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# Electronic waste recycling: A review of U.S. infrastructure and technology options

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**Abstract**

The useful life of consumer electronic devices is relatively short, and decreasing as a result of rapid changes in equipment features and capabilities. This creates a large waste stream of obsolete electronic equipment, electronic waste (e-waste).

Even though there are conventional disposal methods for e-waste, these methods have disadvantages from both the economic and environmental viewpoints. As a result, new e-waste management options need to be considered, for example, recycling. But electronic recycling has a short history, so there is not yet a solid infrastructure in place.

In this paper, the first half describes trends in the amount of e-waste, existing recycling programs, and collection methods. The second half describes various methods available to recover materials from e-waste. In particular, various recycling technologies for the glass, plastics, and metals found in e-waste are discussed. For glass, glass-to-glass recycling and glass-to-lead recycling technologies are presented. For plastics, chemical (feedstock) recycling, mechanical recycling, and thermal recycling methods are analyzed. Recovery processes for copper, lead, and precious metals such as silver, gold, platinum, and palladium are reviewed. These processes are described and compared on the basis of available technologies, resources, and material input–output systems.


*Keywords:* End-of-life (EOL); Electronic waste (e-waste); Recycling; Materials recovery; Infrastructure

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## 1. Introduction

Since the 1980s, with the development of consumer-oriented electrical and electronic technologies, countless units of electronic equipment have been sold to consumers. The useful life of these consumer electronic devices (CEDs) is relatively short, and decreasing as a result of rapid changes in equipment features and capabilities. This creates a large waste stream of obsolete electronic equipment.

The conventional and primary disposal method for this waste in the U.S. is disposal in landfills and incineration. Increasing the need for landfills is a burden to our environment. Also, with a shortage of landfill capacity and an increased concern about environmental quality, diverted waste treatment methods are desired. New waste management options are needed to divert end-of-life (EOL) electronics from landfills and incineration. However, there are several factors to consider in the development of a successful diversion strategy. This strategy must be based on its economic sustainability, technical feasibility, and a realistic level of social support for the program. One aspect of the strategy should include recycling and reuse of EOL electronic products.

It should be noted that, at present, electronic waste recycling has a short history in the U.S., so that there is not yet a broad and fixed infrastructure in place. The International Association of Electronics Recyclers (IAER) estimated that in 2003 the U.S. electronics recycling industry consisted of just over 7000 employees and annual revenue of over US$ 700 million (IAER, 2003). Electronic products are an integration of numerous modern technologies and are composed of many different materials and components. This means that to recycle EOL electronics effectively, many parties and technologies should be involved.

As with the recycling of other products, the establishment of appropriate infrastructure is essential to the successful implementation of electronic waste recycling. Infrastructure

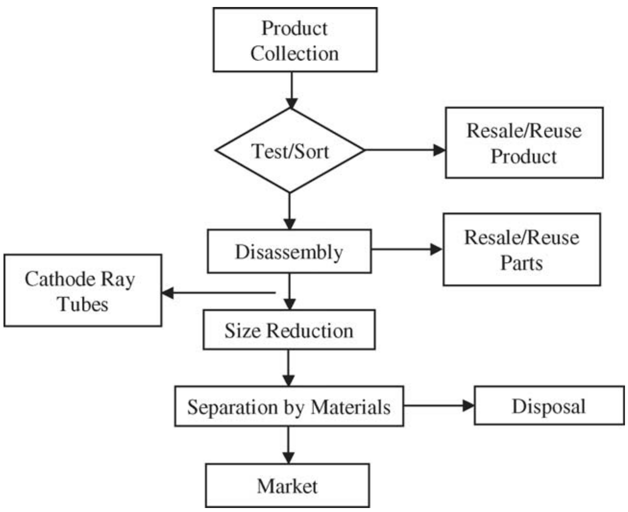


Fig. 1. Simplified flow diagram for the recycling of an electronic product.

determines the process methods and amounts of waste that can be processed. It includes transportation, collection, recovery, and resale establishments. Factors that affect the recycling infrastructure are the amount of waste in the waste stream, the recycling technologies available, government regulations, and the economics of EOL products.

To provide a better understanding of the current processes and infrastructure available for electronic recycling within the U.S., we start at the point when CEDs first become waste (either through obsolescence or through operational failure) and proceed through the collection, treatment, and final disposition of recycled electronic waste. This description includes key players at each step and provides a comprehensive view of the infrastructure available for the recycling of electronic waste.

Key factors in the recycling of e-waste are collection, sorting and recovery, recycling and disposal, as shown in Fig. 1.

## 2. Quantity and types of e-waste

Millions of tonnes of electronic waste from obsolete computers and other electronics are being generated in the U.S. each year. Electronic waste already constitutes from 2 to 5% of the U.S. municipal solid waste stream and is growing rapidly (Silicon Valley Toxics Coalition, 2004). Fig. 2 shows actual and estimated values for the number of personal computers (PCs) shipped (Silicon Strategies, 2001) and becoming obsolete in the U.S. for the years 1997–2005. In 2003, more than 54 million PCs were sold. In comparison, according to a May 1999 study from the National Safety Council (NSC) in Itasca, Illinois (National Safety Council, 1999), nearly 63 million personal computers in the U.S. were expected to become obsolete in 2003. The rate of PC obsolescence now exceeds the rate of production.

The lifespan of PCs is getting shorter as a result of technology development and higher standards for PCs. For example in 1992, the average lifespan of a PC was 4.5 years, but this

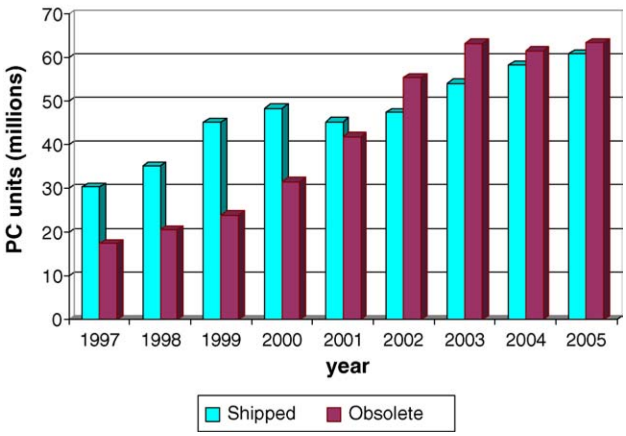


Fig. 2. Personal computer (PC) shipments and obsolescence in the U.S.

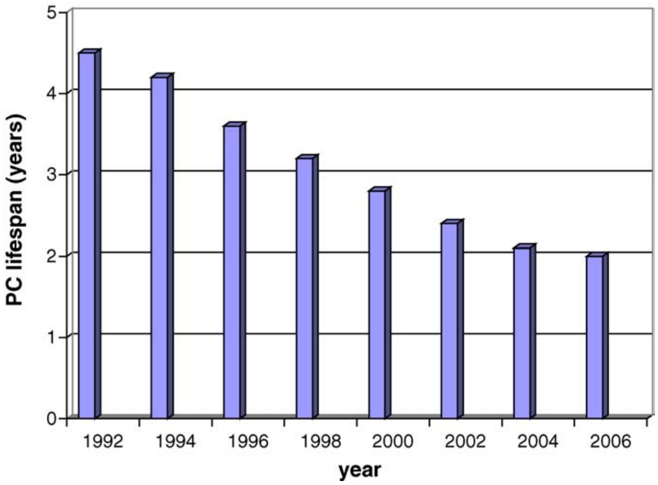


Fig. 3. Personal computer (PC) average lifespan in the U.S.

value was estimated to decrease to only 3 years by 1999 and is expected to further decrease to 2 years by 2005 (National Safety Council, 1999). Fig. 3 shows this change in PC lifespan.

Used electronics contain significant amounts of hazardous materials, such as mercury, lead, cadmium, and polychlorinated biphenyls. Cathode ray tubes (CRTs) are one of the largest sources of lead in municipal solid waste (Jung and Bartel, 1998). On the other hand, used electronics contain high-value materials such as gold, palladium, copper, and plastics. Furthermore, several obsolete electronic devices, which are clean and functional, can be reused if identified and sorted out by experts.

Major milestones that encourage electronic recycling are the bans on both the disposal of CRTs in landfills and their incineration, which began in Massachusetts in 2000 and in California in 2001 (USEPA, 2000; DTSC, 2001). Maine and Minnesota have also recently banned CRT disposal (Silicon Valley Toxics Coalition, 2004). According to these bans, all CRTs must be recycled in these states. Another milestone for electronic recycling is extended producer responsibility (EPR). EPR is a principal for pollution prevention in which producers take responsibility for their products at their EOL. The State of California

Table 1
Generation and recovery of consumer electronics in the U.S. waste stream in 2001 (unit: $10^6$ kg)

| Types of consumer electronics | Total generation | Total recovery | Recovered (%) |
|---|---|---|---|
| Video product[a] | 806.2 | 1.1 | 0.1 |
| Audio product[b] | 377.9 | 0 | Negligible[*] |
| Information product[c] | 1076.3 | 204.5 | 19 |
| Total | 2260.4 | 205.6 | 9 |

[a] TVs, VCR decks, camcorders, TV/VCR combinations.
[b] All types of compact disc players, rack audio systems, compact audio systems.
[c] Personal computers, computer monitors, telephones, fax machines.
[*] Less than 5000 tonnes or 0.05 wt.%.

has passed the 'California Electronics Waste Recycling Act' and according to this Act, by 2010 each manufacturer that sells electronic devices must either collect an equivalent to 90% of the number of devices they sell or they must pay the alternative fee for recycling the devices they sell (The California Electronics Recycling Act, 2003).

Table 1 shows the generation and recovery of e-waste for recycling in the U.S. waste stream in 2001 (USEPA, 2003). The recovery rates are distinguished by product type. The total recovery rate is approximately 9 wt.%, which is less than half that of the value in the general U.S. municipal solid waste stream, such as for paper, glass, and metals (USEPA, 2003).

## 3. Electronics recycling programs

### *3.1. Public recognition of the need for e-waste recycling*

Because electronic recycling is in its infancy, consumer recognition of the need for recycling is a critical factor to the further expansion of this industry. Many consumers do not recycle their electronic products when they first become defunct or obsolete. In fact, more than 70% of retired CEDs are kept in storage, typically for as many as 3–5 years (USEPA, 2000). Consumers think that these CEDs have some value. This reasoning is flawed. With the development of electronic technologies, the residual value of outdated electronic devices decreases rapidly. Both the recovery value of parts and the machine resale value drop rapidly with the age of the machines. For example, a computer's value approaches zero for machines with technologies more than two generations old. Furthermore, old equipment is more difficult to recycle than newer equipment. In general, this old equipment contains a larger variety of materials, such as different plastics, and a larger amount of hazardous materials, such as lead. Consequently, it is better to get rid of old computer equipment as soon as it seems to be obsolete.

### *3.2. Advertisement for recycling*

Effective electronics recycling requires that consumers both have access to recycling programs and have knowledge of such programs. This essentially means that consumers need to know where to take their electronic devices when they become obsolete or defunct. Several municipalities have piloted collection programs that are now available to the consumer (IAER, 2003). As a result, ongoing electronics collection programs are more common. Their success requires advertising (Jung and Bartel, 1998; USEPA, 2000). Collection might involve either a permanent collection site or a special event site. Advertising is needed, especially for special event collection. Advertisements should indicate collection time, collection site, and items that can be accepted. The media for advertisements include: newspapers, radio, local television (TV) stations, signs, and flyers. E-mail and web sites are also used.

Some reports and pilot projects have shown how advertising can affect the amount of collection for recycling, especially if special events are used (USEPA, 2000). Appropriate advertising methods should be selected according to regional characteristics. Methods differ, for instance, between rural and urban areas, and residential and business areas. For a

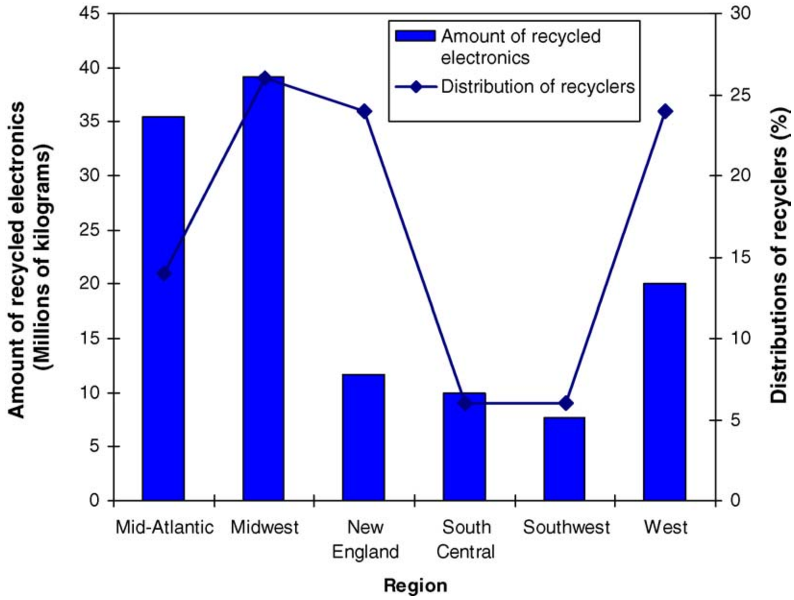


Fig. 4. Distribution of recyclers and the amount of electronic equipment recycled in the U.S.

commercial area, a newspaper advertisement might be preferred; for a rural area, radio or a local TV station might be selected. At a large university or company, an e-mail advertisement can be an efficient advertisement method.

### 3.3. Key players and distribution of electronic recycling programs

In the U.S., government, usually municipalities, plays the primary role in offering e-waste collection and recycling programs. These programs include special drop-off event as well as ongoing collection event. However, special events demonstrate that a significantly higher percentage of programs are being operated by non-government entities, such as recyclers, charity parties, and solid waste haulers (Northeast Recycling Council, Inc., 2002).

Approximately 500 residential used electronics collection programs were held in the U.S. between 1999 and 2001. These programs were held in 30 of the 50 states.[1] Most of the programs targeted consumer electronics and residential collection methods, and a majority of the programs had been in operation for 36 months or less, which highlights the short history of e-waste recycling programs (Northeast Recycling Council, Inc., 2002). Also, some manufacturers and retailers provide e-waste collection and recycling programs, which are implemented across the U.S. (IAER, 2003; USEPA, 2003).

Fig. 4 shows the distribution of recycling companies and the amount of electronic equipment recycled in the U.S., by geographic region. This figure reflects the presence of recycling

[1] The majority of the programs have been conducted in the states Massachusetts, Illinois, New York, Minnesota, California, New Jersey, North Carolina, and Michigan.

operations in each region.[2] Recycling companies are concentrated in the midwest, New England, and the West, each of which accounts for approximately one-quarter of the recycling companies. The regional distribution of recycling activity indicates that the midwest and mid-Atlantic regions have the highest level of recycling activity, followed by the West (National Safety Council, 1999; IAER, 2003).

## 4. Collection and transportation

At present, there is no single collection strategy being implemented within the U.S. that can achieve a satisfactory recovery rate of used electronics (Eglise and Pierre, 2000). The collection and transportation step is often the most costly step toward the reuse and recycling of electronic devices (Lonn and Stuart, 2002; IAER, 2003). It has been estimated that collection and transportation costs represent more than 80% of the total cost of recycling (Hainault and Smith, 2000). Collection methods have been widely studied in connection with many pilot e-waste recycling projects (Lonn and Stuart, 2002; Eglise and Pierre, 2000; Hainault and Smith, 2000). Table 2 shows a summary of collection options and transportation responsibilities.

Curbside collection consists of the collection of e-waste either on a periodic basis like a general municipal waste collection or by request. Co-existence of the e-waste collection with an existing curbside waste collection program can substantially reduce the operating costs. This collection model is the most convenient for residents. However, operating costs can be higher than for other collection options. Also, there is the potential for theft of devices that are set out for recycling, and for the abandonment of waste other than e-waste.

A special drop-off event is a 1- or 2-day event that is usually held over a weekend to maximize resident participation. In this collection option, the quantity of devices collected will depend on the extent of participation by consumers and the weather during the special event period. A special drop-off event is considered to be an ideal recycling program when experts from the repair industry work together with the program, because these experts can sort out the most valuable items for resale, repair, and reuse.

A permanent collection option is essentially a year-round collection event. The municipal solid waste collection site can be used for collection of e-waste, which results in negligible costs. This type of program has been found to be the most cost-effective (IAER, 2003), however, this type of collection program is not desirable for every community size. This collection option requires that the quantity of collected devices be checked regularly and that the devices be transported to a recycler when certain quantities are collected.

In the point-of-purchase collection model, retailers of electronic products serve as the collection agency and consumers can bring old electronic equipment to a retailer when they purchase new electronic equipment. This collection option can be implemented as either a permanent or special drop-off event, depending on the retailer's preference. The active participation of the retailer is essential for this method of collection to be successful.

[2] Mid-Atlantic: New York, New Jersey, Pennsylvania; midwest: Iowa, Indiana, Minnesota, Ohio, Wisconsin; New England: Connecticut, Massachusetts, New Hampshire, Rhode Island, Vermont; south central: Texas; southeast: Florida, Georgia, North Carolina; west: Arizona, California, Washington.

Table 2
Summary of collection options and transportation responsibilities

| Collection options | Responsible for transportation | | Advantages | Disadvantages |
|---|---|---|---|---|
| | To collection site | To recycling site | | |
| Curb side | – | Local government or recycler | Convenient. Resident participation | Potential theft and abandonment. Need extra sorting. High transportation cost |
| Special drop-off event | Consumer | Local government or recycler | Increase recycling awareness. Good for rural area | Irregular collection amount. Need storage space |
| Permanent drop-off | Consumer | Local government or recycler | High sorting rate. Low transportation cost. Most cost-effective | Need regular checking. Not effective for all communities |
| Take-back | – | OEMs or recycler contract with OEMs | No collection site needed | High shipment cost. Need special packaging. Consumers visit shipping location |
| Point-of-purchase | Consumer | Retailer | Low cost. High visibility if promoted by retailer | Retailer commitment. Need storage space |

OEM: original equipment manufacturer.

Several original equipment manufacturers (OEMs) have established 'take-back' collection systems for collecting used electronic products from consumers. IBM, Dell, HP, and other computer manufacturers collect unwanted computer and related products regardless of the original manufacturer (Environmental and Plastics Industry Council, 2003). For example, United Recycling[3] has a take-back collection service for Compaq Computers (United Recycling, 2004). Some OEMs require a minimum volume of used electronic products to be collected and restrict the pick up location (HP Hardware Recycling, 2004).

One pilot project by the United States Environmental Protection Agency (USEPA, 2000) shows that special drop-off events are the most effective collection method in rural areas. Special drop-off event that take place at retail stores is the single most successful collection method, when measured by the percent of participants or by cost per participant (Hainault and Smith, 2000). Although curbside collection is most convenient for consumers, an extra sorting process is required. Among these collection options, permanent collection (47%), special drop-off events (45%), and curbside collection (8%) are the most extensively used programs (IAER, 2003).

An appropriate collection site can be selected by taking into consideration the geographic location, the ease and convenience to consumers, and the population distribution. For special drop-off events, electronic equipment retail stores (Jung and Bartel, 1998) or large public parking lots can be used for the collection site.

Transportation is also an important aspect of electronic recycling. With curbside collection, transport is provided by local government, a private recycler, or a third party. In permanent collection, residents are responsible for the transportation to the collection site, and the transportation of the collected e-waste to the processing site is the responsibility of the recycler. In the case of a special drop-off event, consumers need to bring their e-waste to the collection site. Local government or the recycler then takes responsibility for the transportation to the recycling processing site.

## 5. Materials recovery facility (MRF) processing

Once transported to the recycling facility, or MRF, electronic waste is tested and sorted (see Fig. 1). In the U.S., the MRF process is the most critical step in electronic recycling. The ultimate fate of the collected equipment is determined at the MRF. In MRF processing, collected equipment can be divided into two categories, reusable or recyclable. The equipment and parts that can be reused are sorted and everything else will eventually become either recycled or scrap materials. The important factors at this stage include the age of the equipment and its mechanical condition so as to maximize economic value from the collected devices. A schematic diagram of the process steps in an MRF is presented in Fig. 5. These steps are discussed below.

### *5.1. Sorting and demanufacturing processes*

Upon arrival at the MRF, used equipment is sorted into three secondary markets, which represent different economic values. The first market is for refurbished systems that can

[3] West Chicago, IL.

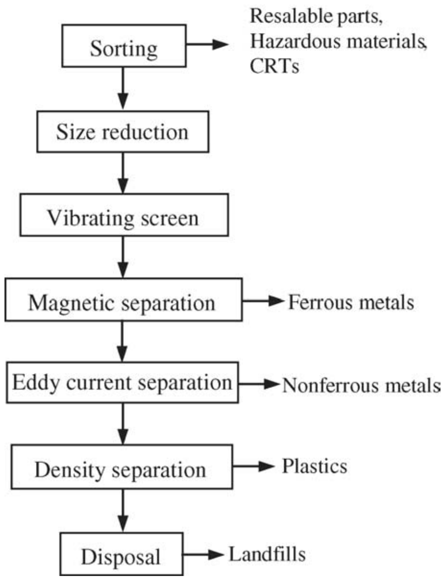


Fig. 5. Simplified schematic of the process steps at a materials recovery facility (MRF).

be sold or donated to secondary users, and the second market is for components that can be reclaimed, resold, and reused. The third market is for salvaged and recycled materials. Although straight-forward, examination and testing for reuse are time consuming and labor intensive tasks. A plug-and-play test is used to identify equipment that is operational. Equipment that fails the plug-and-play test may be dismantled for component resale and reuse. Recovery of individual components from e-waste is more complex than the simple plug-and-play test that can be used for a complete system. Employees responsible for component recovery must know (1) how to disassemble the system, (2) which components are valuable, and (3) which components, such as a hard drive, require special care in handlings.

To maximize economic value, the disassembly process starts with high-end parts, which are more valuable, and finishes with low-end parts. Another purpose for the demanufacturing step is to remove hazardous materials. For instance, printer ink cartridges must be removed before the printer can be recycled, because ink is a hazardous substance. Laminated metals are also removed and disposed of because of the difficulty in removing the laminated film from the metal. Proper selection of the order for demanufacturing steps is key to output efficiency.

### *5.2. Markets for used and demanufactured electronics*

Data from special drop-off event collection programs have revealed that more than 50% of the computers are in good working condition, even though they are discarded. These used computers are easily sold to secondary markets because markets still exist for these computers. In 1997, the market size for the TV repair industry in the U.S. was over US$ 17 billion and the number of people employed was 588,000 (USEPA, 2000). But the TV repair industry is in a state of decline. The State of Massachusetts has reported that most owners of TV repair shops are planning to retire (USEPA, 2000). Because new TV sets are often selling for under US$ 300, paying more than US$ 100 to repair an older TV does not make economic sense. But this trend can be beneficial to electronic recyclers, because if fewer TVs are repaired then more TV sets will be available for recycling.

In contrast, the computer repair industry is growing. This industry relies on high-tech, qualified labor, because a computer is a mixture of modern electronic technologies. As a consequence, this industry has two segments: organizations that repair computer monitors, and organizations that repair the computer, itself.

There is the potential for those in the computer repair industry to work together with the recyclers. Some electronic equipment that has been collected for recycling can be refurbished and resold by the repair industry, if the collected equipment has some market value. However, if the unit is old and obsolete, such as 286 CPUs, there is no market for these out-of-date machines even if they still work (Jung and Bartel, 1998). It should be noted that, for electronics recyclers, equipment and parts with value represent the most profitable items in their revenue stream, even though quantities are small. One repairable or resalable item or part out of 10 will dramatically affect the profit of recyclers (USEPA, 2000). For example, one TV (23 kg) resold at US$ 75 (USEPA, 2000), generates the same revenue as 3.25 tonnes of scrap plastic computer housing at US$ 20 per tonne (Computer and Electronic Recycling Index, 2004).

The largest market for electronics products collected in the U.S. is overseas. It is estimated that more than 50% of the e-waste collected for recycling in the western U.S. is exported to other countries such as China, India, and Pakistan, because the costs for recycling are very low compared to the costs of domestic recycling (The Basel Action Network, 2002). This situation, however, is in a state of flux as a result of pending registration in several of these countries.

### *5.3. Materials recovery*

After working systems, valuable components, and hazardous materials are removed from the e-waste, the materials recovery process begins. The primary goal of this process is to separate different types of materials that can be recovered and sold. Residential electronic waste collection programs in the U.S. show that the majority of the items collected consist of TVs, computers and monitors, and other appliances. Metals (49 wt.%), plastics (33 wt.%), and CRTs (12 wt.%) account for over 90 wt.% of collected e-waste (USEPA, 1999), as seen in Fig. 6. When only computers are collected, the distribution is different: glass (25 wt.%), metals (48 wt.%), and plastics (23 wt.%) (Silicon Valley Toxics Coalition, 2004). When only TVs are considered, the distribution is glass (48 wt.%), plastic (15 wt.%), and metal (32 wt.%) (Materials for the Future Foundation, 1999b).

Table 3 shows a summary of the material types in demanufactured TVs and computers. These results show that the major materials in electronic equipment are metals, plastics, and glass.

The rate of material recovery at a given MRF will depend on various parameters such as the size of the facility and the target electronic products (IAER, 2003).

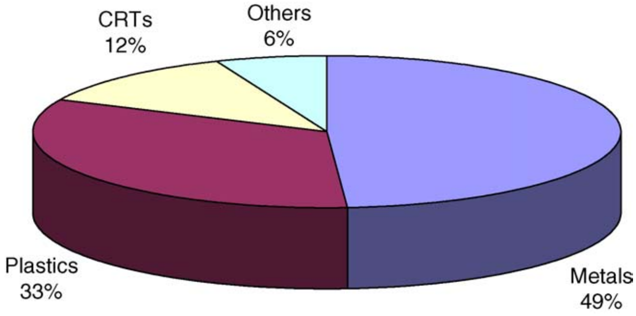


Fig. 6. Distribution of materials within collected residential electronics waste in the U.S.

Table 3
Summary of material types in demanufactured TVs and computers (unit: wt.%)

| Materials | TV | Computer* |
|---|---|---|
| Glass | 47.6 | 24.8 |
| Plastic | 14.7 | 23.0 |
| Printed wiring board | 5.6 | –** |
| Precious metals | 27.1 | 0.02 |
| Iron | – | 20.47 |
| Lead | – | 6.3 |
| Aluminum | – | 14.17 |
| Copper | 4.8 | 6.93 |
| Others | – | 4.3 |
| Total | 100 | 100 |

* CPU and monitor.
** Disassembled to plastics, metals, and other parts.

In order to separate the materials, the remaining steps in the MRF (see Fig. 5) are implemented, as discussed below.

## 6. Cathode ray tube recycling

Cathode ray tubes are a major item in electronic recycling due to their volume, recycling costs, and disposal restrictions. Fig. 7 shows an estimate of U.S. CRT shipment and obsolescence. This graph shows that in 2003 the rate of obsolescence has caught up with that for CRT shipments. A CRT consists of two major parts. One is the glass components (funnel glass, panel glass, solder glass, neck) and the other is the non-glass components (plastics, steel, copper, electron gun, phosphor coating). CRT glass consists of $SiO_2$, NaO, CaO, and other components for coloring, oxidizing, and protecting from X-rays ($K_2O$, MgO, ZnO, BaO, PbO). Because CRTs contain lead (Pb), proper handling is necessary to avoid contamination of air, soil, and ground water. There are two technologies currently available for CRT recycling: glass-to-glass and glass-to-lead recycling. To date, the preferred process for the disposal of CRT glass is to recycle it into new CRT glass.

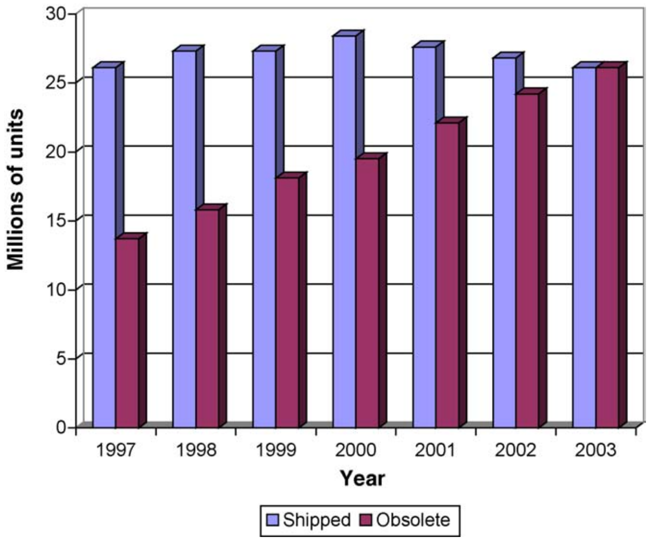


Fig. 7. Cathode ray tube shipments and obsolescence in the U.S.

Before recycling the CRTs, the case must be removed and the tubes are depressurized at the MRF. Metals are separated and plastics are shredded and then the CRTs are sent to CRT recyclers where they proceed through either glass-to-glass or glass-to-lead recycling. This process, shown schematically in Fig. 8, requires manual disassembly.

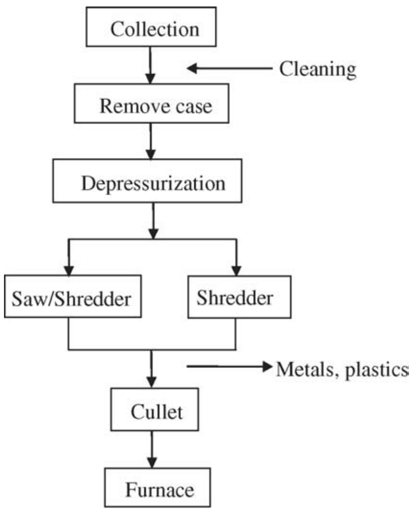


Fig. 8. Process flow diagram for recycling of CRTs.

### 6.1. Glass-to-glass recycling

Glass-to-glass recycling is considered a closed loop recycling process because glass that is collected is used as a raw material for new CRTs. Collected CRTs are sent to the recycler and whole glass is ground into cullet without separation of panel and funnel glass. The recycler sends the cullet to the CRT manufacturers for use in making new CRTs. CRT glass compositions differ depending on the manufacturer and when it was made, especially for panel glass. This is one reason why glass manufacturers are reluctant to take recycled CRT glass. Glass companies do not want to mix different types of glass. Using recycled CRT glass can create some risk to the glass manufacturing company due to the difficulty in determining the exact composition of recycled glass. The risk involved with using glass with an unknown composition is that a small addition of the wrong composition can contaminate the contents of an entire glass furnace and lead to changes in glass properties. To correct an incorrect glass composition can require the glass furnace to be shut down for 3–4 days (Monchamp et al., 2001; Dnis and Skurnac, 1998).

One approach to reduce the risk of contamination is to use a special saw to separate the panel glass from the funnel glass, as shown in Fig. 9 (Demanufacturing of Electronic Equipment for Reuse and Recycling, 2003). The sawing method allows the panel glass to remain intact, and therefore, identifiable, which is in contrast to the conventional method of breaking all the glass components simultaneously (Lowery and Voorhees, 1998).

There are several benefits to the glass-to-glass process. First, recycled cullet can replace the virgin materials at an equal or lower cost and improve the efficiency of the furnace, which lowers the energy consumption for making CRT glass. Also, this process can improve the quality of the output glass and reduce emissions from the glass making process, because recycled glass already has high purity. The value of cullet to a primary CRT glass manu-

Fig. 9. CRT components separated by saw cut.

facturer is higher than that to the lead smelter, which is the other glass recycling method. Furthermore, when compared to glass-to-lead, the glass-to-glass process reduces the regulatory burden by treating CRTs as universal waste instead of as hazardous waste, which would be governed by the Resource Conservation and Recovery Act (RCRA) (Monchamp et al., 2001).

There are several glass-to-glass recyclers in the U.S., such as NxTCycle,[4] Dlubak Glass,[5] and Envirocycle.[6] For example, Envirocycle produces 400 tonnes of cullet per week. The end-market for CRT cullet is Techneglas,[7] which in 2001 manufactured the glass components for more than 235 million TV CRTs (Materials for the Future Foundation, 2001). Techneglas estimates that the prescent recycled glass in new CRTs could reach a level of 40 wt.%, if high-quality glass cullet could be provided in sufficient quantity (Lowery and Voorhees, 1998).

But there are barriers for glass-to-glass. The barriers include the difficulty in identifying glass composition, the cost of CRT demanufacturing, the cost and complexity of the required collection infrastructure, and insufficient supply of recycled cullet. Overall, this is a labor intensive and expensive process compared to lead smelting, discussed below.

However, research done by the Electronic Industries Alliance (EIA) (Monchamp et al., 2001) found that the CRT glass manufacturing industry in the U.S. does not have sufficient capacity to absorb the total amount of recycled cullet, if the widespread collection of EOL CRTs were to begin. Another variable is high-definition TV (HDTV). At present, the market for new TVs in the U.S. is nearly saturated (more than 99%), but the introduction of HDTV in the near future and the preference of consumers for flat panel displays will accelerate the rate of obsolescence and replacement of conventional CRT TV sets. To cope with these changes, legislation and research will be needed to facilitate the optimization of glass-to-glass recycling, as well as the development of new applications for used CRT glass.

### *6.2. Glass-to-lead recycling*

In the glass-to-lead recycling process, metallic lead (Pb) and copper (Cu) are separated and recovered from the CRT glass through a smelting process. Although there are variations, CRTs generally contain 0.5–5 kg of lead (in the glass) (Hainault and Smith, 2000), which is used in the glass to protect people from exposure to X-ray emissions, and 1–2.3 kg of copper (in the yoke) (Materials for the Future Foundation, 2002). Before smelting, CRTs are shredded and the metals and plastics are separated. Recovered CRT glass goes to the lead smelter. CRT glasses behave as a fluxing agent in the smelting process.

This process is automated compared to the glass-to-glass recycling and is more cost-effective. It also provides safe working conditions because workers are protected from lead dust by the automated nature and the emission control system. The glass-to-lead recycling process has a high overall throughput. However, this process reduces the value of high-quality glass.

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[4] Mesa, AZ.
[5] Natrona Height, PA.
[6] Hallstead, PA.
[7] Pittston, PA.

In North America, there are a limited number of smelters for CRT glass, which leads to the need for long-distance transport for the CRTs, which is very expensive. For instance, in California, CRTs can be sent to shredding facilities, such as ECS.[8] HMR[9] and Kinsbursky Brothers,[10] Inc. provide CRT crushing services, whereas Micrometallics[11] ships CRTs to the Noranda[12] smelter. Although there are several secondary smelters in North America, the major end-markets for glass-to-lead CRTs are Doe Run[13] and Noranda (Materials for the Future Foundation, 1999a, 2002).

One special feature of CRT recycling is that there is a low-cost alternative: overseas recycling, which is approximately one-tenth the cost of domestic options. The factors affecting cost include labor cost, differences in work practices, and differences in acceptable waste disposal practices and environmental impact (Jung and Bartel, 1998). Another reason for exporting CRTs overseas is that the shipping cost is relatively cheap: empty containers need to go back to their countries after unloading the goods in the U.S. Filling these containers with CRTs and other obsolete electronics provides value. Even though this option is applicable to other electronic waste, CRTs are the most relevant item because exportation usually is from the west coast of the U.S. and because CRT recycling facilities are located on the east coast.

## 7. Plastics recycling

Plastics in electrical and electronic equipment are highly visible, for instance in telephones, televisions, and personal computers. However, there are also many plastic components, hidden from view, that provide the infrastructure to connect and support modern lives. The unique electrical insulating properties of plastics and their strength, stress resistance, flexibility, and durability make plastics important materials for use in electronics.

In Western Europe, plastics consumption by the electrical and electronic industry was 2.78 million tonnes in 2002 (Association of Plastics Manufacturers in Europe, 2003). The quantity of plastic waste from the electrical and electronic industries is estimated to increase to approximately 1.13 million tonnes by 2005 in Western Europe (Association of Plastics Manufacturers in Europe, 2000). The two major types of plastic resins that are used in electronics are thermosets and thermoplastics.

Generally, thermosets are shredded when recycled, because they cannot be re-melted and formed into new products. Thermosets are used in electronics for circuit wiring boards, electrical switch housings, electrical motor components, electrical breakers, etc. (Materials for the Future Foundation, 1999a). Thermoplastics are used in a wide variety of applications within computers and other electronic devices. These resins can be re-melted and formed into new products. As a result, thermoplastics show better recyclibility than thermosetting

[8] San Jose, CA.
[9] San Francisco, CA.
[10] Anaheim, CA.
[11] San Jose and Roseville, CA.
[12] Quebec, Canada.
[13] Boss, MO.

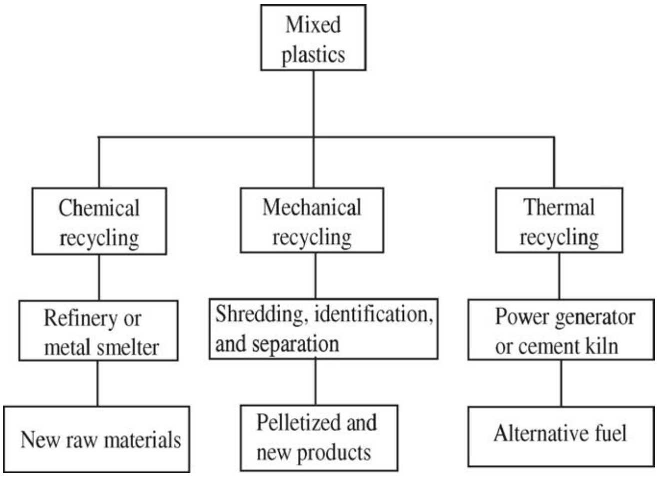


Fig. 10. Recycling options for managing plastics from end-of-life electronics.

plastic resins. After metals, plastics have the greatest potential salvage value from electronic products. The plastics used in electronic products are mainly ‘engineering thermoplastics’, which have high intrinsic value. When pelletized, these engineering thermoplastics typically sell for dollars-per-pound as compared to cents-per-pound for bottle and container-grade plastics (Computer and Electronic Recycling Index, 2004).

As shown in Fig. 10, there are three types of recycling processes for plastics. Chemical recycling processes use waste plastics as raw materials for petrochemical processes or as a reductant in a metal smelter. Mechanical recycling is a conventional method, which uses a shredding and identification process to eventually make new plastic products. In thermal recycling, plastics are used as an alternative fuel.

## *7.1. Mechanical recycling processes*

The major concern in plastics recycling is the need to identify and separate the plastics found in EOL electronics. The need to identify additives and contaminants is problematic. Also, to use the recycled plastics in high-end products, the properties (physical and mechanical) of recovered resins must meet those of virgin resins. Plastics used in electronics have several characteristics. Acrylonitrile butadiene styrene (ABS) and high-impact polystyrene (HIPS) provide good impact protection. These resins are generally used in monitors and TVs for CRT protection. Polyphenylene oxide (PPO) has good properties at high temperature. Polyethylene and polyvinyl are excellent electrical insulators. Commonly used resins in electronics are shown in Table 4 (Minnesota Office of Environmental Assistance, 2001; Materials for the Future Foundation, 1999a).

The major resins in TV sets and computers are HIPS and ABS. Generally, 8–12 different basic types of plastics are found in EOL consumer electronics (Minnesota Office of Environmental Assistance, 2001; Association of Plastics Manufacturers in Europe, 2000). The most widely used plastics in the electronic industry are HIPS (56 wt.%), ABS (20 wt.%),

Table 4
Resins used in various electronic products

| Equipment | Resins |
|---|---|
| TVs | HIPS, ABS, PPE, PVC, PC |
| Computers | ABS, HIPS, PPO, PPE, PVC, PC/ABS |
| Miscellaneous | HIPS, ABS, PVC, PPE, PC/ABS, PC |

HIPS: high-impact polystyrene; ABS: acrylonitrile butadiene styrene; PPE: polypenylene ether; PVC: polyvinyl chloride; PC: polycarbonate, PPO: polyphenylene oxide; miscellaneous: fax, telephone, refrigerator, etc.

and polyphenylene ether (PPE) (11 wt.%) as shown in Fig. 11 (Minnesota Office of Environmental Assistance, 2001).

Due to the difficulty of working with materials of unknown composition, the market value of mixed (unsorted) plastics is very low. To recycle plastics from discarded electronics, the first step is the sorting process. Contaminated plastics such as laminated and/or painted plastics must be removed. Because different major resins are used in different electronic products, separation of plastics, based on product type as shown in Table 4, can provide a better recycling rate. The importance of sorting and separation processes is described in the Minnesota Report (Minnesota Office of Environmental Assistance, 2001). This report shows that good sorting and separation are critical for the plastic recycler, because clean post consumer plastics and the same type of plastics will increase the purity and quality of the output. This in turn can solve the problem of OEMs not wanting to accept the recycled plastics, because of the difficulty in identifying the recycled resins.

### *7.1.1. Issues in mechanical recycling*

Compared to the limited number of different metals used in electronics, a large variety of resins are used. Also, plastics can be coated, mixed with additives, and made flame-retardant. This versatility acts as a barrier to plastics recycling. As is the case in other recycling programs, the key factors for success are a steady supply of high-quality feedstock, ready customers for recycled resins, and the existence of a market for recycled materials. Recyclers need a constant supply of the same type of plastic, but the actual situation is very

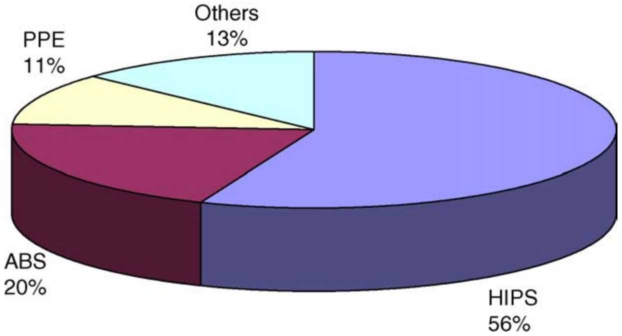


Fig. 11. Major resins found in consumer electronics (unit: wt.%). HIPS: high-impact polystyrene; ABS: acrylonitrile butadiene styrene; PPE: polyphenylene ether.

difficult because each product uses different types of resins. Even if the same type resin is used, there can be different colors and additives. For example Hewlett-Packard Co. tried to use recycled plastics in its printer housing, but they could not find enough material and had problems matching the color of the recycled and virgin resins. So, they focused, instead, on using recycled materials for internal components where color matching is not important (Toloken, 1998).

For better recycling of plastics it is necessary for manufacturers to reduce the number of plastic resins used in electronics. For example, the automotive industry is reducing the plastic grades it uses from 100 to 7 or 8 types, 3 or 4 of which would be used in greater volume (Biddle, 1998). Physical and mechanical properties are another barrier in plastics recycling. Plastics have different properties according to their purpose in the electronic equipment. For instance, plastics used in the housing and in printed wiring boards (PWBs) have different properties. For more effective plastics recycling, better sorting and separation techniques are needed.

MBA Polymers, Inc.[14] is an example of a company that has developed processes for mechanical recycling of plastic resins. This company accepts materials from a variety of sources and converts these materials to high-value engineering plastics for reuse in similar applications. Fig. 12 shows a representative flow diagram for the mechanical recycling of plastics. Details of the key steps in this process are described below.

#### *7.1.2. Technologies for sorting and identification of plastics*

*7.1.2.1. Removal of paint and coatings.* The paint and coatings must be removed. If paint and coatings are not completely removed, the properties of recycled plastics can be reduced because of stress concentration created by these coating materials.

A grinding method can be used to remove coatings. For example, the chrome from plated plastics can be removed by simple grinding, sometimes assisted with cryogenic methods to enhance the liberation process and to prevent the plating materials from being embedded in the plastic granules. These cryogenic methods provide good liberation, but the actual separation of plastic particles from the paint is problematic (Biddle, 1999). Another method of paint removal is abrasion. Abrasive techniques are applicable to large whole parts, but not to small parts. The solvent stripping method, which involves the dipping of the coated plastic into a solvent, liberates coatings from the plastic. This method is applicable for compact disc coating removal (Biddle, 1999). Another technique is the high-temperature aqueous-based paint removal method. The high-temperature aqueous environment, which can hydrolyze many coatings, makes it easy to liberate the coating from the plastic. Olefin-based car bumpers can be handled with this technique because this plastic is not degraded under these conditions (Plastic Technology, 1994).

But none of these techniques are completely satisfactory and they require that processing conditions be carefully controlled. Furthermore, the degradation that can occur to the plastic substrate during these processes decreases its resale value.

*7.1.2.2. Size reduction.* There are three primary purposes for size reduction. First is the generation of particles that can be more easily handled than bulky parts. Second is the

[14] Richmond, CA.

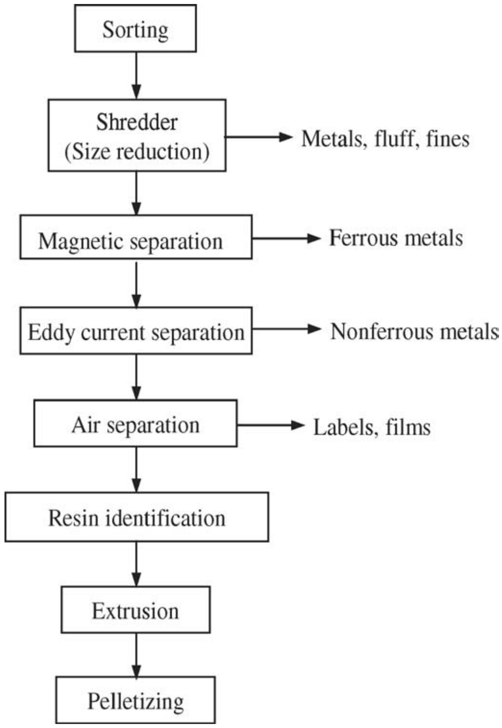


Fig. 12. Representative process flow diagram for the mechanical recycling of post consumer plastics.

generation of uniform sized and shaped particles that can be separated effectively in down stream processes. The third purpose is the liberation of dissimilar materials from one another.

Shear-shredder and hammer mills are generally used to perform coarse size reduction and liberation. Metals must be removed in this step, because metal can damage traditional particle size reduction equipment, such as granulators and mills. After the metal is removed, granulation and milling can be used for further size reduction and liberation. Granulators use a fixed screen or grate to control particle size. Hammer mills allow only particles that can pass between the hammers and the wall to exit the mills (Stessel, 1996).

The additional size reduction steps are usually used when the recycling stream contains well-adhered foreign material, such as paint and coatings, requiring aggressive liberation. Alternatively, or additionally, wet and cryogenic techniques can be used to enhance liberation (Biddle, 1999).

*7.1.2.3. Foreign materials separation techniques.* To remove ferrous metals from the plastics waste stream, a magnetic separation technique can be used. If strong magnets are used, many grades of stainless steel can also be removed. Among the non-ferrous metals, aluminum can be separated by the eddy current process. An air classification process is used to separate lights fraction, such as paper, by controlling the air velocity (Stessel, 1996).

*7.1.2.4. Identification and sorting of plastics.* To identify and separate plastics, several technologies have been developed (Minnesota Office of Environmental Assistance, 2001; Environmental and Plastics Industry Council, 2003).

Identification techniques need to provide both fast and accurate identification of the primary plastic contained in a particular item, followed by some type of manual or automated sorting. Automated plastic bottle sorting techniques exist but, for a variety of reasons, these techniques are not applicable to most of the plastics found in EOL electronic products.

The first reason is the wide variety of shapes and sizes compared to those for bottles. Another barrier is the coatings and paint on the plastics. These coatings and paint interfere with the analysis technique. Furthermore, the greater variety of plastics in electronics makes it hard to identify the plastic materials. Only three to five materials are commonly used for plastic bottles. Also, the larger wall thickness and opacity of plastics in electronics lead to difficulty in using energy transmission and radiation techniques for sorting (Biddle, 1999). Density sorting methods are not particularly helpful, because most plastics are very close in density. If used, however, for the rigid plastics from electronic goods, the density of the medium used must be greater than that of water. This can be done by adding a modifier to the water or by using a different liquid such as oil, tetrabromoethane (TBE). However, this is more costly and can lead to contamination of the recovered plastic (Veit and Pereira, 2002). Hydrocyclones, which use centrifugal force, are used to enhance the effectiveness of density separations and to enhance material wettability. Some of the factors affecting liquid separation of a given material are its wettability, its variation in density (from porosity, fillers, pigments, etc.), shape factors of size-reduced particles, and its level of liberation from other materials. Even surface air bubbles, which can attach to plastics as the result of poor wetting or surface contamination, can cause an individual flake of material to float in a solution less dense than that of bulk material (American Plastics Council, 1999).

Triboelectric separation can distinguish between two resins by simply rubbing them against each other. A triboelectric separator sorts materials on the basis of a surface charge transfer phenomenon. When materials are rubbed against each other, one material becomes positively charged, and the other becomes negatively charged or remains neutral. The principle behind the operation of a triboelectric separator is shown schematically in Fig. 13 (Xiao and Laurence, 1999).

Particles are mixed and contact one another in a rotating drum to allow charging. Negatively charged particles are pulled toward the positive electrode and positively charged particles are pulled toward the negative electrode. For example, when ABS is mixed with HIPS, HIPS becomes negatively charged and ABS becomes positively charged. As a result, HIPS is collected at the positive electrode and ABS is collected at the negative electrode. The most important factor in the triboelectric technique is particle size. If the particles are too large, much larger than 4–5 mm, they will not be deflected by the electric field and if the particles are too small, they will tend to accumulate on the electrodes, causing other falling particles to be insulated from the electric filed. Materials with a particle size of approximately 2–4 mm were the highest in both purity and recovery (Xiao and Laurence, 1999). Other factors that can affect the performance of a triboelectric separator are humidity and surface wetness. With this technology, the separation rate of ABS and HIPS can reach 98 wt.% or higher (Xiao and Laurence, 1999).

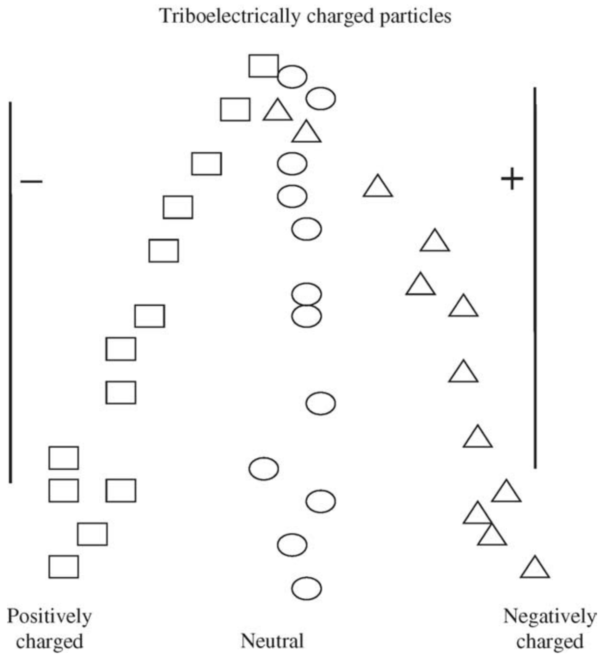


Fig. 13. The principle of triboelectric separator operation.

One Swiss company, Result Technology AG, has developed a technology to delaminate and separate the plastics used in circuit boards. This technique uses a high-speed accelerator to delaminate shredded waste, and the delaminated material is separated by air classification, sieves, and electrostatics (Environmental and Plastics Industry Council, 2003).

MBA Polymers, Inc. developed a proprietary technology that not only can identify the resins in collected plastics but can also separate them into pure resin streams (Toloken, 1998). Technology that can separate plastics with flame-retardants (FRs) from those without has also been developed by MBA Polymers, Inc. By this technique recycled plastic containing FRs can be used to meet the fire safety standard. It is estimated for instance, that about 30% of new photocopiers contain recycled plastic with FRs (American Plastics Council, 2003).

By using X-ray fluorescence (XRF) spectroscopy, different types of flame-retardants can be identified. Fig. 14 shows one example of the XRF technique as used to distinguish two different toner cartridges (Riise and Biddle, 2000). Phosphorous is detected in the PC/ABS toner cartridge, suggesting the presence of a phosphorous-based flame-retardant. The HIPS–FR toner cartridge contains a number of elements, including Br, Sb, and Fe. The XRF technique can be used to identify regulated heavy metals (Pb, Hg, Cd) as well as flame-retardants (Br, Sb, P).

MBA Polymers, Inc. developed a technology that is able to produce a 100% pure stream of HIPS from television plastics. HIPS from recovered televisions can be used in applications similar to those for virgin HIPS (American Plastics Council, 2000). Table 5 shows

Table 5
Typical properties of virgin resins and the recycled resins produced at MBA Polymers, Inc.

| | | Density ($g/cm^3$) | Izod impact (kg cm/cm) | Melt flow rate (g/10 in.) | Yield tensile stress (MPa) |
|---|---|---|---|---|---|
| HIPS | Recycled | 1.15 | 9.7 | 7.5 (200 °C/5 kg) | 22 |
| | Virgin | 1.17 | 10 | 13.5 (220 °C/5 kg) | 22 |
| ABS | Recycled | 1.18 | 11.34 | 17.7 (230 °C/3.8 kg) | 42.8 |
| | Virgin | 1.19 | 26 | 14 (230 °C/3.8 kg) | 42 |
| PC | Recycled | 1.20 | 75.6 | 15 (230 °C/3.8 kg) | 60.7 |
| | Virgin | 1.19 | 60 | – | 63 |
| PC/ABS | Recycled | 1.2 | 64.8 | 11 (230 °C/3.8 kg) | 69.3 |
| | Virgin | 1.2 | 52 | 30 (250 °C/10 kg) | 55 |

HIPS: high-impact polystyrene; ABS: acrylonitrile butadiene styrene; PPE: polypenylene ether; PC: polycarbonate.

representative properties of both virgin resins (Plastics Information, 2004) and the recycled resins produced by MBA Polymers, Inc. under indicated ASTM test conditions (MBA Polymers, Inc., 2003).

### *7.2. Chemical (or feedstock) recycling of plastics*

#### *7.2.1. Depolymerization and conversion process*

For chemical recycling of plastics several processes have been developed. One of these processes, shown schematically in Fig. 15, was developed by the Association of Plastics Manufacturers in Europe (APME) (Association of Plastics Manufacturers in Europe, 1997). In this process, mixed plastic waste (MPW) is depolymerized at about 350–400 °C and dehalogenated in this stage. During this stage, metals are removed. The remaining polymer chains from the depolymerization unit are cracked at temperatures of 350–450 °C

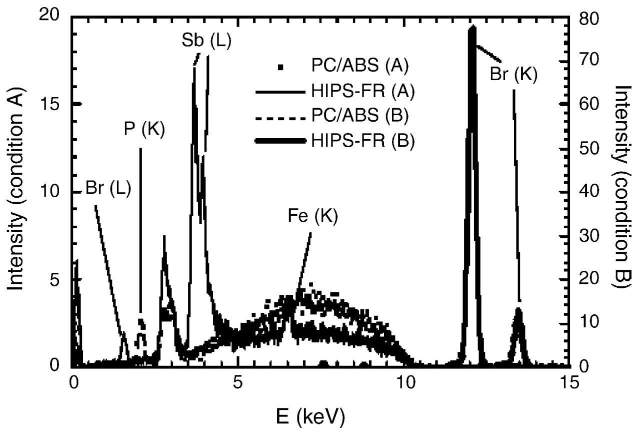


Fig. 14. X-ray fluorescence (XRF) spectra of toner cartridges. Condition A: tube voltage 10 kV, 50 μA. Condition B: tube voltage 25 kV, 40 μA.

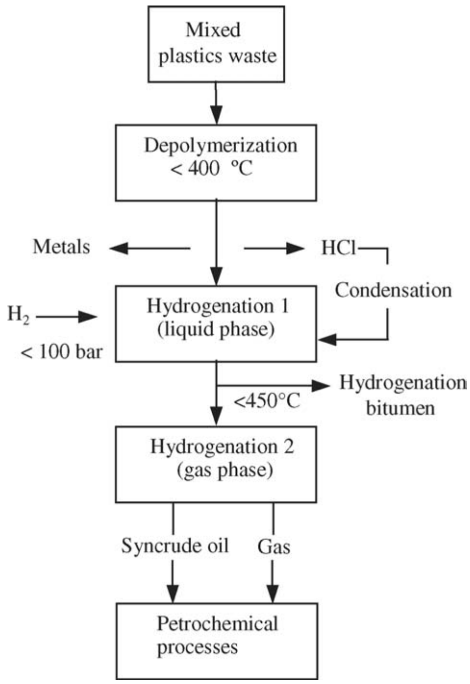


Fig. 15. Depolymerization of plastics and conversion processes.

in the Hydrogenation Unit 1. The open carbon bonds are saturated by hydrogen because of high hydrogen pressure, more than 10 million $N/m^2$. The liquid product goes through the distillation process. Any left-over inert material, which is not separated and removed in the depolymerization step, and the unconverted plastic portion are collected in the bottom of the distillation column and removed as a residue, hydrogenation bitumen. The final high-quality products, off-gas and syncrude, are obtained by hydrotreatment (Hydrogenation Unit 2). These final products are sent to conventional petrochemical processes.

The mixed plastic waste is converted into the following products: 80 wt.% into liquid product, 10 wt.% into off-gas (methano-butane), and 10 wt.% residue. The liquid product is free of chlorine and extremely low in oxygen and nitrogen; 85 wt.% can be used as cracker feed (Association of Plastics Manufacturers in Europe, 1997). The rest, depending on the properties of the plastic waste, is ethylbenzene, which is an excellent gasoline component. The solid residue, which could also be blended with the coal for a power plant, can be used to improve the properties of coal for coke production.

*7.2.2. Coke oven process*

Nippon steel company developed a different process for plastic chemical recycling, the flow diagram for which is shown in Fig. 16 (Nippon Steel Environmental Report, 2002). The coke making process is essentially the carbonization of coal. The process conditions for carbonization in a coke oven are also suitable for the recycling of waste plastics, because at

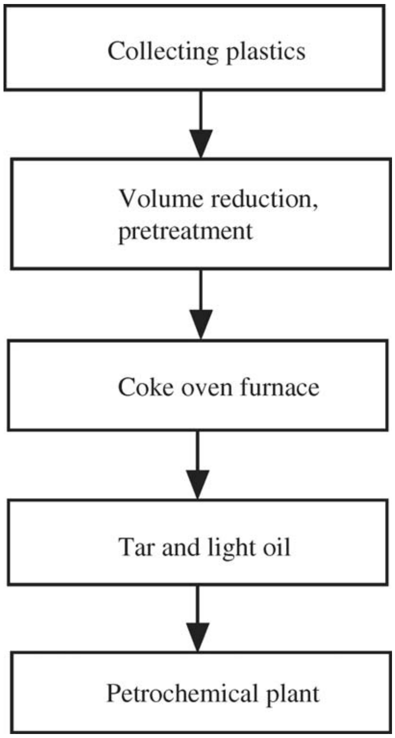


Fig. 16. Flow chart of coke oven chemical recycling process.

high temperature in a reducing atmosphere, charged plastics can be decomposed thermally without combustion.

In the pretreatment step, foreign materials, such as metal, glass, and sand, are removed. The remaining plastic waste is then crushed and reduced in size, before being charged into a coke oven. This process involves high temperature and a reducing atmosphere. General waste plastics were added to coal at a level of 1 wt.%, and the plastics decomposed easily. In the coking chamber, the waste plastics are heated to about 1200 °C in an oxygen-free environment. The charged plastics are pyrolyzed at 200–450 °C, generate gas and are completely carbonized at 500 °C. The hydrocarbon oils and coke oven gas are refined from high-temperature gas generated by pyrolysis, and the residue is recovered as coke. The yields from carbonization of general waste plastics were 20 wt.% of coke, 40 wt.% tar and light oil, and 40 wt.% of gases, approximately. The primary components of the product gas are methane and hydrogen.

#### *7.2.3. Reducing agent for $Fe_2O_3$ in blast furnace*

The third example of feedstock recycling of plastics is the use of plastics as a reducing agent in the metal recovery process. Recent research in Sweden showed that using plastics from EOL electronics as an energy and carbon source in metals processing is environmentally sound (Mark and Lehner, 2001).

For the production of pig iron for steel production, iron ore ($Fe_2O_3$) must be reduced to Fe. Conventional reducing agents can be replaced by plastic waste. Generally, coke is used as the reducing agent.

### *7.3. Thermal recycling of plastics*

Thermal recycling means to use plastics as a fuel so that the main purpose of thermal recycling is energy recovery. Plastics have a high heat value. Because plastics are derived from oil, plastics have a calorific value equivalent to or greater than coal. Plastic materials can be combusted and produce energy in the form of heat. For instance, 1 tonne of plastics can replace 1.3 tonnes of coal in cement kilns (USGS, 2001).

This plastic recycling option is considered by the APME to be the most environmentally sound option for managing EOL electronic plastics in Europe. In 2002, Switzerland and Denmark recovered about 70 wt.% of their total plastics waste through thermal recycling (Association of Plastics Manufacturers in Europe, 2003). In 2003, about 23 wt.% of total plastics waste in Western Europe was thermally recycled, which represented the largest portion compared to other recycling methods (American Plastics Council, 2003). Pilot scale municipal solid waste combustion facilities equipped with suitable wet scrubbing systems have demonstrated that energy recovery from plastic waste that contains brominated flame-retardants is technically feasible (Association of Plastics Manufacturers in Europe, 2002).

### *7.4. Markets for recycled plastics*

About one-third of the material in electronic devices is plastic, but only 25% of that is clean, homogeneous, and free from contamination (American Plastics Council, 2000). In the U.S., plastics recovered from electronics are used primarily in plastic lumber, outdoor furniture, and road materials (Environmental and Plastics Industry Council, 2003; American Plastics Council, 2000). Recycled plastics can be used in new equipment like an HP printer. Also, recycled ABS can be used for battery boxes, compact disc trays, and camera casings. Thermoplastic resins are used for hot mix asphalt concrete. Mixed plastic resins including ABS and HIPS can substitute for stone and gravel. These resins are used to enhance the bond strength.

Tufts University and IBM showed that recycled HIPS could be used in the manufacture of some high-end consumer electronic products at no cost to the manufacturer (American Plastics Council, 2003). Another market for plastics is laminated flooring (American Plastics Council, 2000). Pallets used for moving heavy goods are another market for recycled plastics. The recycled-plastic pallets are a longer-life, cost-effective, and convenient alternative to the traditional wooden pallets. Several companies currently use recycled-plastic pallets. There is much on-going research to develop new applications for EOL electronic plastics. This research is focused on substantiating the economic and functional viability of recycled electronic plastics, and broadening the markets into which recovered plastics can go as supplies increase. For example, the Western Europe electrical and electronic industries consumed about 2.78 million tonnes of plastics in 2002 (Association of Plastics Manufacturers in Europe, 2003). If 30% of the resins can be recycled, 0.83 million tonnes will be available annually. It is generally believed that some plastics from EOL electronics are also going overseas, but there is not sufficient information about the amount exported. In order for plastics to be recycled responsibly and used competitively with virgin plastics in new products, used plastics must be properly collected, sorted, and cleaned.

The APME has suggested that energy recovery may be the most beneficial option for managing EOL electronic plastics in Europe. In the U.S., however, industry continues to favor an integrated approach to handling plastics from EOL electronics. Such an approach includes varying the combination of mechanical recycling, feedstock recycling, energy recovery, and when necessary, the safe landfilling of plastics, as supported by current U.S. regulations. The exact balance of management options, of course, differs according to the resources, technology, and supplies available in different regions of the country.

## 8. Metals recycling

In 1998, over 29,000 tonnes of metal were recovered from recycled electronic equipment in the U.S. aluminum: 4500 tonnes, steel: 19,900 tonnes, copper: 4600 tonnes, and precious metals (gold, palladium, platinum, silver): 1 tonne (USGS, 2001).

After being sorted in the MRF, the metallic components are generally sent to metal recovery facilities. In the case of a large MRF like the one at Hewlett-Packard,[15] copper and precious metals are sent directly to the Noranda smelter for processing. Sometimes circuit boards are sent to the smelter for extraction of copper and other precious metals. But for small and/or intermediate sized MRFs, these materials go to a scrap dealer first and then the scrap dealer resells the metals to the overseas markets or to a smelter for processing. Excluding the precious metals, most of the metals recovered from electronic waste generally sell for less than US$ 1 $kg^{-1}$ (Scrap Metals Index, 2004).

### *8.1. Magnetic separator*

A magnetic separator can separate ferrous components with a permanent or electric magnet. The overhead belt magnet is the most common magnetic separation system (Stessel, 1996). After shredding, particles are moved on the conveyer belt and over the magnet. The ferrous metal particles adhere to the belt because of the magnetic attraction, and the non-ferrous metals are dropped into a non-ferrous metals collection bin by gravity. The ferrous metal particles remain attached to the belt and are carried away from the remaining particles and dropped into a collection bin when they are no longer affected by the magnetic field.

### *8.2. Eddy current separator*

Eddy current separators can remove non-ferrous metals such as aluminum and copper from non-metallic materials. When a piece of non-ferrous metal, such as Al or Cu, passes over the separator, the magnets inside the shell rotate at high speed. This forms eddy currents in aluminum, which in turn creates a magnetic field around the piece of aluminum. The polarity of that magnetic field is the same as the rotating magnet, causing aluminum to

[15] Roseville, CA.

Table 6
Materials that can be separated by an eddy current separator, and their properties

| Materials | $\sigma$ ($10^{-8}/\Omega$ m) | $\rho$ ($10^3$ kg/m$^3$) | $\sigma/\rho$ ($10^3$ m$^2/\Omega$ kg) |
|---|---|---|---|
| Al | 0.35 | 2.7 | 13.1 |
| Zn | 0.17 | 7.1 | 2.4 |
| Ag | 0.63 | 10.5 | 6.0 |
| Cu | 0.59 | 8.9 | 6.6 |
| Brass | 0.14 | 8.5 | 1.7 |
| Pb | 0.05 | 11.3 | 0.4 |

$\sigma$: electrical conductivity; $\rho$: density; $\sigma/\rho$: ratio of electrical conductivity to density.

be repelled away from the magnet. This repulsion makes the trajectory of the aluminum greater than that of the non-metal, allowing the two material streams to be separated. Table 6 shows the materials that can be separated by an eddy current separator (Stessel, 1996). The main separation criterion for an eddy current separator is $\sigma/\rho$, where $\rho$ is the density of the material and $\sigma$ is the electrical conductivity of material. The materials that have a higher ratio of conductivity to density can be separated more easily than those with lower ratios. As shown in the table, aluminum is the most easily separated material.

Stainless steel, plastic, and glass have a zero value for the conductivity-to-density ratio indicating that these materials cannot be separated by an eddy current separator (Dalmijn, 1990). It should be noted that non-ferrous metal trapped in a non-metallic material may be impossible to separate. For instance, Cu wire covered with insulation would be impossible to separate.

### *8.3. Lead (Pb) recovery*

For the recovery of lead, a reverberatory furnace is charged with lead-containing materials. In this furnace, reduction of the lead compounds to metallic lead bullion occurs and foreign materials are oxidized as slag. The purity of the lead bullion is more than 99.9 wt.% Pb. This furnace is tapped for slag, which typically contains 60–70 wt.% Pb, and a soft (pure) lead product (Prengaman, 1980). Slag consists of a thin, fluid layer on top of the heavier lead layer. The slag is tapped continuously from the furnace onto the slag caster. While slag is tapped continuously, the bullion is tapped from the furnace when the metal level builds up to the height that small amounts appear in the slag. Dust in the flue gas are collected by baghouse and fed back into the furnace to recover Pb. The following reactions occur in the reverberatory furnace (Prengaman, 1980):

$$PbO + C \rightarrow Pb + CO \quad (1)$$

$$2Sb + 3PbO \rightarrow 3Pb + Sb_2O_3 \quad (2)$$

$$2As + 3PbO \rightarrow 3Pb + As_2O_3 \quad (3)$$

$$Sn + 2PbO \rightarrow 2Pb + SnO_2 \quad (4)$$

The blast furnace is then charged with the slag generated from the reverberatory furnace, as well as other lead-containing materials. Iron and limestone are added as fluxing agents

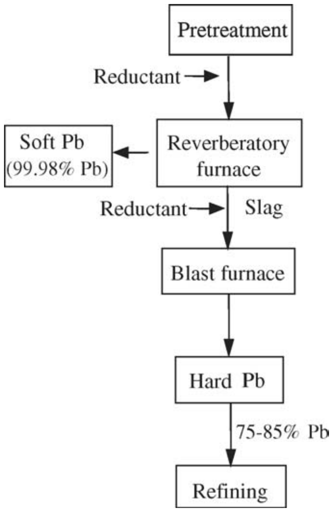


Fig. 17. Processes flow for secondary lead recovery.

to enhance furnace efficiency. Eq. (1) is the main reaction for Pb recovery and reactions (2) through (4) are for slag formation and reduction of Pb in the reverberatory furnace (Prengaman, 1980). Hard Pb, the product of the blast furnace operation, contains about 75–85 wt.% Pb and 15–25 wt.% Sb, as well as 1–3 wt.% Pb that is contained in the slag. The blast furnace is tapped continuously to recover lead and intermittently to remove slag. Also, slag includes CaO, $SiO_2$, and FeO (The World Bank Group, 1998). The blast furnace slag, which contains primarily silica and iron oxides, is disposed of in landfills. Fig. 17 shows the process flow for secondary lead recovery.

### *8.4. Copper (Cu) recovery*

Electronic scrap containing 5–40 wt.% Cu are fed into a blast furnace. Copper compounds have to be reduced by reducing agents such as scrap iron (because Fe is less noble than Cu) and plastics. Impurities, such as Sn, Pb, and Zn, are also reduced as gas fume (Notle, 1997). The following reactions occur in a blast furnace:

$$Fe + Cu_2O \rightarrow FeO + 2Cu \tag{5}$$

$$2ZnO + C \rightarrow 2Zn(g) + CO_2 \tag{6}$$

The product of the blast furnace when used for Cu recovery is called black copper and includes 70–85 wt.% copper. This black copper is fed into the converter to be oxidized (Hazen Research, Inc., 1998). A converter uses air or oxygen-enriched air to make oxides form. Impurities (Sn, Pb, Zn) are burned out and Fe is removed as slag. Blister copper purity is 95 wt.%. In an anode furnace, blister copper and scrap Cu are melted. Less noble metals than copper are selectively oxidized. By adding a reducing agent, molten Cu is reduced

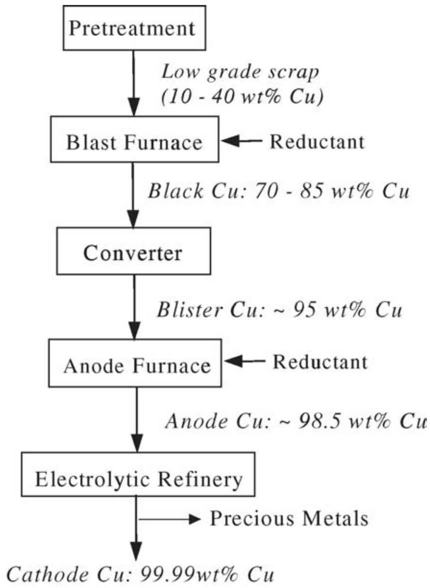


Fig. 18. Processes flow for secondary copper recovery.

(Notle, 1997). The reduction reaction in the anode furnace is shown below:

$$2CuO + C \rightarrow 2Cu + CO_2 \quad (7)$$

Coke and wood can be used as the reducing agent to promote the reduction reaction, but waste plastics can also be used. The reduction reaction also removes sulfur. The reduced Cu is cast into an anode for further copper recovery (Kindesjo, 2002).

The recovered anode copper can be further purified by dissolving it in a $H_2SO_4$ electrolyte with other elements, such as Ni, Zn, and Fe. The pure copper (99.99 wt.%) is deposited on the cathodes (Hazen Research, Inc., 1998). Fig. 18 shows the process flow diagram for copper recovery.

After extracting the Cu, the by-products of the copper secondary smelter, the slag, can be used as roof shingles, sand blasting, and ballasts for railroads (Queneau and May, 1991). A secondary copper smelter is not based on ore, so the costly steps associated with a primary smelter, such as oxidation and reduction of ore, can be omitted. However, a highly efficient scrap collection system is needed.

According to studies undertaken by the Association of Plastics Manufacturers in Europe, the energy needed to reclaim copper from EOL electronic scrap such as PCs and PWBs is only one-sixth of the energy that would be required to produce Cu from ore (Mark and Lehner, 2001).

### *8.5. Precious metals recovery*

In a precious metals refinery, gold, silver, palladium, and platinum are recovered. The anode slime from the copper electrolysis process is leached by pressure. The leach residue

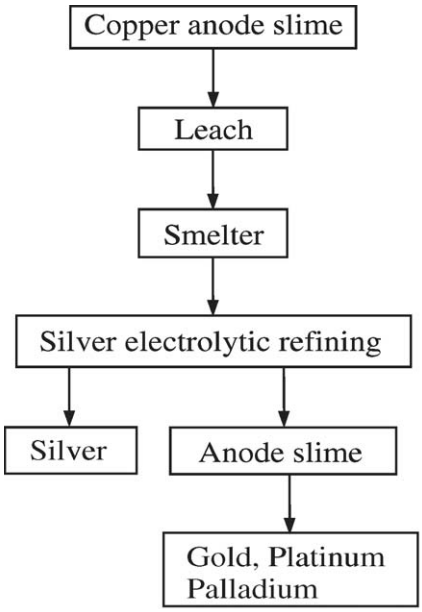


Fig. 19. Precious metals recovery process.

is then dried and, after the addition of fluxes, smelted in a precious metals furnace. During smelting, selenium is recovered. The remaining material, primarily silver, is cast into a silver anode. At a subsequent, high-intensity electrolytic refining process, a high-purity silver cathode and anode gold slime are formed. The anode gold slime is then leached, and high-purity gold, as well as palladium and platinum sludge, are precipitated (Kindesjo, 2002). Fig. 19 shows the precious metals recovery process.

It has been noticed that recovering precious metals from electronic scrap is one of the greatest economic profits for the recycling industry. About one-third of the precious metals recovered from electronic scrap are gold, as electronic scrap contains more than 40 times the concentration of gold contained in gold ores found in the U.S. (USGS, 2001).

## 9. Conclusions

As one of the options for the diversion of EOL electronics, the recycling option is considered. To clarify the recycling option, the authors have researched the electronic recycling infrastructure in the U.S. However, because recycling of electronic waste started only recently, the methods and infrastructure for collection and processing are not yet well established. As a result, large amounts of collected electronics are exported overseas. For better recycling, an established recycling program is needed. There have been various attempts to collect e-waste or to establish take-back systems, but these are still in early stages of development. A major challenge for e-waste recycling is the need for a continuous and stable supply of materials to be recycled. Another barrier is the lack of cost-effective technologies for recycling. To date, many aspects of recycling depend on manual operations. Also, existing methods are limited in their ability to handle complex products such as CRTs and PCs, which contain a large variety of materials. Finally, to mature the recycling industry it will be necessary to have stable demand for the recycled materials.

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