PROVIDING SOUND RECOMMENDATIONS ON HAZARDOUS EMISSIONS DURING E-WASTE MANAGEMENT: REDUCING ADVERSE HUMAN AND ENVIRONMENTAL HEALTH EFFECT IN TAIWAN

The flame retardants, Polybrominated Diphenyl Ethers (PBDEs) as a case example

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Abstract

Waste electrical and electronic equipment (e-waste) accounted for an increasing waste stream, both in growing rate and volume, during the past three decades. The compositions of e-waste include various metals and organic chemicals (used as plastics and additives like flame retardants). To recycle and/or reuse these metals or plastics from e-waste, industrial processes must dismantle, shred, and separate components. Such physical actions create hazardous exposure to human workers and the environment. This project was built on literature reviews regarding e-waste management and focuses on the problems of occupational exposure to toxic components present in e-waste streams. A class of toxic flame retardants, polybrominated diphenyl ethers (PBDEs), has been chosen. In this report I provide more definition of the problem and characterize PBDEs in the e-waste management in Taiwan, where I am from. Based on this information, I propose recommendations to minimize PBDEs exposure in the e-waste recycling systems.

While shredding e-waste to retrieve materials, PBDEs are released from plastic components into air, and/or partitioned to atmospheric or dust particles. Workers thus become a high-risk exposure group from inhalation and ingestion pathways. Due to the ability of bioaccumulation, PBDEs pose an ongoing threat to exposed individuals. Also of concern is exposure to children due to the known effects on developmental neurotoxicity. Two commercial PBDEs, penta- and octa-BDEs, were banned or phased-out from use since 2004. The third mixture, deca-BDE, is scheduled for phase-out in 2013. Improved worker safety can reduce occupational exposure. However, dust carried to households of workers can be transferred to other family members, particularly children. In addition, attention to women workers of childbearing age can reduce exposure to the most vulnerable individuals.

The Taiwan Environmental Protection Administration (TEPA) mandated e-waste recycling from 1998. Total of 22 registered facilities handled about 4.25 million e-wastes devices in 2010. Although Taiwan has reached an average recycling rate of over 50%, the items on recyclable in Taiwanese regulations represent only a small portion of those in the Waste Electrical and Electronic Equipment (WEEE) Directive. If worker safety can be improved, a greater proportion of used components can be recycled. Thus, improving occupational safety is critical.

Recommendations made in this report include: use of proper personal protective equipment such as barrier clothing (i.e., aprons, high visibility shirts), dust respirators (N-95) and fabric gloves, improved workplace ventilation to filter out contaminated dust, requirement for separated storage lockers for worker protective devices and clean clothing. In addition, showering prior to donning individual street clothing and departure for home should be required. Furthermore, the hazardous substance guidelines in the processing facilities are not strictly framed. Regulated certification and inspections to ensure compliance auditioning should be performed regularly to prevent hazards exposure. Monitoring of PBDE levels of workers and in the working place is essential. With careful attention to the above, worker safety will be enhanced and exposure minimized while providing a means to recycle valuable materials from e-waste.

Key words: e-waste, flame retardants, occupational health and safety, PBDEs, neurodevelopmental toxicity, occupational exposure

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Chapter 1. Introduction

For most products developed, marketed and discarded by humans, consideration of their impact on the environment during manufacture, use, and disposal should be evaluated. As we shall see below, some products do not consider these endpoints. For example valuable components of electronic wastes (hereafter referred to as – "e-waste") favor their recycling and re-use. Therefore, potential impact on the environment from the removal of valuable components, their recycling/re-use in a second generation of products and – more importantly health of workers performing those procedures, also need to be considered. Companies exist for retrieval and recycling/resale of components. During acidic extraction of metals and shredding of plastic components, volatilization of priority pollutants may occur. Although there are important issues with metal toxicity in e–wastes, it is my intention to focus on an investigation of human health effects in occupational exposures to organic chemicals found in e-waste, specifically flame retardant compounds. I made this selection after reviewing various methods to detect organic pollutants in the environment near recycling plants. This would have involved evaluating passive sampling devices and other collection procedures. However, my major interest has now developed into a consideration of occupational safety in e-waste recycling.

There are instances where workers in e-waste facilities have become exposed to substantial amounts of flame retardants such as the polybrominated diphenyl ethers (PBDEs) (Sjodin et al. 1999, Bi et al. 2007, Qu et al. 2007, Wang et al. 2010a, Rosenberg et al. 2011). Governmental agencies in the United States of America and the European Union have produced documents related to recycling platform and industrial health and safety in e-waste management. The European Union (EU) enacted Directives on the Waste Electrical and Electronic Equipment (WEEE), and the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) (European Union 2003a, b). California first established Electronic Waste Recycling Act in 2003 in the United States. Currently 25 states in the US have the e-waste laws (NCER, 2011)

Taiwan, a small island (36, 008km^2) having one of the world's highest population density (668 people/km^2), is inhabited by 23 million people and receives between 2.3 and 4.25 million e-waste items annually (TEPA 2009). E-waste disposal and handling faces two problems: limited landfill capacity and possible hazards from contaminant exposure to communities near landfills and incinerators. Unregulated or uncontrolled disposal and processing procedures lead to exposure to toxic substance in the environment. Thus, these issues further threaten the limited natural resources in Taiwan.

While the environmental release of organic pollutants from e-waste facilities is worthy of consideration, my emphasis is on occupational safety and health. If workers can be adequately protected in the workplace environment and taught how to prevent transfer of toxic organics from the workplace to the home, the entire family and local citizens can be protected. To do this, I first considered the toxicity of one class of organic pollutants associated with e-waste, polybrominated diphenyl ethers (PBDEs). As will be described below, certain PBDEs are particularly toxic. They can persist and bioaccumulate in the environment. When women of childbearing age work with e-waste, they may be exposed and it is possible that the fetuses can also be exposed. If work place dusts containing these toxins are transferred to the home on clothing of workers, infants and toddlers may be exposed. The major concern is developmental neurotoxicity and thyroid hormone deregulation caused by certain of the PBDEs. Therefore, contaminated dusts carried by workers into their households pose real threats to their children. From the above, there are safety precautions that can be taken in the workplace and other procedures to decrease transfer of contaminants to the home. As discussed, occupational safety education for the workers, personal protective equipment, occupational hygiene and reduction of transfer of work-related dust particles are key elements to protect individuals. Because regulations exist regarding the components of flame retardants that may be used, it is necessary to understand specific characteristics of PBDEs. The recycling of e-waste means that for a given period of time old, non-regulated and often toxic forms of PBDEs are brought into the recycling stream with outdated electrical equipment. This means that any toxicity assessment of e-waste must consider banned forms of PBDEs as well as the new collections with current use flame retardants.

Based on this information, the major focus of this report is directed to the workplace environment. This does not minimize potential concern for environmental pollution, including terrestrial and aquatic biota. Simply stated, I emphasize the occupational safety and health concerns in this masters project.

Chapter 2. Objectives and Methods

The principal objectives for this project are:

1. Review current global regulations for the management of e-waste;
2. Evaluate potential threats to human health, from exposure to the flame retardants PBDEs in e-waste; and
3. Provide recommendations to create best management practices for managers of e-waste recycling companies in Taiwan.

This project reviews literature in different fields, such as research papers, legal documents, and government or industrial reports to provide overview of issues related to e-waste recycling, both globally and in Taiwan specifically. Exposure risks and human health hazards associated with exposure to PBDEs will be discussed on the basis of potential human exposure through inhalation and accidental ingestion.

PBDEs exposure and toxicity to experimental animals and human will be reviewed to determine risk groups and routes of contact/exposure. Finally, recommendations will be made for future Taiwan e-waste management industries and government.

Chapter 3. Waste Electrical and Electronic Equipment (e-waste)

Background

With the development of new technologies, the life span of electrical and electronic products (e.g. mobile phones, computers, MP3, televisions, refrigerators, etc.) has become shorter and shorter. This means that e-waste volume has proliferated in recent decades, and increased at a more rapid speed. In 1997, it was estimated that 20 million personal computers (PCs), about 7 tons, had become obsolete. But by 2004, this number had increased to over 100 million PCs (Puckett and Smith 2002). Importantly, PCs only account for a fraction of all e-waste. O'Connell estimated in 2002 that about 130 million mobile phones would be discarded in 2005 (O'Connell, 2002). Similar quantities were expected for all kinds of portable electronic devices, such as personal digital assistants (PDAs), MP3 players, computer games and peripherals (Widmer et al. 2005).

Consideration of toxicity issues with e-waste

One obsolete PC with a cathode ray tube monitor consists of metal (43.7%), plastics (23.3%), other electronic components (17.3%) and glass (15%) (Berkhout and Hertin, 2004). Within the metals, there are highly toxic lead, mercury and cadmium; and, precious metals such as silver, gold, copper, and platinum. Within the plastics, we find polybrominated diphenyl ethers (PBDEs) used as flame retardants. Inappropriate dismantling, storage and transporting e-waste may result in human and environment exposure to those hazardous materials. With importing and exporting activities of e-waste between nations, this increasingly large stream of hazardous waste in transport poses a threat at a global scale. For example, Robinson (Robinson 2009) assumed a global e-waste production of 20 million tons per year which would result in an annual global emission from e-waste recycling would total of 198,000 tons of chromium, 820,000 tons of copper, 206,000 tons of nickel, 102,000 tons of zinc and about 50,000 tons of lead and tin respectively. This possibility for pollution is obviously a critical ecological and human health problem. On the upside, recyclers retrieve copper and other precious metals permitting their reuse thereby decreasing the amounts of new ores that must be mined. Clearly, safe recycling and reuse of e-waste would be benefit both internationally as well as locally.

E-waste definitions (Comparison list: Taiwan vs WEEE Directive (EU))

The European Union (EU) Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EC) was adopted in 2003 and came into effect in 2005 (EU, 2003a). This important document provided a list of e-waste products in 10 categories. According to this list, e-waste includes any equipment with an operating voltage (Vop) lower than 1, 000V AC or 1, 500V DC. Specific categories include: household appliances such as, refrigerators, TVs, blowers, toasters, washing machines and electronic devices such as computers, medical devices, dispensers, monitoring and instruments, etc. " Waste management" refers to processes that reuse or recycle materials and to the control of associated hazardous substances.

However, as is important in my master's project, the current e-waste recycling list for Taiwan (see Appendix Table 1) does not include all equipment listed on the WEEE directive. By current Taiwan regulations, only large household appliances, refrigerators, TVs, computers, mobile phones, laser disks, and lightening devices (i.e. light bulbs) are required for recycling. Currently, the average recycling rate in Taiwan is over 50% but the energy recovery rate is only 30% for plants that process e-waste in Taiwan (TEPA, 2007). Typical recycling process includes dismantling, shredding and separation. Resulting resources include copper, iron, aluminum, glass and plastics which are then reused in metal smelting plants, glass plants and/or related reuse factories.

Taiwanese government mandated e-waste recycling under the Waste Disposal Act from 1998. For the last few years, the average recycling rate is over 50 % (TEPA, 2007). Until 2010, 17.5 million domestic appliances and 23.6 million electronic devices have been recycled. In 2010, overall 5.3 million devices entered e-waste recycling facilities. Fig. 1 shows the e-waste recycle amounts during the past years, after the Waste Disposal Act took effect in 1998.

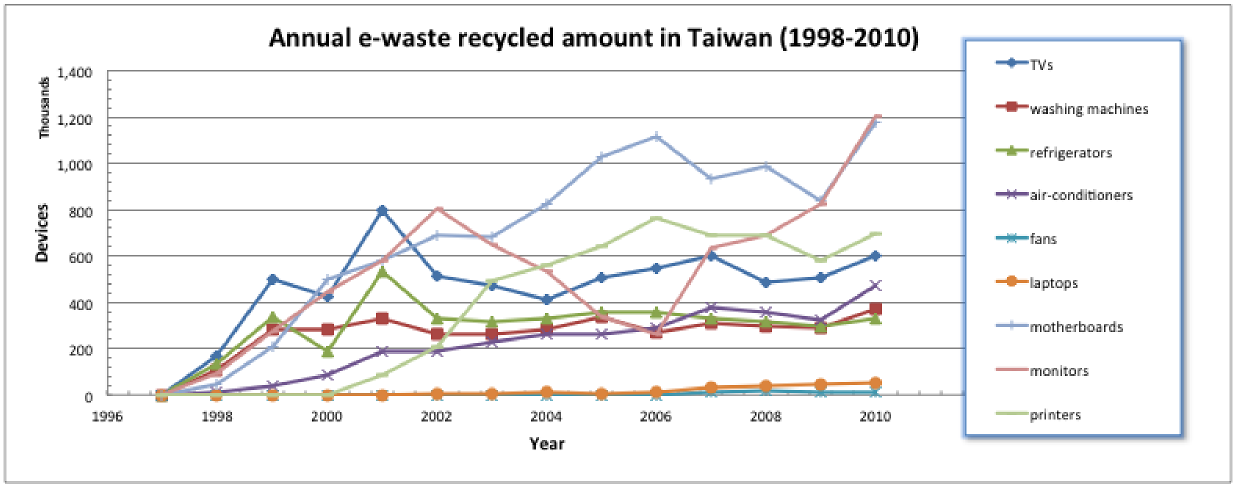

Figure 1E-waste recycling amount during from 1998-2010 in Taiwan. (Recycle Fund Management Board, Taiwan. http://recycle.epa.gov.tw/Recycle/index2.aspx)

Fig. 2 shows the current e-waste recycling plants and their locations in Taiwan. There are totally 22 registered plants responsible for recycling e-waste in Taiwan. All of the plants are close to regional industrial parks. Three plants are in the northern part around Taoyuan, which is the neighbor of Taipei, the capitol of Taiwan with a population of 6.5 million people (National Statistics R.O.C., 2010). Guanyin Township, in Taoyuan has a long history of waste scrap industry. Two other plants are located near HsinChui County, the main computer industry area of Taiwan. FDG and KeBaiSheng are within the third largest metropolitan area, Taichung. The others are in Kaohsiung, the second largest city (2.7 million people (National Statistics R.O.C., 2010)) in Taiwan. Kaohsiung has a long history of heavy chemical industry. Red pins include 9 facilities located close to each other in Dalian District in Kaohsiung.

Figure 2 Registered e-waste handling facilities in Taiwan. Red pins represent 9 facilities locate close to each other in Dalian District in Kaohsiung. (Google map)

International efforts to regulate e-waste practices and their application in Asia

E-waste is under the regulation of the Control of Transboundary Movements of Hazardous Wastes and their Disposal, which was initiated in 1992 after an internal consensus in the 1989 Basel Convention (Widmer et al. 2005). The exporting countries now have to ensure that hazardous wastes are managed in an environmentally sound manner in the receiving countries (i.e., those countries that will dispose of the wastes while reclaiming valuable components). In 2003, the European Union enacted WEEE Directive to set goals on e-waste collection, recycling and reuse. WEEE Directive requires the market electrical and electronic products manufacturers to consider the human health and environmental problems when their products become obsolete. The producers are to enforce more environmentally sound processes and designs, and incorporate the Extended Producer Responsibilities (EPR) for the recycling and reuse of the e-waste from their own products. In 2006, Restriction of Hazardous Substances (RoHS) Directive took effect with respect to processes used in manufacturing in the European Union.

In Asia, Japan's National Institute for Environmental Studies (NIES) organized an e-waste workshop in 2004. They discussed the specific problems in Asian countries (Terazono et al. 2006). Some Asian countries (i.e., China and India) have received a substantial e-waste flow from developed countries in Europe and the United States. On the other hand, countries with small territories, such as Japan, Taiwan, and the Republic of the Philippines, quickly faced limitations of capacity for e-waste storage. Also, for Japan, Korean, China, India, and Taiwan, large fractions of their economies are related to electronics manufacturing. Therefore, an open and interactive platform of experience and interchange regarding e-waste management (reuse, recycle, and reduce) and regulation would have benefits in these countries. Nonetheless no major international agreements regarding e-waste export or recycling came from this 2004 workshop.

How waste management works in Taiwan

In Taiwan, Executive Yuan Environmental Protection Administration began to enforce e-waste recycling in 1997 (TEPA, 2007). Oversight includes all facilities as shown in the map of Taiwan (Fig. 2). The Taiwanese government established a recycling fund which supports and enforces a "Four-in-One" recycling policy to oversee recycling of more than 50% of local e-waste (i.e., those products used in Taiwan). "Four-in-One" policy also incorporates community, local governments, recyclers, and funds for recycling. This includes domestic households as well as community facilities. This policy mobilizes their garbage classification, transportation garbage and separates recyclable from non-recyclable wastes. Local governments are to provide subsidies to the communities to encourage continued recycling activities. Individual recyclers (recycling industries) purchase materials from communities and manufacturers. Recycling funds can be used to subsidize policy establishment, regulate the recycling responsibilities, and add money to maintain the first three components of the "Four-in-One" policy (TEPA, 2007). Figure 3 provides additional information and the movement between the various components of the "Four-in-One" recycling system in Taiwan.

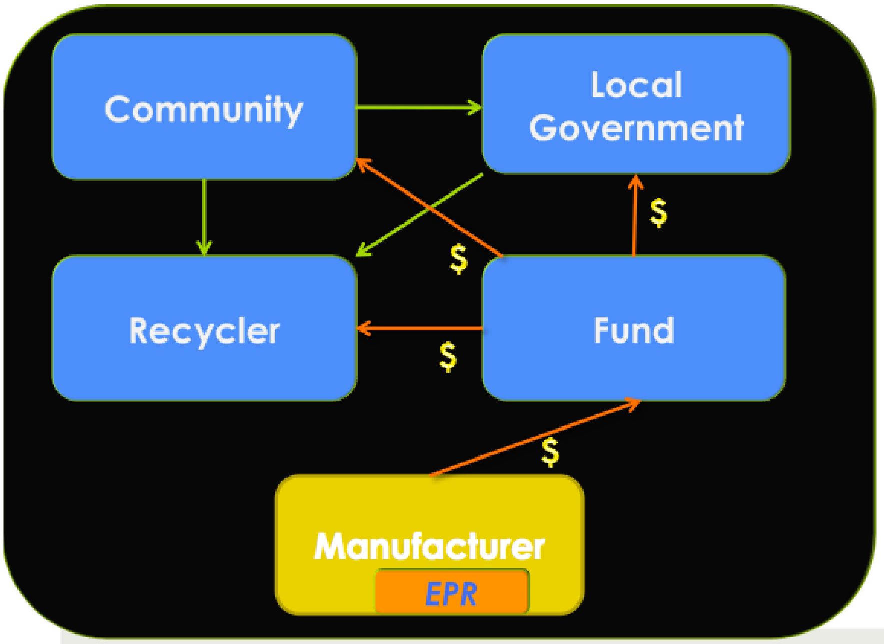

Figure 3 Material and monetary flows in the recycling system in Taiwan. (extracted from Taiwan EPA, http://ivy1.epa.gov.tw/3ok/history03.htm). Green arrows are material flows. Orange arrows are monetary flows.

Figure 4 describes the e-waste management system in detail (. This illustrates the handling processes related specifically to e-waste. After collection (see upper left hand box) from recycling facilities, the incoming wastes are tested and sorted. The local cleaning crew transport sorted waste equipment to dismantling plants. For those with plastic outer shells, such as computer and integrated circuit (IC) boards, dismantling begins and the outer and inner portions of the equipment are separated. The next step involves shredding of plastic components to downsize. After shredding, individual workers identify and separate (at a minimum): fingerglass plastic powders; copper; iron; tin; and lead. After identification and refining procedures, precious metals (i.e., gold, silver, palladium) are selected for sale and recycle/reuse on the market. The non-recyclable materials are entered landfills or incinerators.

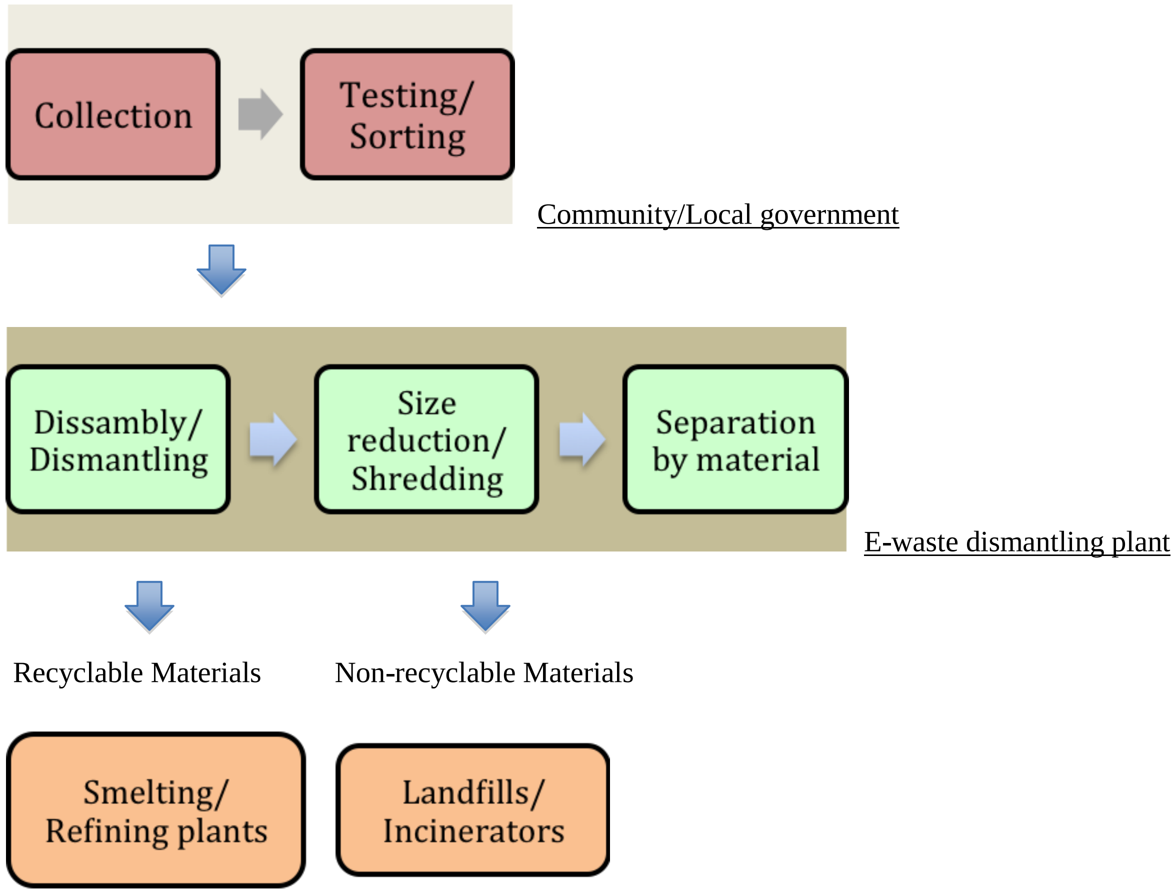

Figure 4 E-waste management processes (adapted from Kang (Kang and Schoenung 2005) and Taiwan EPA websites)

Summary

The above description of e-waste, and the international and Taiwan recycling efforts are important for an overall understanding of the process and various flows associated with e-waste. However, within e-waste management and recycling, I focused on the problems and solutions regarding the PBDEs, an additive flame retardant component in e-waste, which is not recycled but must be dealt during recycling and disposal processes.

Chapter 4. The PBDE Issues in E-waste

Flame retardants

Flame retardants are added to furniture, building materials (i.e., insulation, carpet pads, textures, upholstery/frames), vehicles and electronic/electrical equipment to reduce their flammability. Many of these chemicals are brominated flame retardants (BFRs). Electrical and electronic equipment contains over 1,000 types of BFRs (Herat 2008). Some of these include tetrabromo bisphenol A (TBBPA), hexabromocyclododecane (HBCD), and polybrominated diphenyl ethers (PBDEs).

In a report in 2000 from Bromine Science and the Environmental Forum (BSEF), the major use of BFRs globally was associated with the manufacture of electrical and electronic equipment. This accounted for 56% of BFRs. Nearly two-thirds (59%) of BFRs were used in the housings of electrical and electronic equipment. 30% were in printed wiring boards, 9% were in connectors and relays, and 2% were in wire and cabling (Herat 2008).

Polybrominated diphenyl ethers (PBDEs) as flame retardants

Polybrominated diphenyl ethers (PBDEs) were the largest category of BFRs in the market (BSEF, 2000). Three common market mixtures of PBDEs were penta-BDE, octa-BDE, and deca-BDE. Each of these three manufactured products consisted of mixtures of different PBDE congeners. For example, a penta-BDE, 2, 2’, 4, 4’, 5-pentabromodiphenyl ether (BDE-99) was 43% of the mixture while 2, 2’, 4, 4’-tetrabromodiphenyl ether (BDE-47) was 27%. An octa-BDE contained 44% heptabromodiphenyl ether (BDE-183) and 21% unidentified octa-BDEs. And deca-BDE was almost exclusively 2,2’,3,3’,4,4’,5,5’,6,6’- decabromodiphenyl ether (BDE-209). Widespread use of the above congeners has led to their being reported in environment media worldwide (Peng et al. 2007).

As flame retardants, octa-BDE and deca-BDE, have historically been applied to acrylonitrile-butadiene-styrene (ABS) in computer casings and monitors and to high-impact polystyrene (HIPS) in TV cabinets, and were more commonly applied to electronic and electrical equipment than the flame retardant mixture known as penta-BDE, which was used mainly in flexible polyurethane foam (PUF) (Herat 2008). Actually, deca-BDE can make up 10 to 15% of the plastic casing of a television (Lassen et al. 2006).

Chemical structure of PBDEs

PBDEs are similar in chemical structure to another form of persistent organic pollutants (POPs), the polychlorinated biphenyls (PCBs), and are named using the same IUPAC numbering scheme.

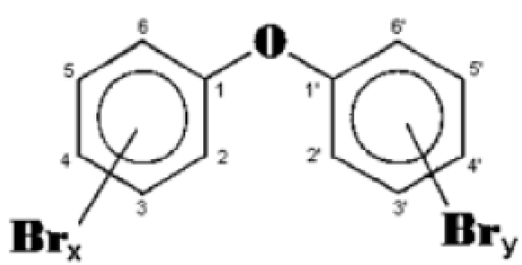

Figure 4 General chemical structures of PBDEs (x + y = 1 to 10). (from Costa, 2008)

PBDEs are more polar than PCBs because of the presence of the oxygen atom and the resultant asymmetric plane. The physicochemical properties of PBDEs differ based on the degree of bromination. The commercial PBDEs have boiling points ranging between 310 and 425°C.

PBDEs with fewer bromine atoms (e.g., BDE-47) usually have lower molecular weights, are smaller in size, and more soluble in water than PBDEs with larger numbers of bromine atoms (e.g., > 6). However, highly brominated PBDEs (e.g., BDE-209) can be broken down to lower brominated congeners abiotically and in biota via debromination transformation mechanisms (Zhao et al. 2008).

Historical usage and occurrence of PBDEs

Because of a continuingly large annual consumption and increasing levels found in the environment and in animals including humans, PBDEs are receiving more and more attention in the past two decades. Five congeners, BDE-47, -99, -100, -153, -154 are particularly predominant in biota and in human tissue (Costa et al. 2008). PBDEs have been found in mussels, fishes, human serum, breast milk, and are clearly ubiquitous pollutants. PBDEs are persistent and they can bioaccumlate. PBDEs can also biomagnify as they move up the food chain.

In 2003, the Europe Union banned penta-BDE and octa-BDE marketing and use, which became effective in 2004 (EU 2005). Deca-BDE is still widely used while several risk assessment reports and investigation are ongoing. However, it should be remembered that within e-waste recycling facilities, old (i.e., likely to contain currently banned PBDEs) as well as newer electronic equipment will be found. This means that worker safety in these facilities must consider both banned as well as currently approved forms of PBDEs.

Environmental fate and distribution of PBDEs

PBDEs are additive flame retardants, meaning they are not chemically bonded to the plastic resins in electronic and electrical products. Thus, PBDEs are more likely to be removed from products during dismantling and other related procedures. It should be noted that, for example, about 10-15% deca-BDEs by weight exist in the plastic components of TV casing. Thus, wastes produced may contain appreciable amounts of PBDEs (Lassen et al. 2006). These could enter the workplace and/or the greater environment, or be taken up and be bioaccumulate in various species. Not all PBDEs have similar solubility characteristics. Those with lower bromine numbers are more soluble, and are believed to be more toxic. Put another way, the common PBDEs in aquatic environments are those with lower bromine numbers. In a survey of riverine, estuarine, and oceanic water in Japan in 1977, and again from 1987-1988, there was no finding of higher brominated PBDEs such as hexa-, octa- and deta-BDEs at all (Watanabe and Sakai 2003).

Major sources for dietary exposure are fish, meat, and dairy products. These came through the consumption of contaminated food items. Major sources for adults in the United States are meats, while in European countries, it is fish (Schecter et al. 2004).

Airborne -- Because of their very low vapor pressures (3.85-13.3 Pa at 25°C), PBDEs are stable solids at room temperature. PBDEs with higher bromines are more likely to adsorb to air particles, and have short transportation distance. On the other hands, those with lower bromines have higher vapor pressure than the higher brominated compounds and are more likely to present in gas phase. This means they are likely to be detected at higher concentrations in the air, and are capable of long-distance transportation. Tetra- and penta-BDEs were two major species in the Great Lakes and Arctic areas (Strandberg et al. 2001). However, deca-BDE was found at 50 folds higher levels then tetra- and penta-BDE in a Singapore study (Tan et al. 2007). In the surrounding air sample from e-waste dismantling plants, deca-BDE accounted for 99% of PBDEs (Sjodin et al. 2001). By contrast, the concentration of PBDEs with higher bromines was substantially greater in sediments due to low solubility and resultant deposition in humic organic materials and suspended particles. In addition, effluent and sludge from municipal sewage treatment plants were often used as fertilizer on agricultural lands, or by way of irrigation. These were physical means of introducing PBDEs to soils (de Wit 2002).

Photodegradation and debromination of PBDEs in different environmental media have been observed (Fang et al. 2007, Stapleton and Dodder 2008). However, it is possible for PBDEs to become even more toxic as occurs through their incomplete pyrolysis during incineration. In this instance polybrominated dibenzofurans and polybrominated dibenzodioxins (PBDFs/PBDDs) may form. These are even more toxic than PBDEs (Agency for Toxic Substances and Disease Registry 2004). This is described in greater detail below.

General and occupational exposure of humans to PBDEs

Infants and toddlers represent the two most susceptible groups to toxic effects from PBDEs. The exposure is mainly from breast milk and house dust. The estimated daily exposure level for infants could be as high as 1500 ng (in the US) and house dust account for 80% of exposure source for toddlers (Costa et al. 2008).

Wu et al. (2007) found positive associations between PBDEs in breast milk and house dust. The PBDEs in breast milk is also positively related with mother’s dietary habits, especially for those consuming mainly dairy products and meats. Their study pointed out that both indoor environment (house dust) and diet were important concerns for PBDEs exposure to mothers of reproductive age, and subsequently to their children.

The evidence for occupational exposure was based on the PBDE serum levels (37 pmol/g) from workers at the electronics-dismantling plant were significant higher than two other groups: clerks (7.3 pmol/g) and cleaners (pmol/g) in Sweden (Sjodin et al. 1999). Significant higher PBDE levels in indoor air near the shredder in a computer dismantling plants was observed (Sjodin et al. 2001). An epidemiology study in China indicated the workers and residents living near an electric dismantling plant had 11-20 times higher hepta- to deca-BDEs in blood than did reference groups. A world highest BDE-209 levels in blood was also detected at 3436 ng/g lipid weight (Qu et al. 2007). This underscores the possibility of offsite movement from improperly handled and mis-managed e-waste plants with exposure by humans living nearby.

In summary, PBDEs have higher level around the e-waste dismantling facilities. Thus, those workers are at higher-risk of exposure to PBDEs dusts. Therefore I am optimistic that proper industrial management and hygiene and decreased offsite movement of PBDEs from e-waste facilities. If we can move to diminish exposure to food animals including fish, these overall procedures could lead to a real reduction in exposure and adverse effects from these contaminants.

Toxicity of PBDEs

In the toxicological profile for PBBs and PBDEs (ATSDR 2004), it stated that bioaccumulation and toxicity increase as the degrees of bromination decrease. Upon exposure, which could lead to toxicity, what is the real concern? The concern includes developmental neurotoxicity and the potential for endocrine disruption. With respect to the latter, a major worry is the effect on endocrine disruption by impact thyroid regulation. (Costa and Giordano 2007, Costa et al. 2008, Herbstman et al. 2008).

Evidences of human neurodevelopmental toxicity were based on prenatal exposure affect childhood development. A Dutch study found children with prenatal exposure to PBDEs had lower fine motor skills and attention (Roze et al. 2009). Prenatal exposure resulted in higher cord blood PBDE levels in children, which associated with lower developmental score (Herbstman et al. 2010).

Intermediate- and chronic-exposure oral studies in rats and mice found that penta- and octa-BDE targeted toxicity to liver and thyroid, leading particularly to enlargement and histological alterations. Changes in serum levels of thyroid hormones were also observed. In addition, penta-BDE may lead to immune suppression under acute applications.

Limited evidence for carcinogenicity of PBDEs exists. Studies of rats and mice showed that those only chronically fed at very large doses developed hepatocellular adenomas and/or carcinomas.

EPA oral reference dose (RfD) for deca-BDE, octa-BDE and penta-BDE are $1x10^{-2}$, $3x10^{-3}$, and $2x10^{-3}$ mg/kg/day, respectively. The Agency for Toxic Substance and Registry (ATSDR) derived several minimal risk levels (MRLs) under different exposure conditions (Table 2). These concentrations were deduced from the neurodevelopmental or thyroid disruption effects in rats/mice (ATSDR, 2004).

Table 2 MRLs for PBDEs (Agency for Toxic Substances and Disease Registry 2004).

Exposure duration	MRLs (Minimal Risk Levels)
Oral exposure	
Acute	0.03 mg/kg/day[1] for lower brominated BDEs
Intermediate	0.007 mg/kg/day[2] for lower brominated BDEs; 10 mg/kg/day[3] for decaBDE
Chronic	N/A
Inhalation exposure	
Intermediate	0.006 mg/m^3[4] for lower brominated BDEs

[1] This is based on a NOAEL of 1 mg/kg/day for reduced serum levels of thyroid T4 hormone in fetal rats exposed to commercial penta-BDE mixture on days 4-20 of gestation

[2] This is based on a minimal LOAEL of 2mg/kg/day for liver effects in rats that were exposed to a commercial penta-BDE mixture for 90 days

[3] This is based on a MOAEL of 1000 mg/kg/day for developmental toxicity in rats exposed to deca-BDE for 19 days during gestation

[4] This is based on a NOAEL of 1.1 mg/m^3 for thyroid effects in rats exposed to a octa-BDE mixture for 13 weeks

History, occurrence and fates of PBDEs in Taiwan

Taiwan has relatively few studies examining PBDEs in the environment – or investigation associations with human health. However, with the increasing e-waste stream and with the WEEE and RoHS in EU, an important market for Taiwan's electrical and electronic manufacturing industries, studies regarding PBDEs in both environments and in human tissues are likely to receive more attention in the future.

The first survey of PBDE concentration in Taiwan was by Peng (2002). He analyzed funnel gas and ash samples from five municipal incineration – and three steelmaking plants. He also studied agricultural soil – and fish samples. PBDEs in ppb levels were found in gas samples from incineration – and steelmaking plants, and riverine fish samples. PBDE concentrations were 59.3-141 ng/m^3 in gas samples from municipal incineration plants and were 10-100 times higher than PCDDs/PCDFs and Dioxin like-PCBs from samples in the same places. This indicated that the improper disposal of flame retardants and construction material wastes led to higher concentration in the incineration plants. However, the deca-PBDEs were not analyzed in the Pong study.

Chen (2005) analyzed the PBDEs concentrations of sediments and fishes from 12 principal rivers in Taiwan. PBDEs concentrations in riverine sediments of Taiwan ranged from 828 pg/g dry wt. to 80120 pg/g dry wt. The average sediment concentration proved higher during the dry period versus time of high flows. PBDEs concentrations of fishes in the same study ranged from 1280 pg/g dry wt. to 33, 724 pg/g dry wt.. BDE-197, BDE-46, BDE-183, BDE-99 were the major components in sediment samples, while BDE-47, BDE-100, BDE-154 were higher in fishes. Chen also calculated the bioaccumulation factor (BAF) between fish and sediments. Certain congeners had high correlation between fish and sediments.

Human and occupational exposure studies of PBDEs in Taiwan

There are also studies related to occupational and human health. Lee (2005) found that serum PBDE levels for workers in computer dismantling plants ranked highest at 128.13 ng/g lipid than workers in electric appliance dismantling plants (39.22 ng/g lipid) and office workers (48.11 ng/g lipid). This likely suggested more PBDEs added into flame retardants of computer products than in general electric appliances.

For general public exposure studies, Chao et al. (2007) found an association between increased PBDEs in breast milk and adverse birth outcome, including: reduced birth weights, birth length and chest circumference. They also found menstruation characteristics differed in relation to PBDEs concentration in breast milk. A correlation study between total PBDEs concentration in breast milk and neurological development in infants (~1-year old) in southern Taiwan indicated that increased PBDEs were significantly related to lower cognitive development and/or adaptation behavior (Lin et al. 2010).

Summary

PBDEs are found in several rivers and sediments in Taiwan. Epidemiology studies also suggested PBDE levels in breastmilk associated with adverse birth outcome. Although there are limited studies about PBDEs in all media in Taiwan, it is obvious that dismantling workers are under higher exposure potential than general public. And, children are susceptible to PBDE exposure from mother blood stream or breastmilk feeding. Considering the Labor Safety and Health Act (2002) did not cover comprehensive regulation particularly for e-waste recycling facilities. Therefore, the recommendations for the health measures in the working areas are the priority concern for workers and their families, who will likely come into close contact when workers return after their daily jobs are completed.

Chapter 5. Recommendations

During e-waste handling procedures, a large volume of dusts, possibly containing PBDEs, would be generated. The workers are working in an environment under high-risk of exposure to the hazardous dust. Therefore, occupational management systems should be designed in accordance with related laws and regulations to protect workers. To do this the optimum approach might be to prevent exposure. This is important also for families of employees and for those living in the immediate area. Emphasis should be on best management practices at work to avoid conditions during discarding, storing, transporting and technical processes involving e-waste.

The workers and their young children are in high-risk exposure group to PBDE in workplace. Therefore, the occupational health and safety precautions should be appropriately applied in the workplace to diminish PBDE exposure to workers. First of all, the women of childbearing age should be restricted from work in the shredding sites to prevent possible exposure to fetus or infants through maternal blood stream or breast-milk feeding. Secondly, personal protective equipment such as barrier clothing (i.e., aprons, high visibility shirts), dust respirators for PM 2.5 (i.e., N-95) and coated fabric gloves should be used appropriately. OSHA's Personal Protective Equipment booklet (OSHA, 2003) illustrates a series of proper personal protective equipment as well as employers' responsibility for hazards prevention and assessment. Different factors include type of chemicals handled, nature of contact, duration of contact, area, and thermal protection would affect the selection of gloves made in different materials. Leather, canvas, and metal mesh gloves mainly prevent cuts and burns. Fabric gloves protect against dirt, slivers, chafing and abrasions. Coated fabric gloves further protect from cuts, thus preventing contaminated dusts enter blood stream through wounds. Gloves made by rubbers (i.e., butyl, neoprene, nitrile and fluorocarbon) or plastic (i.e., PVC, polyvinyl alcohol and polyethylene) can provide protection against erosion chemicals. To protect the workers in e-wastes dismantling plants from contact PBDEs dusts and to provide dexterity while processing and selecting different complements in e-waste, the fabric gloves, or coated fabric gloves are recommended.

Respirators are highly recommended in e-waste dismantling plants. OSHA listed four respirator categories: particulate respirators, chemical cartridge/gas mask respirators, powered air-purifying respirator (PAPR), and self-contained breathing apparatus (SCBA). The latter three can actively filter air by using a cartridge or canister. For e-waste dismantling, a particulate respirator (e.g., N-95 filtering facepieces respirator and dust mask) is enough for filtering out particles. It is also disposable and can be discarded before leaving the plants (OSHA, 2004). The working space should have ventilation with particulate removal from airstreams (i.e., high-efficiency particulate air, HEPA) in compliance with applicable laws and regulations.

Given that during the shredding process, the PBDEs, usually with higher molecular weights (e.g. from hexa- to deca-BDEs) would be released, as particulates and then rapidly settle to the ground or surfaces of objects, protective measures should be considered for every possible surface in the working area. As the particles and dusts may settle down on the surfaces, such as tables, working stations, machines, walls, windows, and floors, the workers should leave the protective equipment in the working space, shower, don personal clothing before departing for home. Requirement for storage lockers for worker protective devices and dedicated lockers for individual workers for storage of extra clothing are essential. In addition, showering prior to donning individual street clothing and departure for home should be required. Furthermore, the hazardous substance guidelines in the processing facilities are not strictly framed. Regulated certification and inspections to ensure compliance auditioning should be performed regularly to prevent hazards exposure. Monitoring of PBDE levels of workers and in the working place is essential. With careful attention to the above, worker safety will be enhanced and exposure minimized while providing a means to recycle valuable materials from e-waste.

The working space and technical operations should be designed for minimum exposure and release of PBDEs. For examples, foods are strictly forbidden in the working space. Additionally, the wastes components should be restricted to legal and properly designed landfills or incineration plants. Potentially toxic products such as brominated dibenzo-p-dioxins and dibenzofurans (PBDDs and PBDFs) may be released during combustion of wastes. PBDDs/Fs are consistent in the environments. They have higher vapor pressure and are more lipophilic than PBDEs (Tange and Drohmann 2005, Wang et al. 2010b).

The Taiwanese government should accelerate the establishment of related regulation and guidelines. For example, increasing recycling rates by enhancing the recycling willingness and responsibilities from companies, communities and individuals would boost the recycling rate and more importantly, reduce the potential hazards threats caused by leaching out from landfills and emission from incinerators. Current e-waste handling facilities should be audited and evaluated either by the governments or by certified third-parties, to make sure that the e-waste are handled properly to protect the employees and prevent adverse health effects related to exposure to PBDEs.

Chapter 6. Conclusions

Nowadays, e-waste management is a necessary and important industry, not only for waste reduction but also for sustainability. However, the handling processer should be taken care of to prevent secondary pollution to the workers, general public or the environment. Taiwanese government has been implementing e-waste recycling policies for manufacturers, communities, local governments and waste managements. The resulting over 50% recycling rate is productive. The government should evaluate the current regulation and consider including more items on the recyclable list to prevent the secondary pollution of toxic substance from landfills and incinerators.

E-waste dismantling workers are under high-risk of exposure to PBDE dusts. Related protective and prevention measures or guideline should be carried out while handling. Using PBDEs as a possible pollutants from e-waste handling, the prevention precautions should emphasize on avoiding inhalation and digestion by the workers as wells as children in workers' households. Public exposure is not a serious concern in the case of PBDEs in e-waste management. However, the government should establish comprehensive guidelines for e-waste management. The regular monitoring and auditing systems should also be established to preventing wider and more serious exposure.

To sum up, in order to reduce risk of pollution and increase the profit from recycling/reuse of materials, the e-waste recycling management must receive careful attention. Proper recycling e-waste not only alleviates the capacity problem of landfills/incineration and prevent the secondary pollution, but also generates a more sustainable destination for electrical and electronic equipment end-of-life pathway, for a greener contribution to the earth.

Appendix

Table 1 WEEE Annex 1B and Taiwan for mandatory e-waste recycling

Category	**Large household appliances**	**Small household appliances**
WEEE Product detailed list	• large cooling appliances • refrigerators • freezers • washing machines • clothes dryers • dish washing machines • cooking • electric stoves • electric hot plates • microwaves • electrical heating appliances • electric radiators • electric fans • air conditioning appliances	• vacuum cleaners • carpet sweepers • appliances used for sewing, knitting, weaving and other processing for textiles • irons and other appliances for ironing • toasters • fryers • grinders, coffee machines and equipment for opening or sealing containers or packages • electric knives • appliances for hair-cutting, hair drying, tooth brushing, shaving, massage and other body care appliances • clocks, watches and equipment for the purpose of measuring, indication or registering time • scales
List in Taiwan	• refrigerators: household type, compression type and absorption-type • washing machines: capacity less than 15 kg of dry clothes • electrical heating appliances • electric fans: desktop type, floor type; ceiling type, wall type, ventilated type with output power < 125W AC • air conditioning appliances	• N/A

Table 1 WEEE Annex 1B and Taiwan for mandatory e-waste recycling (Count.)

Category	IT and telecommunications equipment	Consumer equipment	Lightening equipment
WEEE Product detailed list	• centralized data processing • mainframes • minicomputers • printer units • personal computing • personal computers (CPU, mouse, screen and keyboard included) • laptops (CPU, mouse, screen and keyboard included) • notebooks • notepad computers • printers • copying equipment • electrical and electronic typewriters • pocket and desk calculators • telephones • answering systems • any other products and equipment for the collection, storage, processing, presentation or communication of information by electronic means (electrical plug, mother board, etc.) • user terminal and systems • facsimile • telex • telephones • any other products or equipment of transmitting sound, images or other information by telecommunications	• radio sets • television sets • video cameras • video recorders • hi-fi recorders • audio amplifiers • musical instruments • any other products or equipment for the purpose of recording or reproducing sound or images, including signals or other technologies for the distribution of sound and image than by telecommunications • (projectors)	• straight fluorescent lamps • compact fluorescent lamps • high intensity discharge lamps, including pressure sodium lamps and metal halide lamps • low pressure sodium lamps • luminaries for fluorescent lamps with the exception of luminaries in households • other lighting or equipment for the purpose of spreading or controlling light with exception of filament bulbs
List in Taiwan	• cases • HDD (hard disk drive) • motherboard • adaptors • monitor (including CRT and LCD) • keyboard: used as computer entering appliances, excluding number keyboard. • Notebooks and laptops • Printers: including dot-matrix, laser, daisywheel printers and etc.	• Televisions: including color picture tubes, non-color picture tubes (this category is restricted to DC) and color picture tubes and digital light processing projector (interior color projected televisions)	• straight fluorescent lamps • 2.self-ballasted fluorescent lamps, compact fluorescent lamps, incandescent light bulb with cap diameter <2.6 cm (High intensity discharge lamps；HID

Table 1 WEEE Annex 1B and Taiwan for mandatory e-waste recycling (Count.)

Category	**Toys, leisure and sports equipment**	**Medical devices**	**Monitoring and control instruments**	**Automatic dispensers**
Product detailed list	• electric trains or car racing sets • hand-held video games consoles • video games • computers for biking, diving, running, rowing, etc. • sports equipment with electric or electronic components • coin slot machines	• radiotherapy equipment • cardiology • dialysis • pulmonary ventilators • nuclear medicine • laboratory equipment for in-vitro diagnosis • analyzers • freezers • fertilization tests • other appliances for detecting, preventing, monitoring, treating, alleviating illness, injury or disability	• smoke detectors • heating regulators • thermostats • measuring, weighing or adjusting appliances for household or as laboratory equipment • other monitoring and control instruments used in industrial installations (e.g. in control panels)	• automatic dispensers for hot drinks • automatic dispensers for hot or cold bottles or cans • automatic dispensers for solid products • automatic dispensers for money • all appliances which deliver automatically all kinds of products
List in Taiwan	• N/A	• N/A	• N/A	• N/A

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