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ScienceDirect
Procedia Environmental Sciences 31 (2016) 867 – 872
Procedia Environmental Sciences

The Tenth International Conference on Waste Management and Technology (ICWMT)

Pollutants release and control during WEEE recycling: A critical review

Lingyu Sun[a], Xianlai Zeng[a], Jinhui Li[a] *

[a]*State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 10084, China*

Abstract

With the rapid development of science and technology especially in the ICT industry all over the world, WEEE has been considered to be one of the most important waste streams during the last decade and will continue to be so in the future. WEEE contains valuable metals as well as potential environmental contaminants so recycling E-waste is an indirect way to reuse valuable resources. In case that it is simple to dismantle the machines and almost all the E-waste consists components like PCBs and CRTs, this paper puts emphasis on the processes of dismantling and recovering resources from PCBs and CRTs as an example for their widely usage. Universal recycling processes for PCBs and CRTs are introduced briefly and pollutants released during the processes are dust and waste water mainly. Measures are proposed to control the pollution, for instance, the shredder and grinders could be isolated during the physical process and it is suggested that personal protective devices such as masks are used to reduce the exposure level to heavy metals. Secondary pollution during the recycling process is inevitable, Thus cleaner technology is urgent to come into service. Although recycling may remove some contaminants, large amounts which are difficult to disposed ought to be concentrated in landfills.

Peer-review under responsibility of Tsinghua University/ Basel Convention Regional Centre for Asia and the Pacific

Keywords: PCBS; CRTs; pollutants; recycling; release; control

* Corresponding author. Tel.: +8601062794143; fax: +8601062772048.
E-mail address: jinhui@tsinghua.edu.cn

Peer-review under responsibility of Tsinghua University/ Basel Convention Regional Centre for Asia and the Pacific
doi:10.1016/j.proenv.2016.02.100

WEEE includes not only waste electronic goods, such as computers, televisions and cell phones, but also traditionally non-electronic goods such as refrigerators and ovens (Robinson, 2009). With the rapid development of science and technology especially in the ICT industry all over the world, WEEE has been considered to be one of the most important waste streams during the last decade and will continue to be so in the future(Martinho, Pires, Saraiva, & Ribeiro, 2012; R. Wang & Xu, 2014). It is estimated that 50 million tonnes of WEEE are generated annually now(J. Wang & Xu, 2015). For instance, the output of TVs in 2013 was 59.62, million units, as much as 3.07 times higher than the output in 2000 in China.

WEEE contains valuable metals (Cu, Al, platinum group) as well as potential environmental contaminants, especially Pb, Sb, Hg, Cd, Ni, BFR， polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls(Robinson, 2009). Only1/6 of the E-waste collected are reused and recycled for 52 billion dollars, including 300 tonnes of gold(equivalent to 11% of global gold production in 2013),16.50 million tonnes of Fe, 1.9 million tonnes of Cu, 0.22 million tons of Al and other scarce metals. Hence, recycling E-waste is an indirect way of the recovery of resources.

The current practice for the recycling of WEEE has received considerable global attention because of the emission amounts of a wide range of toxic chemicals, resulting from uncontrolled and often hazardous recycling methods, as well as the large volume of waste(Man, Naidu, & Wong, 2013). Pollutants are always released even disposed properly. It has been estimated that E-waste is responsible for up to 40% of the lead in landfills in America, and about 70% of heavy metals (such as mercury and cadmium) in US landfills(Ahluwalia & Nema, 2007; Balakrishnan Ramesh, Anand Kuber, & Chiya Ahmed, 2007). In conclusion, the recycling of WEEE makes a big difference from both the economic and environmental perspectives.

It is reported that，the total amounts of E-waste in 2013 and 2014 are 3980 and 4180 million tonnes, respectively, expected to reach 50 million tons in 2015. Table 1 lists the catagories of E-waste generated in 2014 around the word. Non-electronic goods such as refrigerators ovens and washing machines account for almost 60% of the total E-waste amount and 7% of the E-waste is gathered of mobile phones, personal computers, calculators and printers.

Table 1 Catagories of E-waste generated in 2014 around the word

Categories	Amount(million tons)
miniaturized electronics	12.80
large scale equipment	11.80
Conversion equipment	7.00
minitor	6.30
spare parts	3.00
Lighting equipment	1.00

In case that it is simple to dismantle the machines and almost all the E-waste consists components like PCBs 、LCD/CRTs or batteries(Duan, Hou, Li, & Zhu, 2011), this paper puts emphasis on the processes of dismantling and recovering resources from PCBs and CRTs for their widely usage. Pollutants released during the recycling process are expounded and effective control technologies are explored to meet the environmental need.

1. PCBs

Printed circuit boards, as one of the essential components in electronic and electrical equipments, are made up of metals, fiberglass and resin material in which brominated flame retardant are used to prevent fire in case of short circuit. The percentage of PCBs is very huge and Table 2 lists the PCB weight fraction of E-waste total product weight(Duan et al., 2011).

Table 2 PCB weight fraction of total E-waste product weight in 2010

Source	Color TV	CRT screen	LCD screen	PC control unit	Laptop	Mobile phone
wt.%	7.04	11.89	11.87	18.76	21.00	21.30

Dismantling ECs from waste PCBs is a fundamental step from both standpoints of conserving scare resources and ECs reuse in the recycling chain(Chen et al., 2013; Duan et al., 2011). The major common point of primitive disassembling technologies is the recovery of the solder remaining on the board by subjecting it to a temperature greatly higher than the molten point of the solder(Duan et al., 2011). Intelligent and automatic approaches, such as a flexible automated cell identifying and separating reusable parts and toxic components(Duan et al., 2011), automated method applying small amounts of force and heat based on 3-dimensional pictures(Duan et al., 2011), can rarely be practiced due to the complexity and high cost of equipment. Compared to automated approaches, a semi-automated method using heating technology is more flexible(Duan et al., 2011).

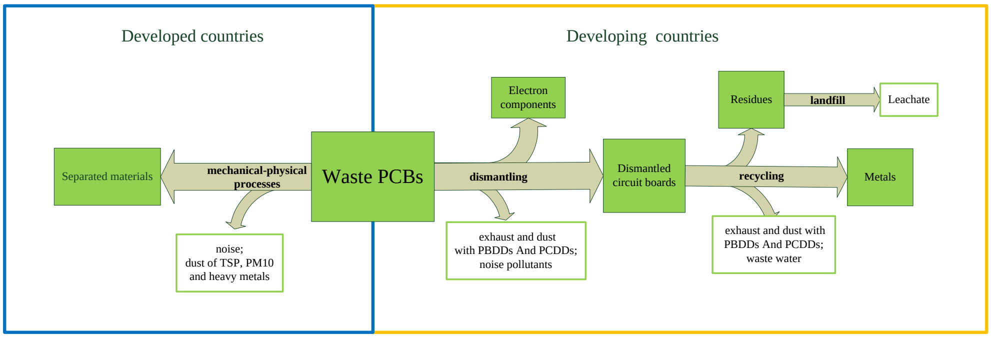

Fig.1 Recycling process of PCBs in developed and developing countries

Dismantling under high-temperature heating, during which the toxic products from resins and adhesives are decomposed, is a common occurrence(Eric et al., 2008). Both PBDD/Fs and PCDD/Fs has been found to form in Huabo Duan's experimental samples, including unheated sample, heated at a temperature of 250℃ and 275℃ under an N_2 or air atmospheres, indicating a rapid increase as the temperature rose, in amounts much higher than in unheated PCBs(Duan, Li, Liu, Yamazaki, & Jiang, 2012). Hence, the composition of the exhaust and dust should be identified as well as the risk to the environment and to humans caused by these substances also should be estimated, and the pollution control and protection measures also should be put forward. Comparatively low temperature is preferred in use.

Recently, ionic liquid is employed to dismantling. P Zh.(Zhu, Chen, Wang, & Zhou, 2012) commend it as clean and non-polluting technology (Zhu, Chen, Wang, Qian, et al., 2012; Zhu, Chen, Wang, & Zhou, 2012). Xianlai Zeng's research shows cyclic utilization of the ionic liquid is available and the dissolution rate of soldering tin can be over 90 percent under the optimum conditions. The key point of the technology is the disposition of the waste ionic liquid.

Afterwards, large ECs or that contains polychlorinated biphenyl should be manually removed and separately disposed of in an appropriate way(Duan et al., 2011). The circuit boards can then be sent to a facility for further dismantling and metals recovery works.

The large amount of residues generated from dismantling PCBs results in a considerable environmental burden because they contain heavy metals and halogen-containing flame retardant that can seep into the environment if not properly managed(Duan et al., 2011). Lots of methods based on hydrometallurgy(Kim, Kim, Lee, & Pandey, 2011), pyrometallurgy, biometallurgy(Ilyas, Ruan, Bhatti, Ghauri, & Anwar, 2010), pyrolysis and mechanical-physical processes(Huang, Guo, & Xu, 2009) have been developed to identify cost-effective and environmentally sustainable ways of recycling dismantled waste PCBs(J. Wang & Xu, 2015).

During pyrolysis process which belongs to the category of pyrometallurgy , the existence of a high content of dioxin and related compounds in the e-waste dismantling environment is supported by several investigations(Huang et al., 2009), indicating that there is a potential for dioxin formation when PCBs scrap is heated(Duan et al., 2011). Some researchers reveals that there were two significant factors that influenced the extent of PBDD/F formation(Yi, Wen, & Hsing, 2007). The first factor was temperature and results showed that, both the total PBDD/F content in the bottom ash and the flue gas decrease by approximately 50% with an increase of the pyrolysis temperature from 850 to 1200 °C. The second factor was the addition of CaO. The possible mechanism involves the reaction between CaO and HBr to form the solid-phase product $CaBr_2$. Thus, the addition of CaO is effective in adsorbing HBr and results in the inhibition of PBDD/F synthesis by more than 90% and further prevents the acid gases (HCl and HBr) that corrode the equipment. Appropriate temperature attributes to the inhibition of PBDD/F and gas scrubbing apparatus should be equipped for monitoring and filtration. Furthermore, further separation is essential for the mixture of pyrolysis residues and metals; moreover, the pyrolysis residues generally contain toxic materials, like PBDD/Fs and PCDD/Fs and should be disposed of properly(Lin & Chiang, 2014; J. Wang & Xu, 2015).

There are also pollutants emitted from hydrometallurgy proces. Large amount of waste water and free gas containing complex components could be serious problem. In case for environmental accident, self-contained complete sewage treatment facilities and gas scrubbing apparatus are necessary.

Ultimately, residues remained are destined for landfill, undoubtedly the seeped leachate contaminates the soil and groundwater if the impermeable layers are ruptured(Hadi, Xu, Lin, Hui, & McKay, 2015). The impermeable layers should be paved competently and the leachate are exported by layered drainage system timely.

In most developed countries, PCBs are recycled in the mechanical-physical processes: crushed directly without dismantling, then magnetic separation, vortex separation and air separation. Such method shows the merits of efficiency and cost reduction for human resource, and benefits to worker’s health(Duan et al., 2011). Shufang Ding’s research (Ding et al., 2010)shows that the ratio of the dust is about 1.1~2.5% in the crushing process and the copper contained in the dust is about 2.5~4%, the industrial grade of copper is 0.3%, which means that the dust still has the potential to be recycled. Heavy metals and VOCs in the dust collected from PCB crushing process are lower than the upper limit of Screening Value for Identification Hazardous Waste and the amount is relatively small. In addition the crushing process at low temperature would make more copper to the dust than the crushing process at room temperature. Thus, optimized work conditions such as optimum temperature can be helpful to the environment.

To determine the potential environmental contamination in the automatic line workshop, Mianqing Xue(Xue, Yang, Ruan, & Xu, 2012) bas evaluated the noise and heavy metals (Cr, Cu, Cd, and Pb) in the ambience of the production line. Her study indicates that noise is generated by each facility in the workshop while the major noise sources are crushing machines like shredder and harmer grinder, which exceed the Occupational Safety and Health Standards (OSHS). So techniques of sound insulating with the purpose of noise reduction are adopted in the workshop. As a result, the mean noise level is reduced from 96.2 to 78.2 dB after introduction of noise insulator.The mass concentrations of TSP and PM10 in the ambience of the production line are 282.6 and 202.0 $\mu g/m^3$ respectively which is safe because the averages of TSP and PM10 are below the Chinese grade III guideline. The concentrations of Cu, Pb, Cr, and Cd in PM10 are 0.88, 0.56, 0.12, and 0.88$\mu g/m^3$, respectively. Among the four metals, Cr and Pb are released into the ambience of the automatic line more easily in crush and separation processes. So it indicates that adverse health effects might be not serious but possible.

Consequently, the shredder and hammer grinders could be isolated within a cabin made of plywood, which is packed with fine glass wool and damping materials and it is suggested that personal protective devices such as masks are used to reduce the exposure level to heavy metals by Mianqing Xue(Xue et al., 2012).

2. CRTs

There are CRTs in various electronic instruments, like TV sets, personal computer monitors and medical equipment(Méar et al., 2007). CRTs are made of five parts, the electron gun, the deflection coils, the Shadow mask, the phosphor and the glass shell. The superficial part is the panel which contains barium and strontium oxides and the phosphor, and the inside part—funnel and neck are rich in lead which is most prominent. The heavy metal (lead, barium, and strontium) content of such glass represents an acute risk to the environment(Hischier & Baudin, 2010; Nnorom, Osibanjo, & Ogwuegbu, 2011; Xu, Li, He, Huang, & Shi, 2012). At present, CRTs are being replaced gradually by new products such as Liquid Crystal Displays (LCD) and Plasma Display Panel (PDPs). However, they are still present in the houses of many people. For example, in Europe, about 50,000–150,000 tons/year of end of life CRTs are currently collected and this flux is not expected to decrease in the next years (Rocchetti & Beolchini, 2014).

Generally, a whole waste CRT-TV was dismantled into different categories of materials in the TV dismantling workshop, then the dismantled materials, such as CRT, PCB, the housing plastic, wire and other electronic components, are treated respectively(Guo, Lin, Deng, Fu, & Xu, 2015). Separation of the panel glass from the funnel glass is the key step in the CRT dismantling process(Guo et al., 2015).

Technologies for separating panel glass from funnel glass are divided into three categories, physical dismantling, dissolution method, and thermal separation(Xu et al., 2012). Direct crush and incision mechanically are feasible technically and prevalent. In this process, noise and dust containing heavy metals and phosphor are the main pollutants. In addition, the mixed and fragmentized glass through direct crush is difficult to be reused. Dissolution is a typical chemical method and strong acid is used for the solvent prevailingly. The theory is simple while the operation is dangerous. Besides, the waste acid is another kind of pollutants. Environmental treatment for the waste acid and water is the key issue to this process. Water treatment system is necessary in this process. Meanwhile, acid gas emitted to the environment should be disposed. Sources of energy in thermal separation methods are different. Heater strip powered by thermal energy is one of the main tools for separation. The heater strips are not efficient after a period of time, so abundant heater strips are in need for this process. The waste heater strips should be disposed formally.

Afterwards, the glass is separated for crushing and cleaning, aiming at removing the fluorescent layer. Measures include pumping under negative pressure, crushing and water scrubbing. Used water with phosphor and lead can be a problem. According to Jinhui Li et al., in China, sampling inspection of the circulation cleaning water reveals that the concentration of the lead is about 8.8mg/L, highly over the national integrated wastewater discharge standard limit (1mg/L).Some researchers have studied on the recovery of yttrium(Innocenzi et al., 2013).In their researches, the recovery ratio of yttrium can reach a high level, over 95%, through a processing of acid leaching, purification of the liquors, precipitation of yttrium and calcination for yttrium oxides. Consequently, waste water generated in this process should be disposed in a formal way.

3 Conclusion

This paper highly summarized the universal recycling processes for PCBs and CRTs are introduced and pollutants released during the processes are dust and waste water mainly. Measures are proposed to control the pollution. Secondary pollution during the recycling process is inevitable, although recycling may remove some contaminants. Meanwhile, large amounts may still end up concentrated in landfills or waste recycling centers, where they may remain stored and adversely affect human health or the environment. Thus cleaner technology is urgent to come into service. The stored contaminants is supposed to be sent off to secure landfill.

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