dominated pollution issues because they are widespread global pollutants and are extremely toxic, their brominated counterparts are also produced unintentionally by some of the same processes. For instance, brominated dibenzo dioxins and furans (PBDD/Fs) have been detected in incinerator emissions and in fly ash (Birnbaum *et al.* 2003). Studies suggest that PBDD/Fs, and mixed brominated-chlorinated dibenzo dioxins and furans, exert a similar range of toxic effects to their chlorinated counterparts (see text box) (Birnbaum *et al.* 2003, Mennear and Lee 1994).

As discussed in section 3.1.2, one method of recycling waste electronic and electrical equipment is by smelting and refining to recover metals. However, it has been noted that a significant drawback of thermal treatment of such waste is the likely production of dioxins and furans (Luda *et al.* 2005). This is due to the presence of brominated flame retardants in the plastics that can result in the production of brominated or mixed brominated-chlorinated dibenzo dioxins and furans when combusted. There is evidence from laboratory experiments, and from tests at municipal waste incinerators, that the thermal treatment of brominated flame retardants can cause the release of these dioxins and furans as discussed below.

4.1 Thermal Treatment of Brominated Flame Retardants

In a review of various thermal treatments of brominated flame retardants, Weber and Kuch (2003) reported that numerous laboratory studies have shown that the thermal treatment of brominated flame retardants results in the formation of polybrominated dibenzo dioxins (PBDDs) and polybrominated dibenzo furans (PBDFs). For example, heating of two types of brominated flame retardants, namely PBDEs and TBBP-A (tetrabromobisphenol-A), to temperatures of 400 to 800 ^{o}C in ovens or quartz tubes/vials, resulted in the production of PBDD/Fs. These dioxins and furans may be produced directly from the PBDEs and TBBP-A themselves under thermal stress. Alternatively, heating PBDEs and TBBP-A may first cause the formation of bromophenols, chemicals which can then subsequently form PBDD/Fs. For instance, Barontini *et al.* (2004) thermally treated TBBP-A and reported the production of appreciable quantities of 2,4,6-tribromophenol, a possible precursor to PBDDs. Thermal treatment of the another brominated flame retardant, hexabromocyclodecane (HBCD), has been shown to produce low level emissions of PBDFs (Dumler *et al.* 1989).

4.2 Uncontrolled Burning of Brominated Flame Retardants

PBDD/Fs are known to be formed during experimental fires of plastics containing brominated flame retardants and from accidental fires. The presence of bromine in a fire inhibits combustion (Evans and Dellinger 2003). Indeed, it is for this purpose that brominated flame retardants have been developed and are so widely used in electrical/electronic equipment.

Environmental Occurrence and Health Effects of Polybrominated Dibenzo Dioxins and Furans

Polybrominated dibenzo dioxins and furans (PBDD/Fs) occur as trace contaminates in brominated flame retardants and are produced by combustion of these chemicals. PBDD/Fs are also produced when organic substances are incinerated in the presence of bromine such as in municipal or industrial incinerators (Mennear and Lee 1994). There is the potential for the existence of nearly 5000 different bromine containing dioxins and furans: 75 PBDDs, 135 PBDFs, 1550 mixed brominated-chlorinated dibenzo dioxins and 3050 mixed brominated-chlorinated dibenzo furans (Birbaum *et al.* 2003).

Studies suggest that PBDD/Fs may be degraded by light (photolytic degradation) but more studies are needed before any conclusion can be reached. Birnbaum *et al.* (2003) noted that the environmental and human health risk from brominated dibenzo dioxins and furans is difficult to gauge because there is virtually no data on environmental occurrence of these chemicals, whether they persist in the environment or are degraded, and therefore little is known about exposure. Since this was reported, however, one study has detected PBDD/Fs and mixed brominated-chlorinated dibenzo dioxins and furans in air samples taken in Kyoto, Japan (Hayakawa *et al.* 2004) and another has detected PBDD/Fs in human adipose tissue from the general population in Japan (Choi *et al.* 2003). Thus the presence of these chemicals in the environment has been confirmed. The study on air sampling detected trace quantities of PBDDs in air samples but higher quantities of PBDFs and monobromo-polychlorinated dibenzo dioxins and furans. Results suggested that one of the sources of the monobromo-polychlorinated dibenzo dioxins was incineration. Also, the levels of PBDD/Fs in the atmosphere related to that of brominated flame retardants (specifically the polybrominated diphenyl ethers, or PBDEs). This suggested that PBDD/Fs in the atmosphere may arise as impurities of PBDE products or may be formed during the combustion of plastics containing PBDEs. The study on human adipose tissue from Japan noted that, whereas previous research in the United States and Sweden had not found PBDD/Fs in human tissue, salmon or osprey, three PBDD/Fs were detectable in human tissue samples that were tested in Japan. These were 2,3,7,8-tetrabromo dibenzo dioxin and furan, which are known to be toxic to laboratory animals, and 2,3,4,7,8-pentabromo dibenzo furan (Choi *et al.* 2003).

There has been extensive research into the toxicity of polychlorinated dibenzo dioxins and furans (PCDD/Fs), particularly the most toxic congener of this group, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD). There has been less research on PBDD/Fs and mixed brominated-chlorinated dioxins and furans, but studies suggest that biological effects of these brominated compounds are similar to their chlorinated counterparts (Birbaum *et al.* 2003, Mennear and Lee 1994). For example, essentially all of the classic effects demonstrated in animal studies for TCDD and other chlorinated dioxins and furans have also been observed for PBDD/Fs. The effects include lethality, weight loss, thymic atrophy, reproductive effects, enzyme induction, skin lesions and toxicity to the immune system (Birnbaum *et al.* 2003). In addition, PBDD/Fs (like TCDD) are potent developmental toxins in mice, that is, they adversely affect the developing foetus (Mennear and Lee 1994). The mechanism by which toxic effects are caused by PBDD/Fs is the same as PCDD/Fs. Mennear and Lee (1994) noted that PBDD/Fs should also be considered to be human carcinogens like the chlorinated dioxins and furans. In animal experiments, the mixed brominated-chlorinated dioxins and furans have been shown to be equally or even more potent than TCDD in some cases (Birbaum *et al.* 2003).

With regard to humans, there are almost no data on effects of PBDD/Fs (Birnbaum *et al.* 2003). However, from animal data on PBDD/Fs, and human toxicity data of PCDD/Fs, it was suggested that the human health hazards that could be associated with exposures to the brominated compounds include carcinogenicity, developmental toxicity, skin toxicity, liver toxicity, gastrointestinal disorders and toxicity to the immune system (Mennear and Lee 1994). It was also suggested that given the common mechanism of action and effects of PBDD/Fs compared to PCDD/Fs, it is reasonable to predict that exposure to PBDD/Fs will add to the total dioxin body burden (5 ng TEQ/kg body weight), which is already at or near to that where effects may be occurring in the general population (Birbaum *et al.* 2003).

However, the action of brominated flame retardants in inhibiting complete combustion can in turn result in the formation of products of incomplete combustion such as PBDD/Fs. In accidental fires, the presence of bromine will be sufficient to inhibit complete combustion and thus increase the likelihood of the formation of products of incomplete combustion such as PBDD/Fs (Evans and Dellinger 2003). Weber and Kuch (2003) noted that PBDD/Fs are formed in experimental fires of electrical appliances and in accidental fires. In one accidental fire, a high level of PBDD/Fs was present in the residues of a burned TV case most likely because of the combustion of brominated flame retardants in the plastic (Zelinski *et al.* 1993).

A study by Greenpeace in China and India has revealed that solder from printed circuit boards is recovered by heating on hot plates or over a open flame. In addition, some electrical/electronic wastes are burned in fires to remove plastics and recover metals. In all of these processes, brominated flame retardants present in plastic are heated. Considering the laboratory evidence on burning brominated flame retardants, as discussed above, it is highly likely that PBDD/Fs and mixed chlorinated-brominated dibenzo dioxins and furans will be emitted to air from all of these processes.

4.3 Incinerators

With regard to full scale operating incinerators, it has been reported that a very high concentration of PBDD/Fs was detected in a municipal incinerator in Germany during the incineration of printed wire boards (i.e. circuit boards) (Menad *et al.* 1998). This is of great concern since Betram *et al.* (2002) reported that a significant proportion of waste electrical and electronic equipment in Europe is still disposed of as part of the municipal waste stream, a route that includes incineration. This is also a likely scenario in many other countries.

Weber and Kuch (2003) noted that studies have shown that an increase in bromine input during tests at incinerators resulted in increased levels of halogenated dioxins and furans. One of these studies also reported an increase in chlorinated dioxins and furans when waste electronics containing PBDEs was combusted (see Vehlow *et al.* 2000). Interestingly, enhanced formation of PCDD/Fs was also observed in an experimental incinerator in response to the addition of bromine (Lemieux and Ryan 1998).

Several studies have investigated the formation of PBDD/Fs from brominated flame retardants in experimental incinerators. Whereas some studies indicate a link between the presence of brominated compounds in the waste stream and brominated dioxin/furan formation, this is not borne out by all studies. For instance, in some studies on test incinerators, only insignificant amounts of PBDD/Fs were found, but in other cases significant quantities were detected as discussed below.

In their review, Weber and Kuch (2003) note two studies in particular (Sakai *et al.* 2001 and Vehlow *et al.* 2000) which indicate that brominated flame retardants can in fact be destroyed using controlled combustion conditions and that only a limited amount of brominated or mixed brominated-chlorinated dibenzo dioxins and furans are thereafter produced in the resulting flue gases.

For example, Sakai *et al.* (2001) combusted PBDEs, TV casing and printed circuit boards in a laboratory based test incinerator and detected only limited amounts of PBDD/Fs and mixed brominated-chlorinated dioxins and furans in the flue gas and in incineration residues. Combustion of a mixture of TV casing and printed circuit boards yielded a total concentration of chlorinated, brominated and mixed chlorinated-brominated dibenzo dioxins and furans in the output that was less than that detected in the waste itself before burning. Overall, the study showed that PBDD/Fs were destroyed in this incineration system but also stressed that further testing using other furnaces and flame retarded plastics would be necessary in order to draw more general conclusions.

Vehlow *et al.* (2000) combusted municipal waste mixed with waste electrical and electronic plastics in a test incinerator and found virtually no PBDD/Fs in the emitted gas and only limited amounts of mixed brominated-chlorinated dibenzo dioxins and furans. The mixed brominated-chlorinated dioxins and furans that were detected mostly contained one bromine atom and the formation of furans exceeded that of dioxins. However, the formation of bromine containing furans did increase with increasing bromine input in the waste. This suggested that the furans could be produced as a result of the presence of brominated flame retardants in the waste.

Another study at the same test incinerator combusted a mixture of municipal waste with plastics containing brominated flame retardants and reported that the production of PBDD/Fs was not altered by the presence of bromine-containing waste (Tange and Drohmann 2004). However, this later study did not monitor mixed brominated-chlorinated dibenzo dioxins and furans which may have been produced.

Despite the findings summarised above, other studies using test incinerators have shown that brominated and brominated-chlorinated dibenzo dioxins and furans can be produced in significant quantities as a result of the combustion of brominated flame retardants. For example, Funcke and Hemminghaus (1997) used the same test incinerator as Vehlow *et al.* (2000) and Tange and Drohmann (2004), but found that dioxins and furans were produced as a result of the combustion of brominated flame retardants. The study involved combustion of municipal waste and co-combustion of municipal waste with electrical/electronic waste containing brominated flame retardants. When the electrical/electronic waste was added, the quantity of PBDD/Fs and mixed brominated-chlorinated dibenzo dioxins and furans in the flue gas increased. The increase in brominated-chlorinated dioxins and furans correlated with the increase in bromine content of the waste.

In another study, Söderström and Marklund (2002) tested the combustion of municipal waste plus PBDEs, TBBP-A and HBCD in a laboratory scale incinerator. Combustion of all three types of flame retardant resulted in the production of PBDD/Fs and mixed chlorinated-brominated dibenzo dioxins and furans. Mono-, di-, tri- and tetra-brominated and chlorinated-brominated dioxins and furans were produced.

4.4 Smelters

There were no data in the peer-reviewed scientific literature on emissions of brominated or mixed brominated-chlorinated dibenzo dioxins and furans from smelting electrical/electronic waste. Direct communication with personnel at the integrated smelters in Belgium (Umicore) and Sweden (Boliden) who are dealing with electrical/electronic waste by smelting gave some data on dioxin emissions. Information from Umicore explained that chlorinated dioxin emissions were low due to destruction by high temperatures (1200 to 1300 ^{o}C), rapid cooling of the gases and a gas cleaning system. The EC regulatory limit for dioxin emissions from flue gases is 0.1 ng I-TEQ/m^3. At Umicore, it was noted that the characteristic values for 6 hourly measurements are < 0.01 ngTEQ/Nm^3 and monthly measurements are < 0.001 ngTEQ/Nm^3 (personal communication). However, only one measurement of brominated dioxins and furnas had been made. This test was carried out on electrical/electronic waste in which the brominated flame retardant fraction was described as ‘rather modest’. Six polybrominated dioxins and nine polybrominated furans were analysed but none were above the detection limits (in the range of <0.02-<0.09 ng/m^3). Further tests during regular operations of processing electrical/electronic waste at the plant would be needed to confirm whether brominated or mixed brominated-chlorinated dioxns and furans are produced. Presently at Umicore and at Boliden, brominated dioxins and furans are not routinely measured. It is, therefore, likely that other smelters do not monitor these chemicals during the processing of electrical/electronic waste containing plastics. From experimental evidence on incinerators, it is clearly possible that brominated and mixed - brominated-chlorinated dibenzo dioxins and furans are formed during smelting and it would therefore seem logical to monitor them.

The process of smelting of electrical/electronic waste which contains plastics in integrated smelters does result in the production of chlorinated dioxins, even though they are within regulatory standards. It may also result in the production of brominated and mixed chlorinated-brominated dibenzo dioxins and furans which would add to the total dioxin TEQ. The emission of dioxins from smelting electrical/electronic waste clearly represents one drawback of processing electrical/electronic waste by this method because, if dioxin production can be avoided, it should be avoided. It is possible that processing of electrical/electronic waste in smaller smelters, which have less sophisticated technology than the integrated smelters, may result in higher emissions of chlorinated and brominated dioxins and furans. However, there appears to be information on this subject in the published scientific literature.

5. Emission of Metals from Smelters

According to the company Nornada Inc. in Canada, one of the functions carried out at its Horne smelter in Rouyn-Noranda, Quebec, is processing of waste electronic material. A scientific study was undertaken around the site of this smelter to investigate the atmospheric transport and deposition of certain elements from smelter emissions (Telmer *et al.* 2004). The study monitored the levels of 35 different elements in snow up to a radius of 50 km around the smelter in March 1998. Results showed that many of the elements (at least 27) were emitted by the smelter and subsequently deposited on the land. These included some potentially hazardous metals, namely copper, lead, zinc, cadmium, beryllium and nickel. The concentration of many of the substances remained elevated above normal background concentrations even at a distance of 50 km from the smelter. The concentrations of copper and lead near to the smelter were 525 and 353 µg/l meltwater (or ppb) respectively and fell to 2.1 and 3.5 µg/l (or ppb) at a distance of 45 km away. For comparison purposes, background concentrations of these metals recorded in snow samples from urban and rural areas of Canada in the St. Lawrence valley in 1997 were 0.04 to 3.79 ppb for copper and 0.04 to 1.17 ppb for lead (Simonetti *et al.* 2000). Thus the levels of these two metals found in urban and rural areas are two orders of magnitude lower than the levels found near to the smelter.

The study on levels of contaminants in the vicinity of the Noranda smelter was the only published study located in the scientific literature on metal contamination from smelters that process electronic/electrical waste. There is, therefore, a lack of published data on this subject

6. Studies on Occupational Exposure to Metals and Brominated Flame Retardants and Health Effects of Recycling Electrical/Electronic Waste

6.1 Health Impacts

One study has investigated health impacts from exposure to disassembling imported electrical waste in China (Shen *et al.* 2004). The study performed tests on workers who worked in open air disassembly workshops in one town. The study also tested residents from this town, including children. A control group of residents and children from another town where there were no disassembling workshops was also tested. The study found differences in one measure of blood biochemistry, measures of immune system functioning and a measure of chromosome aberration between workers and residents of the town with disassembly workshops compared to residents of the control town. The differences indicated a negative impact on health of the workers and residents of the town with disassembly workshops compared to residents of the control town. The study concluded that disassembling electrical equipment can have a negative effect on certain parameters of health, although clearly could not draw conclusions regarding specific chemical/metal exposures which may have been responsible.

6.2 Exposure to Metals

A study was conducted in Germany on exposure to metals resulting from the manual disassembly of waste electrical/electronic equipment at five different companies (Faller *et al.* 2001). Dust exposure was identified to be the core problem. Metals that workers were exposed to included cadmium, lead, nickel, copper and silver. The study noted that, at the time of the study (1998), it was not possible to guarantee that concentrations of mixed metals would fall below the legal limit at these workplaces.

6.2.1 Potential Exposure to Metals and Health Effects

Exposure to metals present in electrical/electronic waste may occur at smelting facilities due to dusts from the raw waste and due to fumes during the smelting process. In this regard, hazardous metals such as beryllium, cadmium, lead and mercury are of particular concern due to their toxic potential. A search of the scientific literature did not reveal any studies specifically on exposure from smelting of electrical/electronic waste.

In India and China, a wide range of processes are being used in small workshops to recover materials from electrical/electronic wastes. There are several potential routes of exposure to metals from these operations. These include exposure to dusts from mechanical shredding and grinding of electrical components. Possible exposure to metal fumes and particulates may also result from burning wastes and from heating printed circuit boards on open flames/hot plates.

6.2.2 Beryllium

Exposure to beryllium can lead to health impacts. Studies on workers involved in the refining and processing of beryllium and its compounds note that fumes and dusts of beryllium and beryllium oxide can be produced. Subsequently, the main route of beryllium exposure for workers in these industries is inhalation (Field 2001). Exposure can cause chronic beryllium disease (CBD), a debilitating and potentially fatal condition that mainly affects the lungs (Infante and Newman 2004). CBD has been identified in workers even after low exposure. For example, CBD was found in workers whose average beryllium exposure levels were 20-100 times lower than the current permissible limit (Kelleher *et al.* 2001). Even individuals with bystander exposures such as secretaries, security guards and inspectors can contract the disease (Infante and Newman 2004). Workers can also carry beryllium dusts away from the workplace on their clothes and shoes, exposing their family members (Cohen & Positano 1986, Sanderson *et al.* 1999). There are reported cases of the spouses of beryllium workers developing beryllium sensitivity and chronic beryllium disease (CBD) (Knishkowy & Baker 1986). Although symptoms of CBD can be suppressed with steroids, the disease is currently incurable (Field 2001). Beryllium has also been classified as a human carcinogen on the basis of increased rates of lung cancer in beryllium production workers (International Agency for Research on Cancer 1993).

Exposure to beryllium may occur during the recycling of electrical and electronic equipment containing beryllium-copper alloys. Beryllium dusts may be generated during shredding and grinding, and fumes may be generated during high temperature processes such as those used at metal refineries (Basel 2004, OECD 2003). Infante and Newman (2004) reported that recycling of electronics and computers to recover copper results in beryllium exposure of an unknown number of workers, many of whom are unaware of the risks. There are no studies which directly relate to exposure to beryllium from recycling only electrical/electronic waste, though one study was carried out on exposure to beryllium at a precious metals refinery where waste printed circuit boards were among the materials that were handled (Cullen *et al.* 1987). The study monitored exposure to beryllium by analysing for the metal in air filtering devices. The study showed that there was exposure to beryllium in the furnace area and also a much higher exposure in the area where printed circuit boards were crushed prior to going to the furnace. The study commented that, in the milling/crushing area, beryllium would be in the form of dusts, whereas in the furnace area it would be in the form of beryllium oxide in fumes. Four of the workers in the study were found to have CBD. This resulted primarily from exposure in the furnace area not the milling area. These results suggested that the exposure to beryllium from the fumes of the high temperature operation were more pathogenic than exposure from “cold” milling operations. It was noted that this is consistent with other studies which found that “cold” working of alloys rarely causes CBD. The study also monitored exposure to other metals and found there was moderate exposure of workers to cadmium, nickel, lead and arsenic at the plant.

Another study showed that exposure to beryllium copper alloy, with no other beryllium exposure, resulted in two cases of CBD in workers (Balkissoon and Newman 1999). The study also noted that beryllium sensitization had occurred in workers with exposure to this alloy. Beryllium sensitization may ultimately develop into CBD (Field 2001).

At the Boliden smelter, where electronic waste is smelted, levels of beryllium are routinely monitored and are apparently below regulatory limits (personal communication). Data from other smelters could not be obtained. It is nevertheless of concern for all workers at smelters who are processing electrical/electronic waste that chronic beryllium disease has been found in workers whose exposure levels were well below regulatory limits.

6.3 Exposure to Brominated Flame Retardants

Brominated flame retardants include PBDEs, HBCD and TBBP-A. The majority are environmentally persistent and some are bioaccumulative. Research in laboratory animals has shown that some of these chemicals exert a wide range of toxicities including adverse effects on development (Eriksson *et al.* 1999), the nervous system (Mariussen and Fonnum 2003), the immune system (Darnerud 2003) and the reproductive system (Birnbaum and Staskal 2004) and may interfere with thyroid hormone binding (Meerts *et al.* 1998, 2001).

Personnel involved in electronics recycling in Sweden have been shown to have elevated blood levels of the PBDEs (Sjödin *et al.* 2003). The brominated flame retardant TBBP-A was also measurable in blood of the workers. In the electronics recycling facility, elevated air concentrations of PBDEs and TBBP-A were also found, possibly as a result of the use of pneumatically operated power tools for dismantling machinery which mobilizes large quantities of dust that has accumulated within the electronic equipment. The dust represents a possible route of occupational exposure to the chemicals. The half-lives of certain PBDEs and TBBP-A were estimated by blood sampling from the electronics recycling workers. The half-lives of the PBDE congener BDE-209 (decabromodiphenyl ether or "deca") and of TBBP-A were short, respectively one week and 2 days. The half-life of BDE-183 (an octabrominated congener) was longer, estimated to be 3 months. Another study on a limited number of electronic recycling workers in Norway showed that the exposure was less pronounced than in the Swedish study, possibly because respirators were worn by the workers in Norway (see Sjödin *et al.* 2003).

7. Conclusions

There are two main goals of modern waste management: to protect human health and the environment, and to conserve resources such as materials, energy and space (Betram *et al.* 2002). Presently, there are problems with meeting both these criteria using current methods for recycling electrical/electronic waste:

- In India and China , metals are being reclaimed from electrical/electronic waste by heating techniques, shredding and grinding. Shredding and grinding will result in formation of metal dusts while heating may cause emissions of metal fumes and particulates. It is of great concern that workers may be exposed to hazardous metals such as lead, cadmium, mercury and beryllium from the processes being used and that environmental contamination may occur. In addition, environmental contamination with hazardous metals and brominated flame retardants in plastics occurs from direct dumping of wastes from such processes. This includes dumping of acidic solutions containing high concentrations of metals both on the ground and to rivers. Processes in which electrical/electronic waste is burned in open fires, or where printed circuit boards are heated to recover solder, will most likely result in the emission of PBDD/Fs or mixed brominated-chlorinated dibenzo dioxins and furans which are a hazard to the environment and to human health.

- In some more developed countries, electrical/electronic waste is being sent to smelters to reclaim metals. In the case of one integrated smelter in Canada, a study has shown that hazardous metals were deposited on the surrounding land, with elevated levels detectable up to 50 km away. In addition, workers at smelters may be exposed to hazardous metal fumes such as beryllium oxide and possibly other hazardous metal fumes. At integrated smelters, plastic from mobile phone cases and from printed circuit boards may be burned, resulting in the formation of chlorinated and possibly brominated or mixed brominated-chlorinated dibenzo dioxins and furans and their emission to air and/or to ashes. Although the emissions of chlorinated dioxins and furans are reported to be within regulatory standards, the emission of these compounds is undesirable and the quantities of brominated dioxins and furans emitted remain unknown. Furthermore, from a waste management point of view, the recycling and re-use of plastics is preferable to burning in smelters.

- In some countries, electrical/electronic waste is mechanically treated to recover metals and plastics. Techniques employed in the initial stages of for mechanical treatment, such as shredding or grinding the waste, can result in exposure of workers to brominated flame retardants and hazardous metals from dusts.

To overcome the problems inherent in dealing with electrical/electronic waste, it is necessary to change radically the design of the products. Firstly, there is a need to remove hazardous chemicals and metals. In Europe, the Restriction of Hazardous Substances (RoHS) Directive will require electronics manufacturers to stop marketing products containing cadmium, lead, mercury, hexavalent chromium and the brominated flame retardants PBDEs and PBBs from July 2006. While this is extremely important, further measures are needed to safeguard human health and the environment both in Europe and on a global basis.

In order to facilitate truly sustainable reuse and recycling of electrical and electronic equipment and to avoid adverse health and environmental consequences of handling the resulting waste, it will be necessary to replace all hazardous substances currently in use with less hazardous, preferably non-hazardous, alternatives at the design and manufacturing stage. This requirement must include all brominated flame retardants, in order to avoid the potential for formation of brominated by-products such as dioxins and furans, and all hazardous metals . In addition, UNEP (2004) suggest the need for increased use of renewable materials, such as bio-based plastics, in future construction of electrical and electronic equipment.

As a second prerequisite, the design of electrical/electronic products must be changed so that the product components can be efficiently and completely recycled. For instance, products should be adapted so that they are easy to dismantle (Boghe 2001) and should only contain recyclable parts and recoverable metals (Li *et al.* 2004). Design should enable simple mechanical separation for recycling of all parts and should, therefore, negate the burning of plastics in smelters.

Both the removal of hazardous components from electronic products, and the re-designing for complete recycling ability, are measures that need to be adopted by manufacturers globally.

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