Journal of Hazardous Materials B136 (2006) 502–512

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Review

WEEE recovery strategies and the WEEE treatment status in China

Wenzhi He, Guangming Li *, Xingfa Ma, Hua Wang, Juwen Huang, Min Xu, Chunjie Huang

State Key Laboratory of Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Tongji University, No. 1239 Siping Road, Shanghai 200092, China

Received 27 October 2005; received in revised form 18 April 2006; accepted 18 April 2006
Available online 2 June 2006

Abstract

The electric and electronic equipment has been developed, applied, and consumed world wide at a very high speed. Subsequently, the ever-increasing amount of waste electric and electronic equipment (WEEE) has become a common problem facing the world. In view of the deleterious effects of WEEE on the environment and the valuable materials that can be reused in them, legislations in many countries have focused their attention on the management of WEEE, and new techniques have been developed for the recovery of WEEE. In China, rapid economic growth, coupled with urbanization and growing demand for consumer goods, has increased the consumption of EEE in large quantity, thus made the WEEE manifold rapidly, posing a severe threat to the environment and the sustainable economic growth as well. This article reviewed the implementation of strategies of WEEE treatment and the recovery technologies of WEEE. It presented the current status of WEEE and corresponding responses adopted so far in China. The concept and implementation of scientific development is critical to the sector of electronics, one of the important industrial sectors in China's economy. To achieve this objective, it is significant to recycle WEEE sufficiently to comply with regulations regarding WEEE management, and to implement green design and cleaner production concepts within the electronics industry to comply with the upcoming EU and China legislation in a proactive manner.

Keywords: Waste electric and electronic equipment; Management; Recovery; Resource; Legislation

Contents

* Corresponding author. Tel.: +86 21 65982688; fax: +86 21 65982688.
E-mail address: ligm@mail.tongji.edu.cn (G. Li).

0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2006.04.060

1. Introduction

The production of electric and electronic equipment (EEE) is one of the fastest growing businesses in the world. In the meantime, both technological innovation and market expansion of EEE are accelerating the replacement of outdated EEE, leading to a significant increase in waste EEE (WEEE) that induces a new environmental challenge. In West Europe, 6 million tonnes of WEEE were generated in 1998, and the amount of WEEE was expected to increase by at least 3–5% per annum [1]. In the USA, it was said that over 315 million computers would reach their date of expiration by 2004 [2]. In Australia, there are approximately 9 million computers, 5 million printers and 2 million scanners currently in households and businesses, and all of them will be replaced, most within the next couple of years [3].

WEEE encompasses a broad and growing range of EEE from home appliances to computers at the end of their lives. WEEE is non-homogeneous and complex in terms of the materials and components. Many of the materials are highly toxic, such as chlorinated and brominated substances, toxic metals, photoactive and biologically active materials, acids, plastics and plastic additives. Major categories of hazardous materials and components of WEEE are listed in Table 1 [1].

With these hazardous elements, WEEE can cause serious environmental problems during disposal if not properly pretreated. For example, the cadmium from one mobile phone battery is sufficient to pollute 600,000 l of water [4]. Growing attention is being given to the impacts of the hazardous components in WEEE on the environment.

However, WEEE also has a high residual value. The Association of Plastics Manufactures in Europe released their statistics of material consumption in EEE in Western Europe in 1995 [5]. Relatively the composition was as follows: 38% ferrous, 28% non-ferrous, 19% plastics, 4% glass, 1% wood, and 10% others. In general, printed circuit board (PCB) scrap contains approximately 40% metals, 30% plastics, and 30% ceramics [6–8]. The typical metal scrap in PCB consists of copper (20%), iron (8%), tin (4%), nickel (2%), lead (2%), zinc (1%), silver (0.2%), gold (0.1%), and palladium (0.005%) [6]. Polyethylene, polypropylene, polyesters, polycarbonates and phenolformaldehyde are the typical plastic components. These materials are valuable and could be recycled by proper technologies. Besides, a significant amount of disposed equipment might be collected for reuse or remanufacturing.

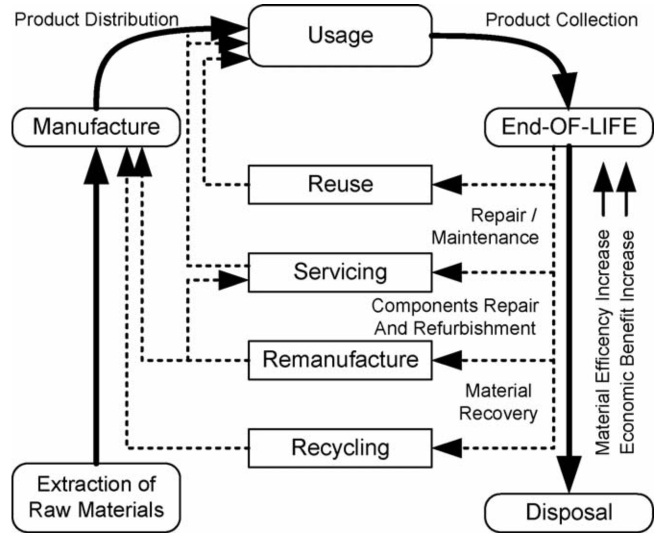

Fig. 1. Generic product's life cycle.

With the recognition on the deleterious environmental effects of dumping WEEE, the decreasing capacity of landfills, and the values of the reusable materials, legislation in many countries has refocused on the management of WEEE [9,10], and many technologies are being developed and used for the recovery of WEEE.

2. Strategies of WEEE treatment

The life cycle of a product refers to the sequence of interrelated steps of a product from the acquisition of raw materials for manufacturing to the disposal of the used product, i.e. its end-of-life. At the end-of-life, the product can be either disposed off, or still in use to extend its life cycle [11,12] (see Fig. 1). The end-of-life of a product in this paper refers to the time point when the

Table 1
Major hazardous components in waste electric 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 fluorescent coating cover the inside of panel glass
Mercury containing components	Mercury is used in thermostats, sensors, relays and switches; it is also used in medical equipment, data transmission, telecommunication, and mobile phones
Asbestos waste	–
Toner cartridges, liquid and pasty, as well as color toner	–
Printed circuit boards (PCBs)	Cadmium occurs in certain components
Polychlorinated biphenyl containing	–
Capacitors	–
Liquid crystal displays (LCDs)	–
Plastics containing halogenated flame	During incineration/combustion of the plastics
Retardants	Halogenated flame retardants can produce toxic components
Equipment containing CRC HCFC or HFCs	HCFC or CFCs are present in the foam and the refrigerating circuit
Gas discharge lamps	Mercury is present in them

product's functionality no longer satisfies the requirements of the original purchaser or the first user [9]. End-of-life strategies describe the approaches or methods in dealing with the product at its end-of-life [11]. End-of-life treatment includes the activities associated with recovering value from the product, through manual labor and/or machinery [11].

In view of the environmental problems and high residual value of WEEE, WEEE management system should be established to extend the life cycle of EEE. This management system comprises collection, classification, pre-treatment, etc., and five conventional end-of-life treatment strategies. In accordance with the potential economic and environmental efficiency, these strategies can be categorized as follows [11,13]:

(1) reuse: the recovery and trade of used products or their components as originally designed;
(2) servicing: a strategy aimed at extending the usage stage of a product by repair or maintenance;
(3) remanufacturing: the process of removing specific parts of the waste product for further reuse in new products;
(4) recycling (with or without disassembly): including the treatment, recovery, and reprocessing of materials contained in the used products or components in order to replace the virgin materials in the production of new goods;
(5) disposal: the processes of incineration (with or without energy recovery) or landfill.

European Union (EU) has established a comprehensive body of environmental legislation, which has been proven innovative and successful in many aspects [14]. The current end-of-life model of EEE implemented in EU was established on the basis of EU Directives on WEEE and Restriction of Hazardous Substances (RoHS) approved in October, 2002 [15–17].

The EU Directive on WEEE is based on the producer-pays principle. The scope of this Directive includes producers, distributors, consumers and all parties involved in the treatment of WEEE. Producers are requested to finance the collection, treatment, recovery, and environmentally sound disposal of WEEE. The directive imposes a high recycling rate for all targeted products. The rate varies from 50% to over 80% depending on the type of WEEE. The strategy includes collection, sorting, refurbishment, dismantling, shredding, treatment of recyclable components/materials, treatment of hazardous components/substances, and landfill or incineration (with heat recovery) of remaining wastes [17]. The objective of the Directive is to reduce the amount of such waste going to landfill and to improve the overall environmental performance of EEE products during their life cycle.

The RoHS directive bans the presence of certain hazardous substances in EEE being traded in EU market. RoHS ensures that new EEE does not contain mercury, lead, cadmium, hexavalent chromium, polybrominated biphenyls, or polybrominated diphenyl ethers. It aims to control the environmental impact of EEE by implementing clean production.

Japan is the country in Asia where WEEE recovery is well performed. In Japan, the Designated House-hold Appliance Recycling Law (DHARL) was enforced in 2001 [17,18]. DHARL turns WEEE treatment into an obligatory take-back system that implements a full scale private-sector-based post-consumer recycling of WEEE [18,19]. The system entails coordinated participation of several stakeholders including manufacturers, importers, retailers, consumers, and governmental offices [17,18]. Manufacturers and importers are obliged to take back their products at designated collection sites, and to recycle them according to regulations set by the government. Retailers are requested to take back used home appliances that they sold and to transfer them to the corresponding manufacturers or importers. Governmental offices can also collect discarded appliances to transfer them to manufacturers or "independent bodies" for recycling. Consumers are obliged to cooperate in transferring used appliances to retailers or municipalities, and to pay the necessary fees for collection, transportation and recycling [18]. In recycling plants, WEEE are sorted, treated, dismantled and crushed. Valuable materials: glass, aluminum, certain types of plastics, copper and iron are recovered by electromagnetic, centrifugal and gravity separation techniques [20]. Hazardous substances are recovered and destroyed via thermal or chemical processes.

3. Recycling of WEEE

Recycling of WEEE is an important step of the end-of life strategies for WEEE treatment. The maximization of valuable material recovery and the consequent minimization of disposal rely on the technologies used in the process. With the steadily decreasing of the precious metal contents in EEE, the precious-metal-oriented recovery techniques, such as hydrometallurgy and pyrometallurgy, are facing great challenges [7]. On the other hand, mechanical/physical recycling of WEEE, due to its better environmental property and easier operability, is drawing more attention. Compared with hydrometallurgy and pyrometallurgy, mechanical/physical processes can achieve full material recovery including plastics.

Mechanical recycling of WEEE can be broadly divided into three major stages [21].

1. Disassembly (dismantling): targeting on singling out hazardous or valuable components.
2. Upgrading: using mechanical/physical processing to upgrade desirable materials content, i.e. preparing materials for refining process.
3. Refining: in the last stage, recovered materials return to their life cycle.

Disassembly and upgrading are two key processes of the mechanical recycling of WEEE.

3.1. Disassembly

Disassembly is a systematic process that removes a component or a part, or a group of parts or a subassembly from a product (i.e., partial disassembly); or splits a product into all of its parts (i.e., complete disassembly) for a given purpose [22].

In WEEE recycling practice, selective disassembly (dismantling) is an indispensable process, since (1) the reuse of com-

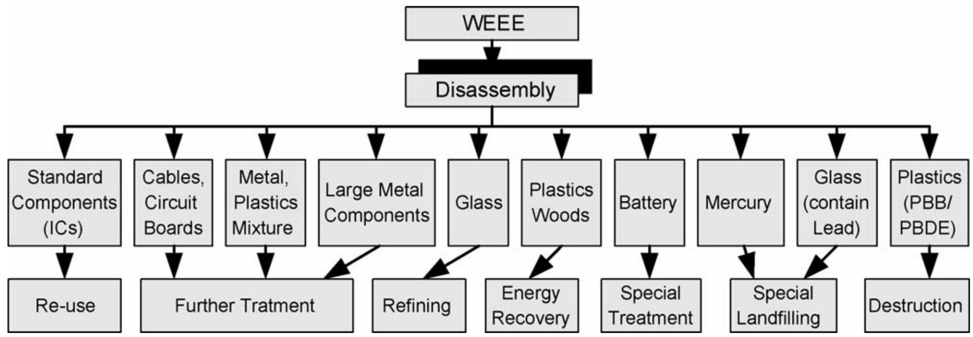

Fig. 2. Recycling process developed by Ragn-Sells Elektronikåtervinning AB.

ponents is of the first priority, (2) dismantling the hazardous components is essential, and (3) it is important to dismantle highly valuable components and high grade materials such as PCBs, cables, and engineering plastics in order to simplify the subsequent recovery of materials [21].

The implementation of disassembly needs highly efficient and flexible tools. Several patented disassembly tools were highlighted in Ref. [23]. The most attractive research on disassembly process is the use of robots. Unfortunately, full (semi) application of automation disassembly for recycling of EEE is full of frustration [21]. Currently, there are only a few pilot projects for automated disassembly of keyboards, monitors and PCBs, and there is no (semi-) automated solution for the personal computer (PC) itself [24,25]. The manual disassembly aided by tools, due to its high flexibility, is currently the main dismantling process.

Ragn-Sells Elektronikåtervinning AB in Sweden is a typical electronics recycling company. Fig. 2 illustrates the disassembly process utilized in the company [26]. A variety of tools are involved in the dismantling process for removing hazardous components and recovery of reusable or valuable components and materials. The disassembled cables, PCBs and metal/plastics mixture, being a mixture of various materials, should be further treated to upgrade the materials contents of them.

3.2. Upgrading

WEEE can be regarded as a resource of metals, such as copper, aluminum and gold, and non-metals. Effective separation of them, based on the differences in their physical characteristics, is another crucial process for recycling of WEEE. The upgrading usually includes two stages: comminuting and separating.

3.2.1. Comminuting

Comminuting is the first step of the physical upgrading process. Only when the disassembled WEEE is shredded to a proper granularity, can the materials of the WEEE be liberated one another, and then be separated effectively.

Basically, the materials present in EEE are attached by fastening, inserting, welding, binding, wrapping and so forth. Therefore, it does not need much intensive energy to unlock the associated materials like ceramics, glass, and metals having distinctive mechanical properties [7]. The optimized comminuting result is that every comminuted particle is made by sole material. The influence of granularities of the comminuted particles on the liberation degree of materials in PCBs was studied carefully [7,27,28].

Characterization of PC scrap and PCB scrap showed, after shredding by a laboratory scale hammer mill, that the main metals present were in the −5 mm fraction for both PC and PCB scrap and showed excellent liberation (ca. 99% [7]). In −3 mm fractions, the metals achieved approximately complete liberation; in coarser fractions, copper had poorer liberation due to the presence of copper pins associated with plastics and copper wire segments encapsulated with plastics; also, the ferromagnetics obtained a good liberation for particles with sizes less than 16 mm, and aluminum in the +7 mm fraction for both PC and PCB scrap accomplished an excellent liberation [27]. Industry scale tests showed that after two stages comminution, the liberation of −5 mm fraction was between 96.5% and 99.5% [28].

3.2.2. Separation

After liberation of the materials in the disassembled WEEE through comminuting, the separation of them can then be performed by mechanical/physical methods. The differences on the physical characteristics of materials in non-homogeneous compounds, such as magnetism, electric conductivity and density, etc., are the bases of the mechanical/physical separation of them. Mechanical/physical separation processes include electronic magnetic separation, electronic-conductivity-based separation, density-based separation and so forth. All of them have application instances in the WEEE recycling field.

Magnetic separation is widely used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Over the past decade, the advances in the design and operation of high-intensity magnetic separators also make it possible to separate copper alloys from the waste matrix [21,29].

Electric conductivity-based separation is used to separate materials of different electric conductivity (or resistivity). There are three typical electric conductivity-based separation techniques: (1) eddy current separation, (2) corona electrostatic separation, and (3) triboelectric separation [30–33].

With the marked density difference between metals and non-metals in WEEE powders, the heavier metal materials can be

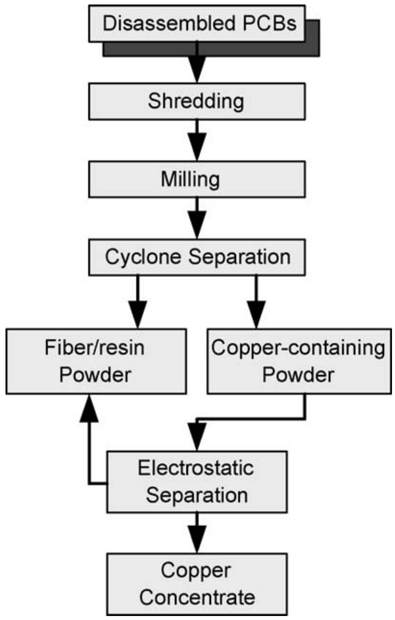

Fig. 3. PCB upgrading processin NEC company.

effectively separated from non-metal materials by the density-based separation methods.

In the practice of recycling WEEE, according to the requirements of the task, some of the above methods can be combined together to fulfil the separation of the materials present in WEEE. For example, in Germany, the Kamet Recycling Gmbh company has successfully reclaimed iron, aluminium, precious metals and plastic from waste PCBs through shredding, gravity separation, electronic magnetic separation and eddy current separation [34]. About 90% of metal and plastic materials can be reclaimed by these processes.

Fig. 3 shows the upgrading process of the waste PCBs implemented in the NEC Company [35]. In this process, the disassembled PCBs are comminuted to powders with particle sizes smaller than 1 mm by shredding and then milling, which makes the copper liberated from other materials sufficiently. After cyclone separation, one of the density-based separation methods, the comminuted PCBs are partitioned to the copper-containing powder and the fiber/resin powder. Then followed by electrostatic separation, a copper concentrate with the purity of 82% is obtained from the copper-containing powder. Over 94% copper recovery can be achieved by this process.

4. Status of WEEE in China

China is the largest emerging market region in the world with both global manufacturing and consuming market. Rapid economic growth, coupled with urbanization and growing middle class, is expected to increase the consumption of EEE, thus increase the WEEE rapidly in this region, posing a severe threat to the environment and sustainable economic growth.

TV sets, refrigerators and washing machines are three kinds of widely used domestic electric equipments in China. Most of them were made in the middle or the latter of the 1980s and should have been replaced by new types after 2000 that millions of them would have been entering into the waste stream per year. Air-conditioners and PCs are another two kinds of typical EEE and their sales volumes have presented a rapidly increasing tendency since the 1990s.

The numbers of the above five kinds of typical EEE put into operation per year are shown in Tables 2 and 3. The data in Table 2 and the date from 1992 to 2001 in Table 3 were obtained from Ref. [36,37]. In Table 3, the date from 2002 to 2005 were based on the investigation of PC market conditions, and the data from 2006 to 2010 were based on the future developing programming of the IT industry and the analyses of current computer market [38]. Fig. 4 shows the variation of the amounts of them hold by per 100 town families with time [37]. From the figure, it can be noted that the amounts present a steady growth trend except washing machines.

It was estimated that the average life span of domestic electric equipments is about 7–8 years for TV sets, 8–10 years for refrigerators and washing machines, and 10–11 years for air-conditioners [39]. With the acceleration of the replacement of PC

Table 2
Electrical and electronic equipment units sold in China per year (thousands)

Year	TV	Refrigerator	Washing machine	Air-condition
1990	–	–	9417	99
1991	21250	6920	8846	259
1992	25685	8307	10352	650
1993	28258	9765	7562	1425
1994	28541	9751	9500	1618
1995	33506	13570	15219	2808
1996	28811	11117	8004	3234
1997	32321	11383	10834	4007
1998	40881	10787	10980	4759
1999	44493	12322	13395	5503
2000	44600	11865	12613	7515
2001	48429	19385	13336	9600
2002	55731	–	–	10350
2003	42291	–	–	11800

Table 3
PC units sold or to be sold in China per year (thousands)

Year	PC	End-of-life PC
1992	105	
1993	611	–
1994	849	–
1995	750	–
1996	1216	–
1997	1269	–
1998	2890	541
1999	3871	999
2000	7088	989
2001	7550	1396
2002	7882	2267
2003	9600	4476
2004	11500	7311
2005	14000	9809
2006	15960	10731
2007	18194	12103
2008	20742	14305
2009	23645	16968
2010	26956	19567

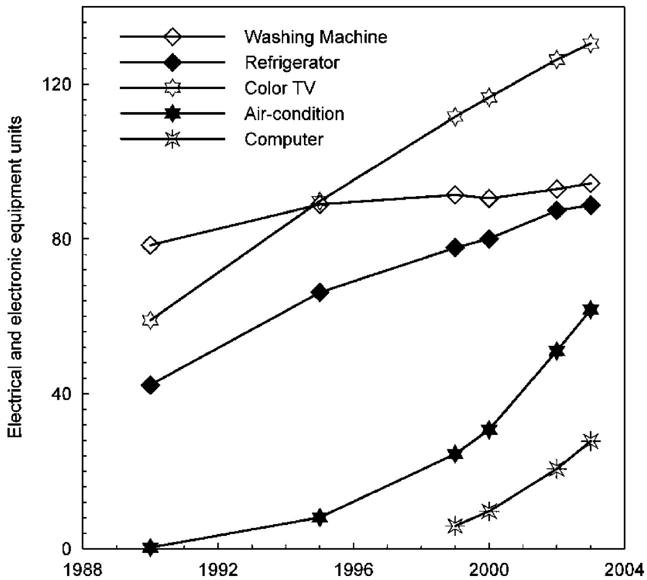

Fig. 4. Amounts of five kinds of typical EEE hold by per 100 town families in China.

by new types, the life span of them is getting shorter. In the 1990s, the life span of computers was about 4–6 years. But, today, computers are often redundant in 2–4 years. Liu et al. [38] estimated the generation of above five kinds of WEEE per year based on the sales volume of the corresponding EEE. Their results are shown in Table 3 and Fig. 5. In the estimation, the average life-spans of TV sets, refrigerators, washing machines and air-conditioners were respectively 8, 10, 10 and 11 year. The average life-span of computers varied from 5.5 to 3.0 year according the time line. From Fig. 5, it can be observed that entering the 21st century, over 45 million WEEE units described above had been entering the waste stream per year and the amounts present marked increasing tendency with time line.

Besides the WEEE generated in China, the increasing demand for resources, caused by the rapid economic growth,

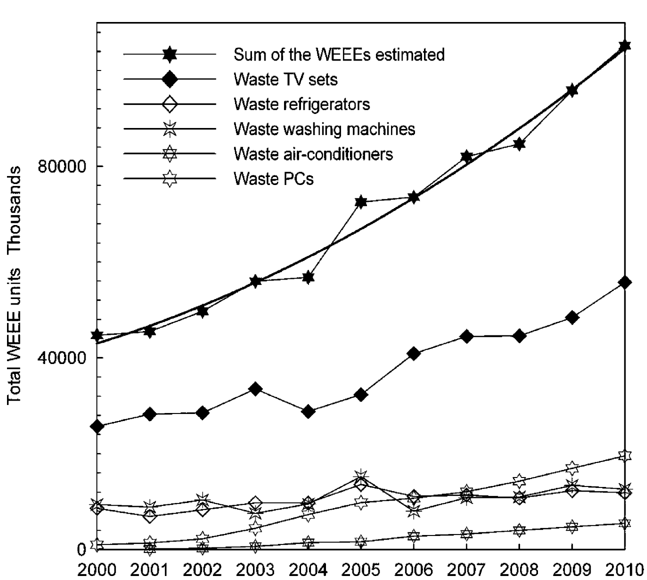

Fig. 5. Generation of five kinds of WEEE per year.

leads to the importation of secondary resources (i.e., wastes and end-of-life products), which contains a large amount of WEEE [40]. For example, according to the report "Exporting Harm" [41], an important document on the transboundary shipment of WEEE, millions of pounds of WEEE, from obsolete computers to televisions, was generated annually in the USA, and 90% of them was exported to China. Large amounts of WEEE were dismantled manually, then treated in household workshops, and assisted by medium and small factories with inappropriate methods such as open burning and acid dipping, which creates serious occupational and environmental hazards and loss of some reusable materials.

Waste substances are the secondary resource in wrong place. Effective recovery of them is important not only for environmental development, but also for rational utilization of natural resources. In view of the serious environmental problems caused by WEEE and the valuable materials contained in WEEE, great attention has been paid to them, and some corresponding projects have been put into action in China.

5. Response to WEEE in China

In China, the first legal document related to WEEE management is the List of Wastes Prohibited for Import. This document was constituted in 1996 based on the Basel Convention. Waste batteries, air-conditioners, refrigerators, microwave ovens, phones, and TV sets, etc. are all on the list. Entering the 21st century, legislation, management strategies and recycling technologies on WEEE arouse great attention of government agencies and researchers. Legislation, research and international co-operation on WEEE treatment have been initiated.

5.1. Legislation

In September 2003, announcement on enhancing the environmental management of WEEE was proclaimed by State Environmental Protection Administration of China (SEPA). On 29 December, 2004, the revised Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste was approved by National People's Congress and has been put into effect since 1 April, 2005. This legislation has joined the regulation on dismantling, recycling and disposal of WEEE. Based on the above announcement and revised state law, "the Management Method on Prevention and Cure of Environmental Pollution in WEEE" was established by SEPA in the early of 2005 and are being discussed. The main contents of this legislation are as follows:

(1) information on WEEE generation, transportation, storage, and disposal should be reported to the local environmental protection department at or above county level;
(2) waste lead/acid batteries, nickel/cadmium batteries, mercury switches and relays, cathode ray tubes, and PCB bearing capacitors, shall be ensured being collected, stored and disposed. Duplicate forms must be filled for WEEE transfer, which are designed for the transfer of hazardous wastes, and

report to the competent administrative department of environmental protection;
(3) outdated recycling technology for WEEE, that may induce pollution, is prohibited. Open burning, simple incineration and rough extraction of metals from WEEE using acid are banned;
(4) enterprises engaged in WEEE collection, storage, disposal shall apply to the competent administrative department of environmental protection at or above the provincial level for the operation license. Any illegal activities will be punished in accordance with the "Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste";
(5) local EPBs should take measures to encourage clean production in EEE manufacturing. Pollutants such as lead, mercury, cadmium, chromium (VI), PBB, PBDE, etc. should be gradually phased out in EEE manufacturing. Environmental sound design and package should be employed.

In view of the WEEE strategies successfully performed in other countries and the current situation of China, the "Management Regulation on the Recycling and Treatment of Disposed Appliances and Electronics Products (MRRTDAEP)" was jointly drafted by six ministries including Ministry of Information Industry (MoII), Ministry of Commerce (MoC) and SEPA in September 2004. The revised version of the Regulation was just approved and will soon be promulgated by State Development and Reform Commission (SDRC). The new Regulation covers all types of EEE on the market, regardless of whether it is produced in, or imported to, China. This Regulation takes resource recycling and environmental protection as the goal, and practices the extended producer responsibility system. Its main contents are as follows:

(1) local governments shall be responsible for the collection and treatment of WEEE and should constitute corresponding detailed implementing rules;
(2) multiple collection and centralized treatment of WEEE should be implemented. WEEE recycling enterprises should be approved and authorized by SEPA;
(3) state should create a special fund for WEEE recycling;
(4) WEEE recycling enterprises shall operate according to market rules;
(5) government promotes and supports WEEE enterprises by formulating favorable policies and regulations;
(6) manufacturers of PCs, TV sets, mobile phones, DVD players, refrigerators and air-conditioners are required to select environmentally-friendly raw materials for their products and to recycle the discarded ones;
(7) manufacturers will be severely punished if they do not obey the new rules. They could either be fined and/or have their business licenses revoked.

The competition in the business of domestic electric appliances is extremely intense in China. The profit per domestic electric equipment is usually trivial. It is hardly performed for the producers entirely to finance the collection, treatment, recovery and disposal of WEEE like EU. Although China's economy is rapidly growing, most of Chinese are still not rich. It will be a heavy burden for Consumers to pay the necessary fees for collection, transportation and recycling of WEEE like Japan. Hereby state is very cautious when concerning the fee source for WEEE management. With the reference of the successful experience in other countries, the rule of the charge for WEEE management that suits for current situation of China is being studied by Chinese Household Electrical Appliances Association.

In view of the influence of EU directives of WEEE and RoHS on the global supply chains (also including China's electronics industry) and on the basis of the state legislation on "Enhancing Clean Production" and the state law of "Prevention and Cure of Environmental Pollution by Solid Waste", the legal document titled "Pollution Prevention and Control Method in Electronics Production" (in discussion) was also constituted by the MoII in 2004 with aim to implement green design and clean production concepts within the electronics industry to comply with the upcoming EU and China legislation in a proactive manner.

5.2. Recovery of WEEE

After the 20th century, with the aggravation of the environmental impacts induced by WEEE, strategies of WEEE treatment began to arouse wide attention in China. Many articles introduced legislation, management and recycling technologies of WEEE implemented in developed countries [42–46]. Studies have been made for the recycling of WEEE. In July 2003, Ministry of Science and Technology of China (MoST) initiated National High Tech Research and Development Program (NHTRDP) on WEEE recycling technology with the aim to promote the research and development on technological aspects of WEEE management.

Duan et al. [47] presented a practical physical process for recycling waste PCBs as well as the reusing process for epoxy resin recovered from PCBs. A special crusher with extra extruding, impacting and shearing forces was developed. With this crusher, the glass-enforced PCBs could be readily crushed to proper granularity. After the powder-making and separation process, the liberation degree of metals from non-metals exceeded 95%. A cooling-spray system, multilevel leaching device and labyrinth-type backwater were used to improve the environmental condition of the crushing and separation processes. The entire recycling process was built as a closed loop system and almost no waste air and water were let out.

In the work by Zhao et al. [48–50], mechanical processes were developed to recover copper or metals from waste PCBs. In their experiments, PCB samples were crushed to particles by a two-stage shredding operation to achieve liberation of metals from other components. In order to calculate and analyze the liberation degree, PCBs were divided into PWBs (printed wiring boards), slots and ICs (integrated cards). Their experimental results showed that the metals in PWBs and ICs were difficult to liberate from non-metals, but metals in the slots (ISA, PCI, AGP, etc.) of PCBs were easy to disengage from plastics after slightly crushing. Metals liberation degree of PCBs increased with the decreasing in particle size. It was found that the optimal liber-

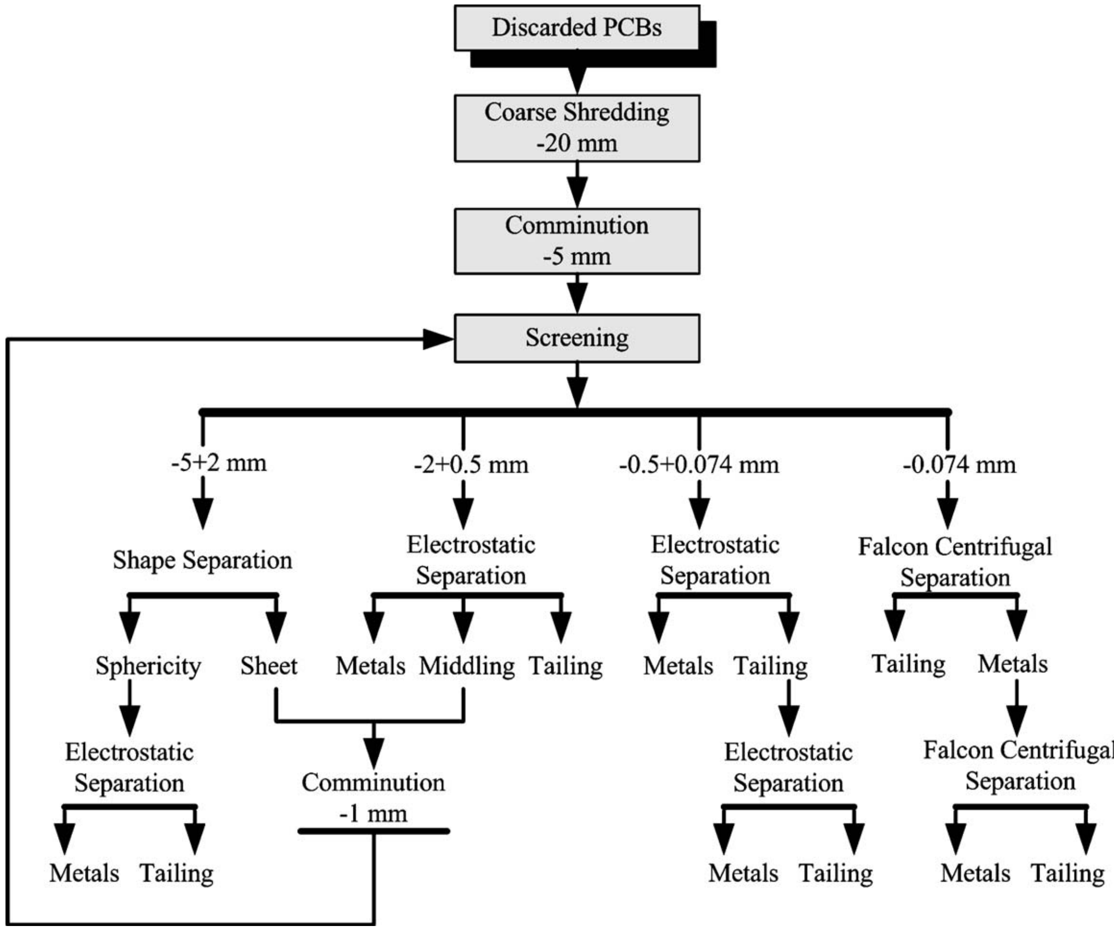

Fig. 6. Flowchart of metals recovery from discards PCBs by physical methods.

ation particle size for PWBs and ICs was around 0.5 mm. For waste PCB powders with particle sizes of 0.075–1 mm, about 90% copper was recovered by the combination of electrostatic separation and pneumatic separation [48], and metals (mainly copper and aluminum) recovery reached 80% averagely using a conventional electrostatic separator [49,50]. For PCBs with particle sizes smaller than 0.074 mm, metals can be effectively recovered by an enhanced Falcon concentrator and 80.77% integration efficiency can be achieved [50]. Based on above observations, an effective mechanical process that combines two-stage shredding, screening, shape separation, electrostatic separation and Falcon centrifugal separation was proposed to recover metals from waste PCBs [50]. Fig. 6 is the flowchart of this process.

Studies on pyrolysis of waste PCBs were carried out by Sun et al. [51–53] under various conditions with thermogravimetry. Liquid yield of 15–21%, gas yield of 15–20% and solid yield of about 60% were obtained in the nitrogen atmosphere [51]. The liquid products had high gross calorific values that might be recycled as fuel oils after simple treatment. CO, CO_2 and N_2 were the main constitutes of the gas products. Using combustion method, 7% organic carbon in the solid products could be removed. Then the solid products, which contained high purity fiberglass and $CaCO_3$, could be reused as filling materials in the process of SMC (sheet moulding compounds) production. It was found that the final pyrolysis temperature and particle size had marked influences on pyrolysis products, and that the yield of gas products increased at high temperatures for powder samples. The dynamic thermogravimetric analysis curve and its derivative were also analyzed to obtain the information on the kinetic parameters [52,53]. Their experiment results showed that there were two reaction stages when oxygen was presented, the reaction would be postponed with increased heating rates, and that the two reactions obeyed different mechanisms.

Besides lab investigations of WEEE recovery, recycling practices of WEEE are also promoted in China. Since December 2003, SDRC designated Qingdao City, Zhejiang Province, Beijing City and Tianjin City as the trial demonstration administrations to establish WEEE recycling system and management method. The four corresponding enterprises are: Qingdao Haier Group Company, Hangzhou Dadi Environmental Protection Company, China Huaxing Group Company and Tianjin Datong Copper Industry Company [54]. Zhejiang Province constituted “Temporary Trial Method for Collection and Treatment of WEEE in Zhejiang Province” which was brought into effect at the beginning of 2005. This method follows the principle of fixed-point collection, centralizing treatment and extended producer responsibility, proposes to establish a formal collection network covering entire province for WEEE, and stipulates corresponding responsibilities of the government, production enterprises, sellers and consumers. Hangzhou Dadi Environmental Protection Company has constructed a recycling center of WEEE and has set up 36 collection spots and 4 collection channels. The four collection channels are: (1) dealers, (2) communities, (3) institutions such as government agencies, universities and colleges, and (4) manufacturers of EEE for collection of by-products. The collected WEEE is delivered to the recycling center, where the products are firstly repaired or maintained for reuse. When reuse is impossible, products are disassembled, comminuted and then separated for recovery of the valuable materials.

Qingdao Haier Group Company, China Huaxing Group Company and Tianjin Datong Copper Industry Company also began to build workshops for WEEE recycling. Corresponding technologies are being developed.

Besides the above four trial demonstration models, some other WEEE recycling plants are also founded. For example, on 25 September, 2004, a WEEE processing center invested by Fortune Group was completed and put into action for recovering precious metals from WEEE. Since 2003, the Tianjin Loyalty Glass Material Company has begun to specialize in recycling glass materials from CRT by-products provided by the Tianjin Samsung SDI Company. In 2004, the company along with Tianjin University successfully developed a waste CRT recovery technology that includes dismantling, separating and recycling processes. Shanghai WEEE Recycling Center Co., Ltd. has begun to construct workshops, and along with Tongji University is developing WEEE recycling technologies and setting up a corresponding WEEE collection network system. Guangzhou GISE-MBA New Plastics Technology Co., Ltd. is a Sino-US joint-venture established jointly by American MBA Polymers Inc. and Guangzhou Iron and Steel Enterprises Group with total investment exceeding US$ 12 million. The joint-venture contract was signed in January 2004, the workshop construction and the equipment installation were completed in March 2005 and in August 2005, respectively, and the company has started operation from November 2005. By utilizing an entirely mechanical separating process, the company recycles mixed scrap plastics into high quality ABS, HIPS and PP in an environmentally safe way. Now, the company mainly imports mixed plastics for processing, but it aims at enormous quantities of end-of-life appliances, cars, plastic-rich consumer goods and WEEE.

5.3. International co-operation

Globalization of electronics has been realized on a very high level with relations between suppliers from different continents. Consequently, the ever-increasing WEEE has become a global problem. Resolving the problem and thus improving the sustainable development of the electronic industry in China require extensively international cooperation not only in technologies, but also in management, knowledge exchange, and education, etc. However, in Asia and the Pacific (including China), despite the initiatives by some of the countries, agencies with the mandate on waste management in the region generally have no specific knowledge of the composition of WEEE and their management; and lack communication, information exchange, and corresponding cooperation among them. So it is necessary to promote WEEE management in Asia and the Pacific by initiating a regional level activity for knowledge sharing under the direction of UNEP. The application for setting up "Asia-Pacific WEEE Database and Management Center" has just been approved by UNEP, and the center will soon be established in UNEP-Tongji Institute of Environment for Sustainable Development. Main activities are as follows:

(1) collecting information regarding WEEE in Asia and the Pacific and establishing corresponding database;
(2) organizing annual international conference of WEEE to exchange related information;
(3) analyzing the performance and logistic aspects of WEEE management systems currently implemented in the European Union, the United States, Japan and so forth, and then investigating regulations, policy and byelaw about WEEE management fit for the local status to service related office;
(4) organizing international forum on recycling technology of WEEE in order to introduce successfully applied cost-effective and environmentally friendly technologies to Asia-Pacific region;
(5) inspecting the operation of introduced technologies and organizing researchers to make innovation with finding problems.

6. Current problems of WEEE recovery in China

As described above, entering the 21st century, with the ever increase of WEEE generated in China and the aggravation of the corresponding environmental problems, some projects on WEEE management are being performed. However, the systematic work on WEEE is just beginning. There are still some problems that restrict the operation of qualified WEEE recycling enterprises in China.

The end-of-life domestic electric appliances, such as TV sets, refrigerators and washing machines, are not wastes, but merchandises for most of their holders in China. Generally, the "merchandises" are collected by hucksters. Most of them are sold to the countryside after simple repair or maintenance. What can no longer be reused are dismantled manually, and then treated in unqualified household workshops or small factories for recovery of valuable components and materials. In these household workshops or small factories, the recovery processes are carried out with inappropriate methods, regardless of the corresponding impact on environment and health of the operators, so their recycling costs are much low. By contraries, the qualified recycling plants have advanced recovery technologies, and proper environmental and healthy protective measures that their operation costs are high. Compared with these household workshops or small factories, the fare paid for collection of the end-of-life domestic electric appliances is a heavy burden for these qualified recycling plants. Before the enforcement of the legislations on WEEE, above unqualified household workshops or small factories could not be forbidden completely. Consequently, the competition for collection of the end-of-life domestic electric appliances can hardly be put to an end.

Besides, the charges for treating waste domestic electric appliances are now paid by recycling companies themselves. As a result, the total charge including the fares for collection and treatment is usually higher than the income gained from selling the reusable secondhand products and valuable recovered materials for a qualified WEEE recycling company. For example, the actual situation of Hangzhou Dadi Environmental Protection Company shows that the average fare for collection and treatment of TV sets is about 120 yuan per unit, while the income gained from selling corresponding valuable reclaimed materials is about 50 yuan per unit.

Due to the problems above, it is impossible for a qualified WEEE recycling company to operate successfully before enforcing the legislations and formulating favorable policies and regulations on WEEE.

7. Conclusions

In view of the environmental impact induced by WEEE and the high residual value of the materials contained in WEEE, the recycling of WEEE is attracting wide attention. In China, some projects on WEEE management are being carried out, but there are still some problems that restrict the commercial operation of qualified WEEE recycling enterprises. In order to accelerate the solution of WEEE in China, it is vital to complete the legislations on WEEE and formulate corresponding favorable policies and regulations as soon as possible. Meanwhile, it is important to introduce and develop cost-effective and environmentally friendly WEEE recycling technologies, and to implement green design and cleaner production concepts within the electronics industry to comply with the upcoming EU and China legislations in a proactive manner. Besides, it is also necessary to arouse and enhance public awareness regarding environmental protection by publicity, education and so forth, in order to change their traditional viewpoint on the end-of-life domestic electric appliances.

Acknowledgements

The authors gratefully acknowledge the financial supports of the Ministry of Science and Technology of China (Grant No. 2004BA908B02) and China Postdoctor Foundation.

References

[1] European Commission, Draft proposal for a European parliament and council directive on waste electric and electronic equipment, Brussels, 2000. Belgium. http://www.eia.org/download/eic/21/www Final Proposal June 2000.htm, 2000-07-31.

[2] Silicon valley toxic coalition, Just say no to E-waste: Background document on hazards and waste from computers. http://www.svtc.org/cleancc/pubs/sayno.htm, 2003-01-06.

[3] Electronic Scrap—A Hazardous Waste, Australian Government, Department of the Environment and Heritage, 2004.

[4] A mobile is not just for Christmas Tuesday. BBC, 2002. http://www.news.bbc.co.uk/2/hi/technology/2603589.stm.

[5] Association of plastics manufacturers in Europe (APME), Plastics—a material of choice for the – electric and electronic industry – plastics consumption and recovery in Western Europe, 1995. APME report code 98-2004, Brussels, Belgium, p. 1.

[6] E.Y.L. Sum, The recovery of metals from electronic scrap, JOM 43 (1991) 53–61.

[7] S. Zhang, E. Forssberg, Mechanical separation-oriented characterization of electronic scrap, Resour. Conserv. Recycle 21 (1997) 247–269.

[8] J. Linton, Electronic products at their end-of-life: options and obstacles, J. Electron. Manuf. 9 (2000) 29–40.

[9] A. Appelbaum, Europe cracks down on e-waste, IEEE Spectr. (2002) 46–51.

[10] A. Nagurney, F. Toyasaki, Reverse supply chain management and electronic waste recycling: a multitiered network equilibrium framework for e-cycling, Transport. Res. Part E 41 (2005) 1–28.

[11] M. Rose, Design for environment: a method for formulating product end-of-life strategies, PhD Thesis, Department of Mechanical Engineering, Stanford University, 2000, pp. 19–144.

[12] B. Billatos, N. Basally, Green Technology and Design for the Environment, Taylor & Francis, Washington, DC, 1998, pp. 3–90.

[13] C. Rose, K. Beiter, K. Ishii, Determining of end-of-life strategies as a part of product definition, in: Proceedings of the IEEE International Symposium for Electronics and the Environment, Danvers, MA, 1999.

[14] M. O'Neill, WEEE & RoHS and trends in the environmental legislation in European Union, in: Proceedings of the Eco Design 2003 Third International Symposium on Environmentally Conscious Design and inverse Manufacturing, Tokyo, Japan, 2003.

[15] European Parliament (2003) Directive 2002/96/EC on waste electrical and electronic equipment (WEEE). Official Journal of the European Union, Brussels, February 13, 2003.

[16] DTI–UK, 2002. Environmental life cycle assessment and financial life cycle analysis of the WEEE directive and its implications for the UK. Price Water House Coopers, UK, 2002.

[17] S. Jofre, T. Morioka, Waste management of electric and electronic equipment: comparative analysis of end-of-life strategies, J. Mater. Cycles Waste Manage. 7 (2005) 24–32.

[18] CJC, Recycle-Oriented Society. II. Towards Sustainable Development, Clean Japan Center, Tokyo, 2002.

[19] M. Yamaguchi, Extended producer responsibility in Japan, in: ECP Newsletter (19), JEMAI, Tokyo, 2002, pp. 1–12.

[20] Y. Tokita, K. Ueno, Y. Iseki, T. Shirai, Some requirements from recycling plant to material manufacturers, in: Proceedings of an International Conference on Ecobalance, Tokyo, 2000, pp. 111–114.

[21] J. Cui, E. Forssberg, Mechanical recycling of waste electric and electronic equipment: a review, J. Hazard. Mater. B99 (2003) 243–263.

[22] A. Gungor, S.M. Gupta, Disassembly sequence planning for products with defective parts in product recovery, Comput. Ind. Eng. 35 (1998) 161–164.

[23] K. Feldmann, S. Trautner, O. Meedt, Innovative disassembly strategies based on flexible partial destructive tools, Annu. Rev. Cont. 23 (1999) 159–164.

[24] B. Kopacek, P. Kopacek, Intelligent disassembly of electronic equipment, Annu. Rev. Cont. 23 (1999) 165–170.

[25] B. Scholz-Reiter, H. Scharke, A. Hucht, Flexible robot-based disassembly cell for obsolete TV-sets and monitors, Robot. Cim. -Int. Manuf. 15 (1999) 247–255.

[26] Ragn-Sells Elektronikåtervinning AB, Elektronikåtervinning, Report, Stockholm, Sweden, 2000.

[27] S. Zhang, E. Forssberg, Intelligent liberation and classification of electronic scrap, Powder Technol. 105 (1999) 295–301.

[28] P. Koch, R. Kasper, Zerlege und aufbereitungstechnik fuer elektroaltgeraete und elektronik-schrott, Aufbereitungs-Technik 37 (1996) 211–220.

[29] C.A. Harper, Handbook of Plastics, Elastomers and Composites, 2nd ed., McGraw-Hill, New York, 1992, pp. 2.1–2.57.

[30] Y. Higashiyama, K. Asano, Recent progress in electrostatic separation technology, Particul. Sci. Technol. 16 (1998) 77–90.

[31] D.A. Norrgran, J.A. Wernham, Recycling and secondary recovery applications using an Eddy-current separator, Miner. Metal. Proc. 8 (1991) 184–187.

[32] H.G. Schubert, G. Warlitz, Sorting metal/non-metal mixtures using a corona electrostatic separator, Aufbereitungs-Technik 35 (1994) 449–456.

[33] I. Stahl, P.-M. Beier, Sorting of plastics using the electrostatic separation process, in: H. Hoberg, H. von Blottnitz (Eds.), Proceedings of the XX International Mineral Processing Congress, vol. 5, Aachen, GDMB, Clausthal-Zellerfeld, Germany, 1997, pp. 395–401.

[34] E.L. Bernd, Recycling von Elektronikschrott, Metall 48 (1990) 880–885.

[35] S. Yokoyama, M. Iji, Recycling of Printed Wiring Board Waste, in: Proceedings of the 1993 IEEE/Tsukuba International Workshop on Advanced Robotics, IEEE, 1993, pp. 55–58.

[36] Ministry of Information Industry, Electronics Industry Yearbook, Publishing House of Electronics Industry, Beijing, 1992–2002.

[37] Chinese National Bureau of Statistics, China Statistical Yearbook, China Statistics Press, Beijing, 1990–2004.

[38] X.L. Liu, J.X. Yang, R.S. Wang, Estimation of WEEE generation in China, China Popul. Resour. Environ. (Chinese) 15 (2005) 113–117.

[39] Y.L. Zhang, H. Tian, Y. Zhu, Interview about collection and recycling of WEEE, Household Appliance 5 (2002) 10–11.

[40] A. Terazono, A. Yoshida, J.X. Yang, Y. Moriguchi, S.I. Sakai, Material cycles in Asia: especially the recycling loop between Japan and China, J. Mater. Cycles Waste Manage. 6 (2004) 82–96.

[41] The Basel Action Network (BAN), Silicon Valley Toxicity (SVTC), 2002. Exporting harms. http://www.svtc.org/cleancc/pubs/technotrash.Pdf.

[42] F. Wu, Preliminary exploring to electronic scrap management and recycling technology: Summarization of foreign present situations, China Environ. Protect. Industr. (Chinese) (2) (2004) 38–39.

[43] J.W. Wang, J.Q. Xu, Introduction of European Union directive method on waste electrical and electronic equipment, China Environ. Manage. (Chinese) 22 (4) (2003) 48–91.

[44] Q.Z. Bai, H. Wang, J. Han, Y.F. Nie, The status of technology and research of mechanical recycling of printed circuit board scrap, Tech. Equip. Environ. Pollut. Control (Chinese) 2 (1) (2001) 84–89.

[45] X.L. Cai, Y.M. Zhao, C.Y. Wang, Mechanical recycling of electronics scrap: Current status and prospects, Pollut. Contr. Technol. (Chinese) 16 (2003) 47–50.

[46] J. Lai, Germany's WEEE recycling system and resource reusing technology, Technol. Electr. Mach. Appliance (Chinese) (5) (2004) 1–4.

[47] P. Mou, L. Wa, D. Xiang, J. GAO, G. Duan, A physical process for recycling and reusing waste printed circuit boards, IEEE (2004) 237–242.

[48] Y. Zhao, X. Wen, B. Li, D. Tao, Recovery of copper from waste printed circuit boards, Miner. Metallurg. Process. 21 (2004) 99–102.

[49] X. Wen, Y. Fan, Y. Zhao, Y. Cao, X. Cai, C. Duan, H. Wang, Study on the metals recovery from discarded printed circuit boards by electrostatic separator, Environ. Eng. (Chinese) 22 (2004) 78–80.

[50] X. Wen, Y. Zhao, C. Duan, X. Zhou, S. Song, Study on the metals recovery from discarded printed circuit boards by physical methods, IEEE (2005) 121–128.

[51] L.S. Sun, J.D. Lu, S.J. Wang, L. Zeng, J. Zhang, Experimental research on pyrolysis of printed circuit board wastes and analysis of characteristics of products, J. Fuel Chem. Technol. (Chinese) 30 (2002) 285–288.

[52] L.S. Sun, J.D. Lu, L. Zeng, L.Y. Yu, Kinetic study on thermal degradation of printed circuit boards, J. Huazhong Univ. Sci. Technol. 29 (2001) 40–42.

[53] L.S. Sun, J.D. Lu, S.J. Wang, J. Zhang, H. Zhou, Experimental research on pyrolysis characteristics of printed circuit board wastes, J. Chem. Industr. Eng. (Chinese) 54 (2003) 408–412.

[54] Progress of trial demonstrations for collection and treatment of WEEE. http://www.gzge.com.cn/qydtInfo.asp?Articleid=731.