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# Construction Aspects of Plasma Based Technology for Waste of Electrical and Electronic Equipment (WEEE) Management in Urban areas

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**Abstract**

The paper presents construction aspects of plasma based technology for waste of electrical and electronic equipment (WEEE) management in urban areas. Urban areas are becoming the new source of "renewable resources" to be "mined" through WEEE waste collection and processing. Authors focus on identification of possibility to process segregated category of waste of printed circuit boards from WEEE locally, instead of using the distant centralized installations. Problem of waste transportation is also presented, proving the advantages of local processing of waste of printed circuit boards. Moreover, the mass of PCB is calculated for each voivodeship in Poland, and throughput of installation required for its processing. Paper presents construction aspects of designed plasma technology for processing of waste of printed circuit boards for metals recovery, with design and exploitation data of plasma reactor: throughput, power, and products. Additionally, currently available technologies for processing of PCB waste are briefly presented.


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*Keywords*: plasma technology, urban mining, recycling, electronic waste utilization, printed circuit boards, metals recovery.

## 1. Introduction

Increasing digitalization of appliances and machines equips them with electronic circuit boards. Those electronic circuit boards, after end of appliance's life, becomes hazardous waste that needs to be handled adequately. Mass production of electric and electronic equipment, requires huge amounts of non-renewable resources, including precious metals, and rare earth metals. That is why it is important to develop new effective ways of recycling electronic printed circuit boards (PCB) waste, as they become new "renewable" resource that can supply recycled metals for new production. By processing the waste of electronic circuit boards, it is possible to recover metals, energy, and decrease its hazardous effect on the environment.

Waste of electrical and electronic equipment (WEEE) is a global concern. In the 27 EU countries it is estimated that the weight of produced WEEE in 2005 was 8.3 – 9.1 million Mg (tones), 25% of which is collected and processed, while remaining 75% is not registered and does not occur in collection points [1–2]. Such state of waste management system can be caused by the lack of processing capacities and suitable technologies which can utilize WEEE effectively. The amount of WEEE increases continuously [3–4] in 2008 Sweden collects 16.7 kg/capita of WEEE, Britain 8.2 kg/capita, Austria 6.5 kg/capita [5]. Moreover, the European Commission proposes rising collection targets from 4 kg/capita to 65% of average mass of electrical and electronic equipment placed on market [19]. WEEE has to be utilized, but it also can become

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a source of valuable resources. In Poland the need for technology allowing recovery and neutralization of this waste is strong, due to huge technological and organizational gap between Poland and west European countries.

## 2. Urban areas – new source of resources from waste

Urban mining as a concept was created in 60's. It has indicated that there will be a new area of possible resources reclamation. Normally, resources are mined processed and used in cities. And now the cities are becoming its new source. Besides the recycling of used cities infrastructure, also waste generated in the cities can be a rich resource to be "mined".

Urban areas are the source of waste of electric and electronic equipment, it is collected in shops and collection points, and its first segregation takes place there. Also, in cities or close to them facilities for processing WEEE are located. In those plants the first step of recovery of resources from waste is carried out. First step in most cases is traditional simple WEEE processing technology: manual dismantling, milling, and segregation. Those processes allow recovery of resources like aluminum, copper, steels, glass, plastics, that cover great part of the waste mass. Also, the new robotic technologies offer a new approach to WEEE dismantling decreasing human labor and energy consumption [6], but they are still not used widely.

During every waste processing operation the secondary waste is also generated, because there is no complete neutralization and recovery process available. Example of such "waste" that is not processed locally, and requires specialist treatment are: printed circuit boards, and the sieved part from milling of WEEE waste. Both of those categories contain Cu, Sn, Pb, some Ag, Au, Pd, and more than 60 other metals and substances [7]. In Poland there is no infrastructure to process PCB, that is why most of it is being transported to western European countries where in specialist installations this segregated WEEE category is being processed, and valuable metals are being recovered.

## 3. Currently available technologies for waste of printed circuit boards processing

There two main approaches to PCB treatment and metals recovery. Pyrometalurgical smelting of waste, and mechanical processing (milling).

Currently in Europe, only few plants process electronic printed circuit boards in pyrometalurgical processes. Those plants process PCB from entire Europe. However, the waste of electric and electronic printed circuit boards, is only a part of the total input in those installations, as they prefer homogenous industrial waste over PCB waste from WEEE. Integrated pyrometalugrical smelters can process up to 300 000 Mg/year [7] of waste, and recover up to 95% of precious metals and Cu. The facilities are located in Belgium – Umicore, Sweden – Boliden, and Germany – Aurubis. There is no such installation in Poland. Pyrometalurgical technologies process waste by incinerating organic matter and smelting the metals and slag from it. Smelted metals are used as collectors Cu, Pb, Ni bonds certain groups of metals together like copper collects Ag, Au. Subsequently, those concentrates are being processed in another specialist units and then refined to recover pure metals. Diagram of Umicore process is presented on Fig. 1.

It is worth mentioning, that the companies exploiting those installations for recovery of precious metals, are interested in maximizing their production instead less valuable ones. That is why the waste is being sorted by the content of Au, for 400 PPM, 200 PPM, 100 PPM and lower. The high grade PCB is being preferred.

Another way of processing waste of printed circuit boards is the application of mechanical methods based on fine milling, and multistep segregation of such powdered materials. Mechanical processing allows recovery of aluminum, copper (heavy category), plastics, ferrous metals, glass, dusts. A disadvantage of those methods is the loss of precious metals [17] and contamination of recovered materials. Also, recovered and segregated resources need to be further processed in pyrometalurgical or chemical processes to recover pure metals and remove the contaminants.

Currently, such technologies are not used in Poland, but there are works being carried out to implement such mechanical treatment of PCB to recover Sn, Cu, Al, Ag and other metals [8]. Unfortunately, those enterprises focus on importing the mechanical treatment technology from abroad. However, recovery of Sn and Ag will be applied in form of chemical process developed in Poland. Nevertheless, mechanical methods are only the first step to recovery of precious metals from PCB, and, as it was mentioned, a huge part of them is being lost during the process.

Mechanical methods used currently in Poland and other countries are applied to process WEEE and recover from it Al, Fe, Cu(brass), plastics, and printed circuit boards. Then, those resources are sold to companies that process them and purify to form of pure products. As to the category of PCB segregated from WEEE this resource is sold to Umicore, Boliden, or Aurubis for recovery of metals.

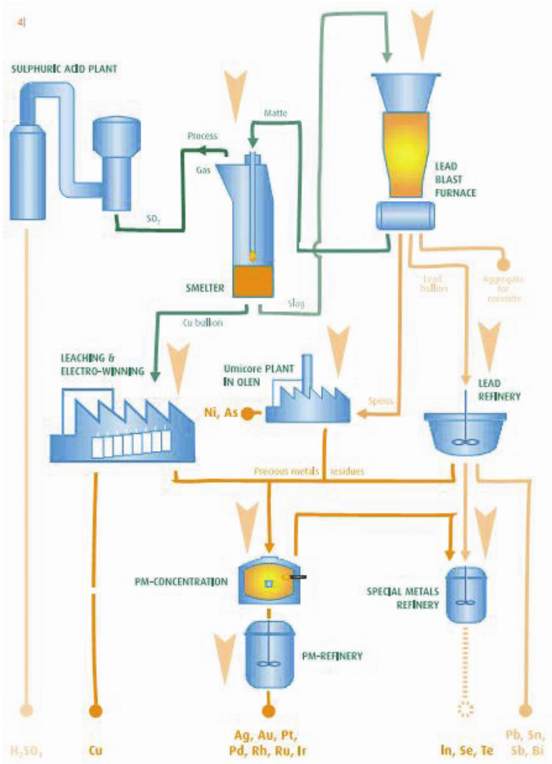


Fig. 1. Umicore waste to metals technology presentation [7]

## 4. The mass of electric and electronic printed circuit boards collected in Poland

According to data from Main Inspector's of Environment Protection summarizing collection of WEEE in year 2011, 143 339 Mg, 3.55 kg per capita [18] was collected in Poland. However, those reports do not cover the data about the WEEE mass collected in each city, or voivodeship. To calculate those factors for each Poland's voivodeship the number of population was taken [9], and the amount of PCB in WEEE 2%–3% and 8% in small appliances [10–11]. In Poland there are 16 voivodeships, 5 small ones (about 1.2 mln people), 9 medium-sized (2.5 mln of people), and 2 big ones (5 mln people). Basing on the amount of PCB in WEEE as 3%, and the collection mass per capita in 2011 (3.55 kg), the average mass of WEEE and PCB from each region was calculated. Table 1 presents the calculation results.

The calculations presented in Table 1 reveal the average mass of PCB being collected each year in Poland in each size of voivodeships. The PCB are present in almost every appliance and their mass is very variable, also the collection of WEEE and its groups varies dependably on the size of the city, wealth of people and other factors, so this should be taken into account while analyzing the calculation.

Despite that, the presented data is very useful and allows the analysis of waste processing needs for each region. Analysis shows that small regions annually collect only 126 Mg of printed circuit boards, and the biggest ones collect up to 532 Mg annually. Calculating the waste processing needs we assume that the installation will work for 300 days per year, 24 h/day. From this point of view the installation for one voivodeship should process daily 0.42 Mg, 0.88 Mg, or 1.7 Mg of PCB.

Table 1. Calculated amount of PCB from collected WEEE in each voivodeship in Poland

| Quantity of voivodeships | Population (mln) | Mass of WEEE collected in 2011 (Mg) | Mass of PCB in collected WEEE (Mg) | Mass of PCB per Day (Mg/Day) |
|---|---|---|---|---|
| 5 | 1.2 | 4 200 | 126 | 0.42 |
| 9 | 2.5 | 8 875 | 266 | 0.88 |
| 2 | 5.0 | 17 750 | 532 | 1.773 |
| 16 | 38 | 143 339 | 4300 | 15 |

## 5. Decentralized small scale processing of electric and electronic printed circuit boards for metals recovery in urban areas

Centralized processing of PCB requires transportation of huge amounts of waste for long distances. An average transport of 1 Mg of cargo by truck carrying 15–28 Mg load for 100 km requires 35–40 $dm^3$ of diesel fuel. Taking the average distance of 1500 km from center of Poland to each of 3 major PCB waste processing facilities in Europe, one can calculate that the transport of 4300 Mg of PCB waste will require 172 transport trucks (25 Mg) and the fuel consumption (37 $dm^3$/100 km) will reach 95 500 $dm^3$ of diesel. The energy of this fuel equals:

$$95\,500\ dm^3 \cdot 43\ MJ/kg \cdot 0.83\ kg/dm^3 = 3\,420\,000\ MJ = 950\ MWh$$

Worth noting is that the transportation of waste causes additional use of resources, infrastructure and emissions related with burning the fuel, and it's still only for the purpose of simply moving the unprocessed PCBs from one point to another. Adding to it some additional "costs" such as usage and wear of trucks, roads, noise, drivers time, etc the environment footprint of waste transportation is very significant.

Moreover, the printed circuit boards segregated from preprocessing of WEEE can be called as "artificial ore" that was "mined", enriched, and is being now exported to other country for further processing. Processing that will recover valuable metals including precious and special, which have high market value. This artificial ore should be processed close to the preprocessing plants, within one country, so the resources will be recovered for own production, bringing additional income for recycling plants located near the collection points in each region.

Taking into account the above listed costs as well as profits emerging from processing of WEEE entirely inland, authors of this paper decided to develop the technology that will allow processing of segregated rich category of waste of printed circuit boards near the place of their segregation. Such new technology will open new possibility for recycling plants and metals processors to "mine" (collect) waste and produce metals form this new rich "artificial ore".

## 6. Construction of plasma technology for waste of electric and electronic printed circuit boards processing and metals recovery

In 2010 research project was undertaken, financed by Polish National Centre for Research and Development, to investigate and design plasma process allowing processing of waste of printed circuit boards and recovery of metals they contain.

In the Industrial Research Institute for Automation and Measurements PIAP the test setup was designed and constructed to investigate plasma processing of waste of electronic and electric equipment for recovering of metals and its neutralization. The stand is presented on Fig. 2. The key component of the test setup is the plasma reactor, equipped with three plasmatrons – plasma sources, each located in 120° around the reactor chamber. The test position is equipped with peripheral systems, measurement and control apparatus for data acquisition and control of the process during research.


Fig. 2. Overview of the laboratory setup: 1) Plasma reactor, 2) Plasmatron, 3) Molten product collection, 4) Fumes Exhaust – chimney, 5) Waste package transporter, 6) Plasmatron power supply, 7) PLC – automation and data collection apparatus cabinet, 8) Automatic waste package feeder

The high temperature plasmatron plasma reactor is the key component of laboratory setup for research over high temperature utilization of waste of printed circuit boards, for metals recovery. Block diagram of laboratory setup is presented on Fig. 3. Designed test setup allows wide range of possible experiments and data acquisition during research over waste processing and metals recovery. Designed plasma process is being carried out by the following steps presented on Fig. 3. Prepared waste portion is transported through automatic feeder to the plasma reactor chamber. In the reactor chamber, the waste is being incinerated and melted by three plasma streams.

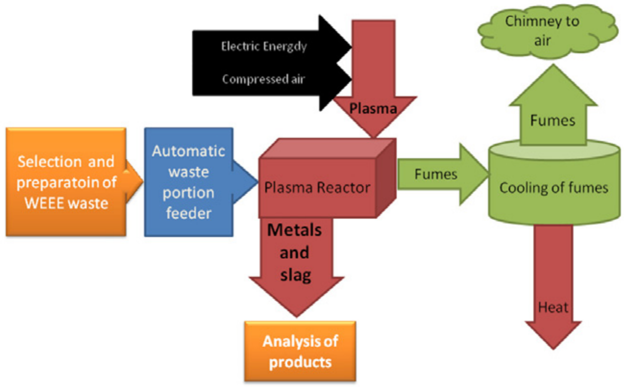


Fig. 3. Block diagram of the designed process for research over high temperature plasma technology for metals recovery and electronic waste utilization

Next, the incineration fumes are being transported to the scrubber where they are neutralized, cooled and then released to the atmosphere. As to the metals and slag, in molten form they flow out from the reactor and set in casts, from which they can be recovered and recycled. Fig. 4 presents the cross section of the reactor, arrows mark the waste and metals route (white arrow), plasma stream (black arrow), and the fumes exhaust direction (gray arrow).

## 7. Reactor chamber construction

Reactor chamber construction consist of three layers: first is a fire-proof concrete, next is the thermal insulation, and last is the external metal construction shell. Reactor chamber is hexagonal and its construction is presented on the Figs 4 and 5. Such construction allows bearing in its volume the temperatures up to 1700 °C. However, in the area where the plasma streams has direct effect on the waste, the temperatures exceed the temperature given above. Nevertheless, due to difficulties with measuring the temperatures above 2000 °C, the actual temperature is currently not measured.

The plasmatron plasma reactor have three sources of heat, which are 20 kW arc plasmatrons. Plasmatrons efficiency reaches up to 80% of energy to plasma heat efficiency. However, calculating the plasmatron efficiency including efficiency of the power source, overall efficiency decreases to 70%. Each plasmatron generates a stream of plasma, that flows out at the bottom of the reactor chamber. The plasma is produced from a compressed air, that is used as plasmatron working gas. Three plasmatrons consume 11 $Nm^3/h$ of air during normal operation.

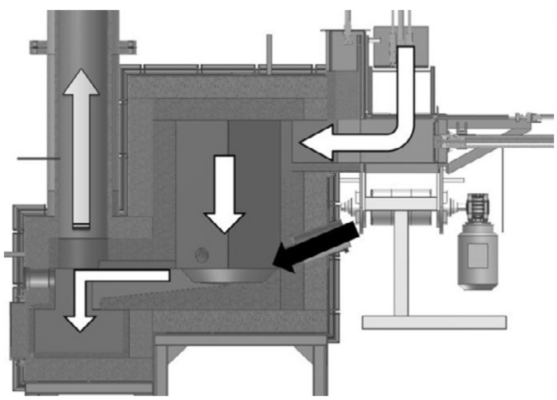

Fig. 4. Cross section through plasma reactor with presented material flow. Waste, and molten product – white arrows, plasma stream – black arrow, fumes – gray arrow

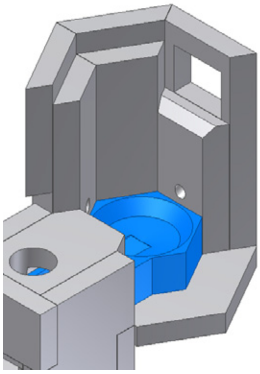

Fig. 5. Internal construction of plasma reactor – CAM model

## 8. Validation of developed plasma technology

Plasma technology for waste of printed circuit boards processing designed in PIAP offers a scalable and end-user-suited solution for PCB neutralization and metals recovery. Research and tests indicate that the developed test stand and technology demonstrator is capable of processing 800 kg/day of printed circuit boards. The process in tests consumed in total 66 kW of power, which corresponds to 2 kWh/kg of processed waste.

The technology offers processing of PCB waste as it is, without shredding it, and without any other preparation processes. This way allows decreasing the amount of energy required for waste processing and number of process steps. It is estimated that energy consumption will be decreased even further due to optimization of reactors construction, and other installation subsystems, leading also to increase of the throughput of this technology.

Energy consumption in metals smelting:

- Smelting of iron and nickel: 5.5–8 kWh/kg [12]
- Smelting of copper – 3.3–5.5 kWh/kg [13]
- Silicone production – 11 kWh/kg [14]

## 9. Products of plasma technology, processing printed circuit boards waste

High temperature plasma technology, processes the printed circuit boards without need of its preprocessing. For tests the complete circuit boards were boxed and feed to the reactor after reaching 1350 °C temperature in the reaction chamber. Single portion mass was 0.589–1.582 kg, while overall 18 kg of PCB was used. Test revealed that 0,55 kg of waste can be processed per minute, resulting in throughput of 33 kg/h and 792 kg/day.

Process products are: molten metal, and slag.

Recovered metal sample was analyzed, to identify and quantify amounts of elements. Summarized data is presented in Table 2. A cut through metal product is presented on Fig. 6.

Table 2. Emission spectrometer analysis of metallic sample

| Element | Mass (%) | Element | Mass (%) |
|---|---|---|---|
| Cu | 90 | Ni | 0.76 |
| Sn | 5.3 | Sb | 0.29 |
| Pb | 1.1 | Ag | 0.06 |
| Fe | 1.1 | Au | 0.0135 |
| | | Pd | 0.0048 |

Fig. 6. Cut through metal product of the process

Slag composition of metal oxides is presented in Table 3. Fig. 7 presents slag sample.

Table 3. XRF analysis of slag sample

| Element | Mass (%) | Element | Mass (%) |
|---|---|---|---|
| $SiO_2$ | 22 | Zn | 0.7 |
| $Al_2O_3$ | 17 | Cr | 0.6 |
| $Fe_2O_3$ | 13 | Ba | 0.5 |
| $TiO_2$ | 0.4 | Ni | 0.3 |
| CaO | 7 | Sb | 0.17 |
| Cu | 6.8 | Ta | 0.1 |
| Sn | 1.4 | Ag | 0.02 |

Fig. 7. Slag from plasma reactor after processing the printed circuit boards waste

The mass balance of processed waste and solid products indicates that the mass of the waste was reduced by 61% – from 17.4 kg of waste to 10.6 kg of solid products. Mass of the recovered metals is 3.5 kg, and the rest of the slag is 7.1 kg.

As it was noted before, the slag consists of metal oxides, and is formed during oxidation of metals in the reactor. That is why slag mass is higher than the mass of metals in the input waste, and thus the mass balance is affected by oxidation of metals that increases the slag mass.

Also, necessary to notice is the occurrence of evaporation of metals from plasma reactor due to the very high temperatures. Some of the metals are being evaporated and can be collected in scrubber during neutralization and cooling of the fumes.

## 10. Application of plasma technology for waste printed circuit boards processing and metals recovery in urban areas

Next to centralized facilities for waste of printed circuit boards processing, it is now possible to apply processing of PCB waste and recovery of valuable metals in small local scale, by plasma technology developed in Industrial Research Institute for Automation and Measurements PIAP. The developed technology allows processing of PCB waste near the facility where this category is being segregated, with no need of its transport to distant plants. Such solution allows processing of waste of electric and electronic equipment collected from urban areas to be completely recycled near the cities where WEEE is being collected. Then, the segregated printed circuit boards will be beneficially processed in the same local facilities that will bring additional income to this urban area.

This new technology is scalable, and can be designed for processing needs of the desired area or region. Considering the amounts of PCB being generated in Poland, the throughput of such installations should be 500–2000 kg/day. This leads to the conclusion that 2–3 solutions should be offered to cover all the needs. However, taking under consideration also some other factors like economic efficiency of such installation, it is possible to narrow the throughput to 1000 and 2000 kg/day. The designed technology allows to be scaled up further enabling the higher throughput. However, such investment in Poland is limited by amount of PCB waste being collected and available for processing. In Poland there are only 2 big urban areas that are populated by 5 mln of people – Voivodeships Mazowieckie and Śląskie.

Apart from shortening the transport time of the waste and costs related to this operation, the local processing of waste has additional advantages for urban areas. Besides the neutralization of waste and recovering of metals the developed plasma technology offers the process heat recovery. Heat recovery option is important for local processing plants in Poland, due to the 7 months cold season. Application of plasma technology for PCB waste processing offers savings on heating of the plant. Also the utilization of heat produced in waste processing generate savings for this region by reduction of transportation of fossil fuels for energy needs. Amount of heat available for recovery can be calculated from electrical power used for operation and amount of heat generated by incineration of waste. Heating value of printed circuit boards is 9.7–11.3 Mg/kg [15–16]. Given 66 kW of electric power consumption on test stand, and 800 kg/day throughput of it, available energy for heating purposes can be calculated:

$$5\ 700\ \text{MJ} + 8\ 000\ \text{MJ} = 13.7\ \text{GJ/day} = 570\ \text{MJ/h} = 160\ \text{kW}$$

## 11. Conclusions

1. Processing of waste collected from urban areas in surrounding locations allows to save energy and resources. Those savings can be used for actual processing needs and recovery of valuable resources from the collected waste. Calculated energy used for transportation of 4300 Mg of waste for 1500 km, is about 950 MWh, and energy required for complete processing of this amount of waste in designed plasma technology, that uses 2 kWh/kg of waste, is 11 180 MWh. This means that the 8% of energy required for processing of waste can be saved by processing it locally (where it's collected) instead of exporting it to distant location. Also, local urban areas can benefit further, due to energy recovery from the waste processing and savings on nonrenewable energy resources and their transportation.
2. Another benefit of processing the waste near the urban areas where it is collected, is that such approach boosts the development and creates new employment opportunities in the given area.
3. Interesting fact revealed in presented calculations is that the 14 of 16 Polish voivodeships collect less WEEE than it is possible to be processed at the test stand designed and build in PIAP for demonstration and research purposes.
4. By developing this new and innovative plasma technology for waste processing in a small scale, we proved that such smelting processes can be designed and the infrastructure of the device can be developed.
5. Taking all of the above into account it is beneficial for every region and area to identify the possibilities that will allow reduction of export of valuable resources in form of an "artificial ore" abroad, and to develop the new ways of utilization and production from resources they have.

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