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# Mechanical processing of end of life printed circuit boards for recovery of metals

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**Abstract**. The main objective of the present paper is to investigate the recoverability of precious metals and critical elements from waste printed circuit boards (PCBs) - originated from automobile industry - by mechanical methods. Firstly. the PCBs were crushed under 5 mm by rotary shear shredder and cutting mill in order to ensure the liberation of metal parts. After the sample preparation, the products were divided into size fractions by using standard sieves. In the different fractions the precious metals were enriched by eddy current and electrostatic separator. The density analysis showed that the liberation of metal parts is appropriate under the particle size of 2 mm. Therefore the samples were crushed and the enrichment experiments were carried out with this fraction again. Based on the results of electrostatic separator the non-ferrous and precious metals are enriched in the conductive product. While the critical elements left in the non-conductive product.

**Key Words**: WEEE recycling, mechanical separation, rare earth elements, circular economy.

**Introduction**. Europe consumes 25-30% of all the metals produced globally, but it is only responsible for 3% of global metal production (Nurmi et al 2010), which results to a high dependency on raw materials. Having noticed the criticality, in 2008 the European Commission launched the Raw Materials Initiative which aims to encourage transparency in raw materials trading worldwide, reduce waste and conserve resources, enhance expertise and develop new technology in the sector, and create a uniform mineral policy in Europe (COM 2008; Defra 2012). The initiative has provided the base of defining list of the critical raw materials as one of the element of the Raw Materials Initiative.

To qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance. In such a case, there is a relatively high probability of barriers to access these raw materials and the impact on the EU economy would be relatively significant (European Commission 2010).

In order to reduce raw material demand in general and thereby reducing the risk of any shortages, products are designed for extended lifetime, for reuse and repair, which leads to the direction of circular economy model. The Circular Economy Action Plan was introduced in 2015 by the European Union (COM 2015) to ensure risks are minimized, competitiveness grown, workplaces are established by reasonable consumption of resources. Regulation impacts product lifetime by focusing on design, which aims to avoid waste generation as products are designed for reuse or repair.

Printed Circuit Boards (PCB) integrated into different electric and electronic devices are becoming more and more important due to increasing digitalization efforts. At the end of their lives, electric and electronic devices are turning into waste (WEEE) and their processing is a very important environmental issue and also PCB's are rich and valuable sources of metallic alloys and elements, including rare earth elements. Nowadays mass production of these PCB panels requires huge amount of non-renewable resources including metals and critical raw material components. According to sustainable development efforts related to the European action plan for circular economy, development of new processes for recycling of these important metals back to the production cycle are vital. The aim of the recycling of WEEE panels are dual, recovery of the metal components and reducing the environmental impact in general (Szałatkiewicz 2014). The Institute of Raw Material Preparation and Environmental Processing, University of Miskolc, Hungary has carried out a large research project TÁMOP-4.2.2.A-11/1/KONV-2012-0005 – CriticEl. Within the framework of this project processing technology development for both primary and secondary raw material sources were targeted including high value.

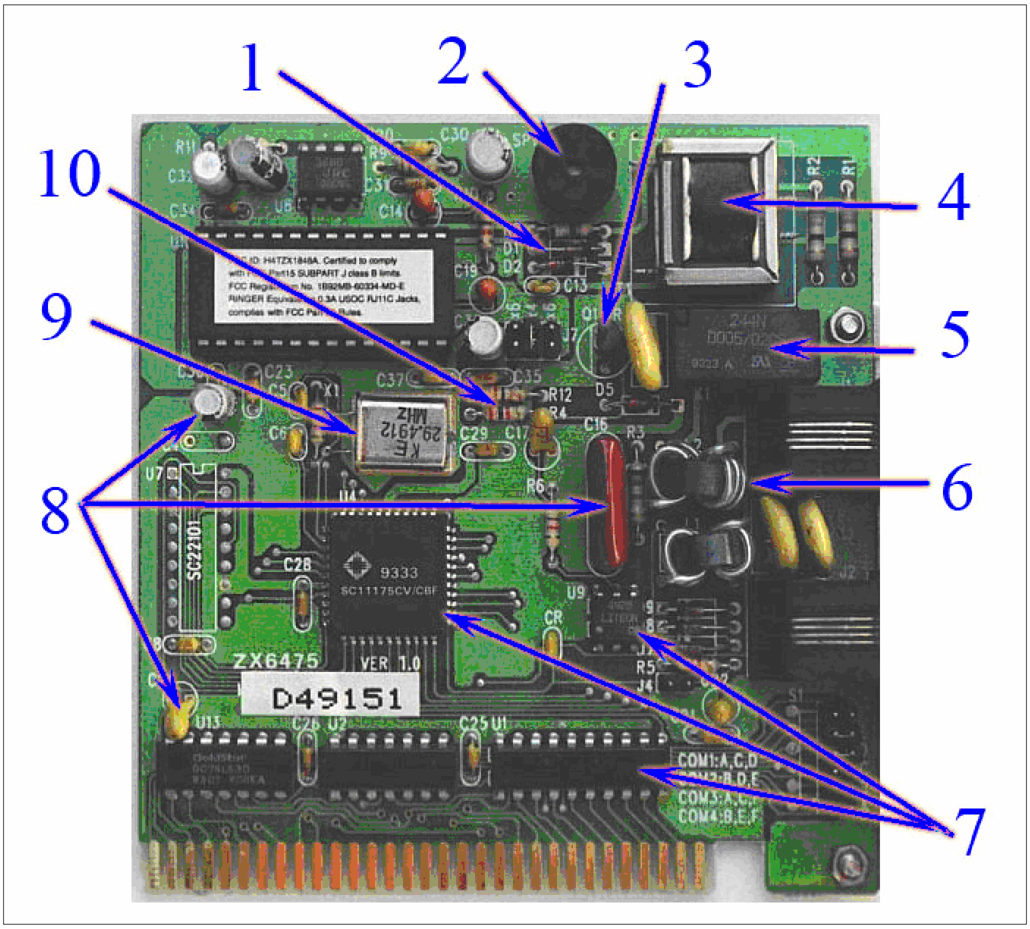

Figure 1. Main electric and electronic components on a typical PCB: 1 - diode; 2 - piezo vibrator; 3 - transistor; 4 - transformer; 5 - relay; 6 - coil; 7 - integrated circuit (IC); 8 - capacitor; 9 - oscillator crystal; 10 - resistance (http://www.uchobby.com).

The typical composition of the non-metallic fraction is epoxy (which is is basically a non-recyclable material), different plastics, glass fibers and different additives such as flame retarders and inhibitors. Metallic components are copper (16 m/m%), tin (4 m/m%), iron (3 m/m%), nickel (2 m/m%), silver (0.05 m/m%), gold (0.03 m/m%), palladium (0.01 m/m%) and rare earth elements. These metals are covering the plastic and ceramic parts and sometimes metal components are capsuled in plastic and ceramics. Composition of PCB's often varies according to their time and place of production and even the producer, therefore material composition is only a general estimation. Some typical PCB composition data is collected and presented in Table 1 (Canal Marques et al 2013). As Lukács & Gombkötő (2014) describes raw material dependency is important for autobile industry, especially when electric drive chain is become widespread, Földessy et al (2014) pointed out, that during separation process, different metals are not representing themselves in the metal concentrates. The aim of the laboratory test described in this paper was to obtain information on the faith of the REE during the liberation and separation process of PCB-s.

Table 1

Compositon of PC boards

| *Source by* | *Shouey et al (2006)* | *Zhao et al (2004)* | *Zhang & Forssberg (1997)* | *Kim et al (2004)* | *Iji & Yokohama (1997)* | *Kogan (2006)* | *Ogunniyi et al (2009)* |
|---|---|---|---|---|---|---|---|
| *Metals (max. 40 m/m%)* | | | | | | | |
| Cu [m/m%] | 20 | 26.8 | 10 | 15.6 | 22 | 17.85 | 23.47 |
| Al [m/m%] | 2 | 4.7 | 7 | - | - | 4.78 | 1.33 |
| Pb [m/m%] | 2 | - | 1.2 | 1.35 | 1.55 | 4.19 | 0.99 |
| Zn [m/m%] | 1 | 1.5 | 1.6 | 0.16 | - | 2.17 | 1.51 |
| Ni [m/m%] | 2 | 0.47 | 0.85 | 0.28 | 0.32 | 1.63 | 2.35 |
| Fe [m/m%] | 8 | 5.3 | - | 1.4 | 3.6 | 2 | 1.22 |
| Sn [m/m%] | 4 | 1 | - | 3.24 | 2.6 | 5.28 | 1.54 |
| Sb [m/m%] | 0.4 | 0.06 | - | - | - | - | - |
| Au [ppm] | 1000 | 80 | 280 | 420 | 350 | 350 | 570 |
| Pt [ppm] | - | - | - | - | - | 4.6 | 30 |
| Ag [ppm] | 2000 | 3300 | 110 | 1240 | - | 1300 | 3301 |
| Pd [ppm] | 50 | - | - | 10 | - | 250 | 294 |
| *Ceramics (max. 30 m/m%)* | | | | | | | |
| $SiO_2$ [m/m%] | 15 | 15 | - | 41.68 | 30 | - | - |
| $Al_2O_3$ [m/m%] | 6 | - | - | 6.97 | - | - | - |
| Alkali and alkali earth oxides [m/m%] | 6 | - | - | CaO 9.95<br>MgO 0.48 | - | - | - |
| Titanates and mica [m/m%] | 3 | - | - | - | - | - | - |
| *Plastics (max. 30 m/m%)* | | | | | | | |
| Polyethylene [m/m%] | 9.9 | - | - | - | - | - | - |
| Polypropylene [m/m%] | 4.8 | - | - | - | - | - | - |
| Polyester [m/m%] | 4.8 | - | - | - | - | - | - |
| Epoxy based | 4.8 | - | - | - | - | - | - |
| PVC | 2.4 | - | - | - | - | - | - |
| Polytetrafluorethane | 2.4 | - | - | - | - | - | - |
| Nylon | 0.9 | - | - | - | - | - | - |

## Material and Method

***Sample description***. The laboratory analysis was carried out in 2016 on printed circuit boards originating from the automotive industry. The samples were categorized into two parts, one with covers and one without covers. The boards with covers were covered with a hard-plastic housing in order to mechanically protect the electric – electronic component.

***Sample preparation and mechanical processing tests***. First step of the sample preparation and test were a comminution stage, where metal and non-metallic components were liberated from each other. Only liberated independent components are possible to separate from each other by mechanical means. The comminution stages are illustrated in Figure 2.

The sample comminution was a 3 stage crushing process where a rough crushing took place in a rotary shredder while the product particle size were below 10 mm. Following that two stage comminution in a vertical cutting mill were applied with an inbuilt screen of 10 mm and a 5 mm gap sizes. The particle size of the product were below 4 mm.

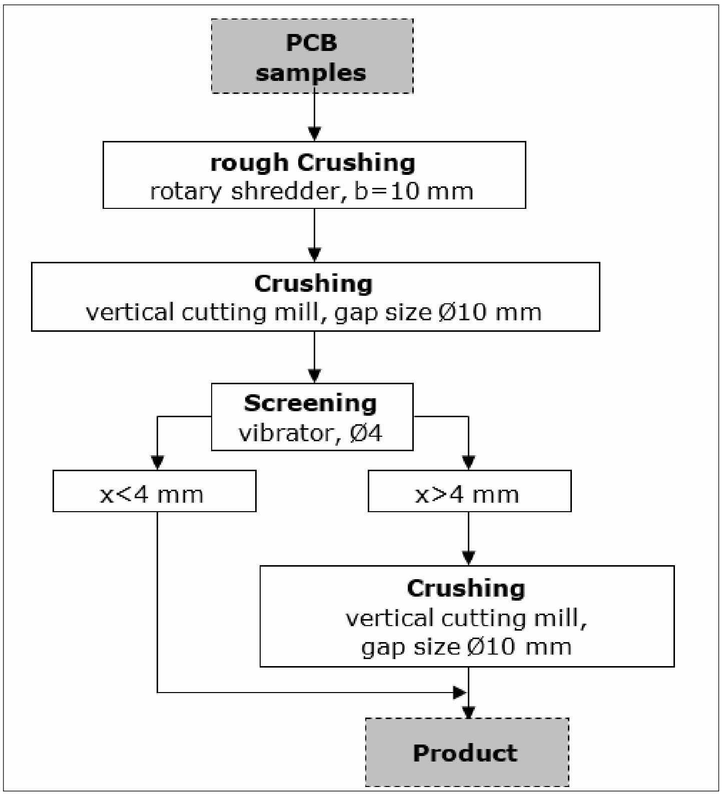

Figure 2. Flowsheet of sample comminution stages.

***Separation tests***. Size reduced PCB samples were screened and feed into different mechanical separators such as magnetic separator, eddy current separator and electrodynamic separator. The flowsheet and the different recovery rates of the tests can be seen in Figure 3. For better understanding, results with plastic covers are indicated in red numbers while yield data for non-covered components are indicated in blue.

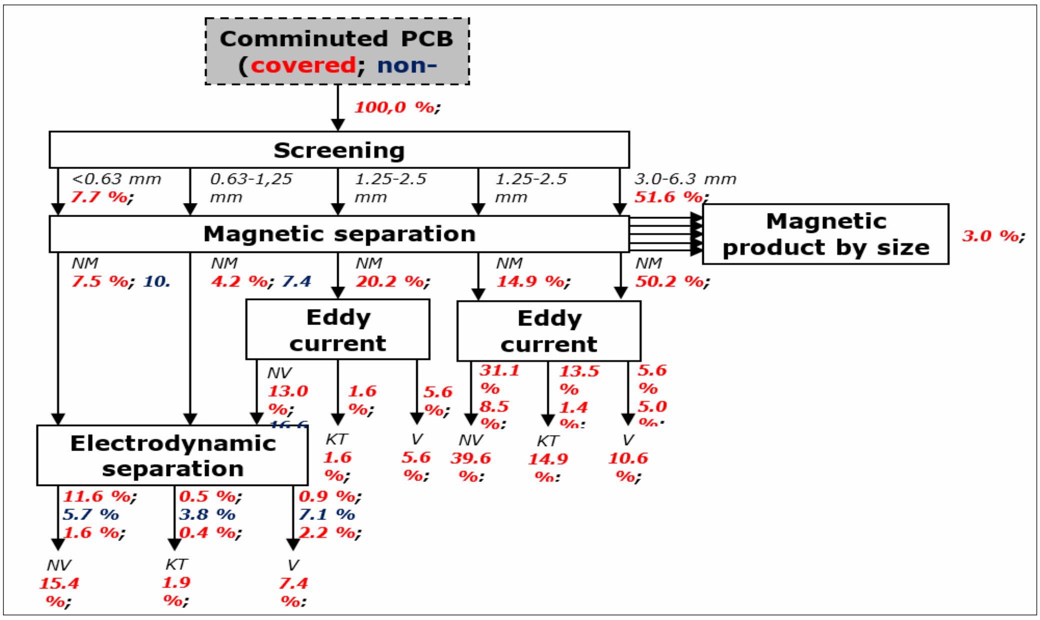

Figure 3. Flowsheet of the separation test were carried out, yield of the components are included.

Following screnning and magnetic separation, eddy current separation were applied to the samples. An ERIEZ type eddy current separator (ECS) was used for the non magnetic products of the magnetic separation. The particle size fractions were as follows: < 0.63 mm; 0.63-1.25 mm; 1.25-2.5 mm; 2.5-3.0 mm; and 3.0-6.3 mm. For the test, the separation plate was set first. For this, the magnetic rotor of the ECS was stationary and only the belt conveyor was in motion with an increasing velocity. The separation plate was set in a way that all the particles fall behind it. After that, test with running magnetic rotor was carried out. The rotor was used at two speeds (n = 1600 rpm and n = 2400 rpm) while the belt were moved v = 0.5 m $s^{-1}$ and v = 0.75 m $s^{-1}$ for the coarser size fractions and v = 1.0 m $s^{-1}$ for fine (1.25-2.5 mm) size fraction.

Electrodynamic separation was also applied for the non-magnetic product of the fine fractions and the non-conducting product of the eddy current separation of the 1.25-2.5 mm size fractions. Electrodynamic separation was carried out using the following parameters:
- drum rotation: n = 30 rpm;
- voltage: U = 15 kV and U = 20 kV and in case of the finest size faction ( < 0.63 mm) U = 27 kV;
- separation plate: a = 80° and 90°;
- separation method: two stage separation with the re-feeding of the non-conducting product of the first stage.

The products were as follows:
- 1.25-2.5 mm and 0.63-1.25 mm size fraction:
    U = 15 kV conductor product,
    U = 20 kV middling (conductor product at 20 kV),
        non-conductor product;
- finest suize fraction (< 0.63 mm) U = 27 kV
    U = 15 kV conductor product,
    U = 20 kV (conductor product at 20 kV)
    U = 27 kV (conductor product at 27 kV),
        non-conductor product.

**Results and Discussion**. According to the test results, the amount of the magnetic components in each size fractions are generally less than 10%. The yield of the non-conductor product recovered in the ECS was generally between 57-65% while the yield of the conductor were 11-33% and the yield of the middling was approximately 8-26% according to the test parameters. Yield of the conductor components in the electrodynamic separator was relatively high for the size fractions 0.63-1.25 mm and < 0.63 mm, between 37-57% while the yield of the middling was less than 10%. The physical liberation of the products was tested by analyzing the particle density of the products. Physical liberation was sufficient below 2 mm particle size. According to these results, samples were comminuted below 2 mm and the same separation test were carried out in the sample. Results of this experiments are indicated in Figures 4 and 5.

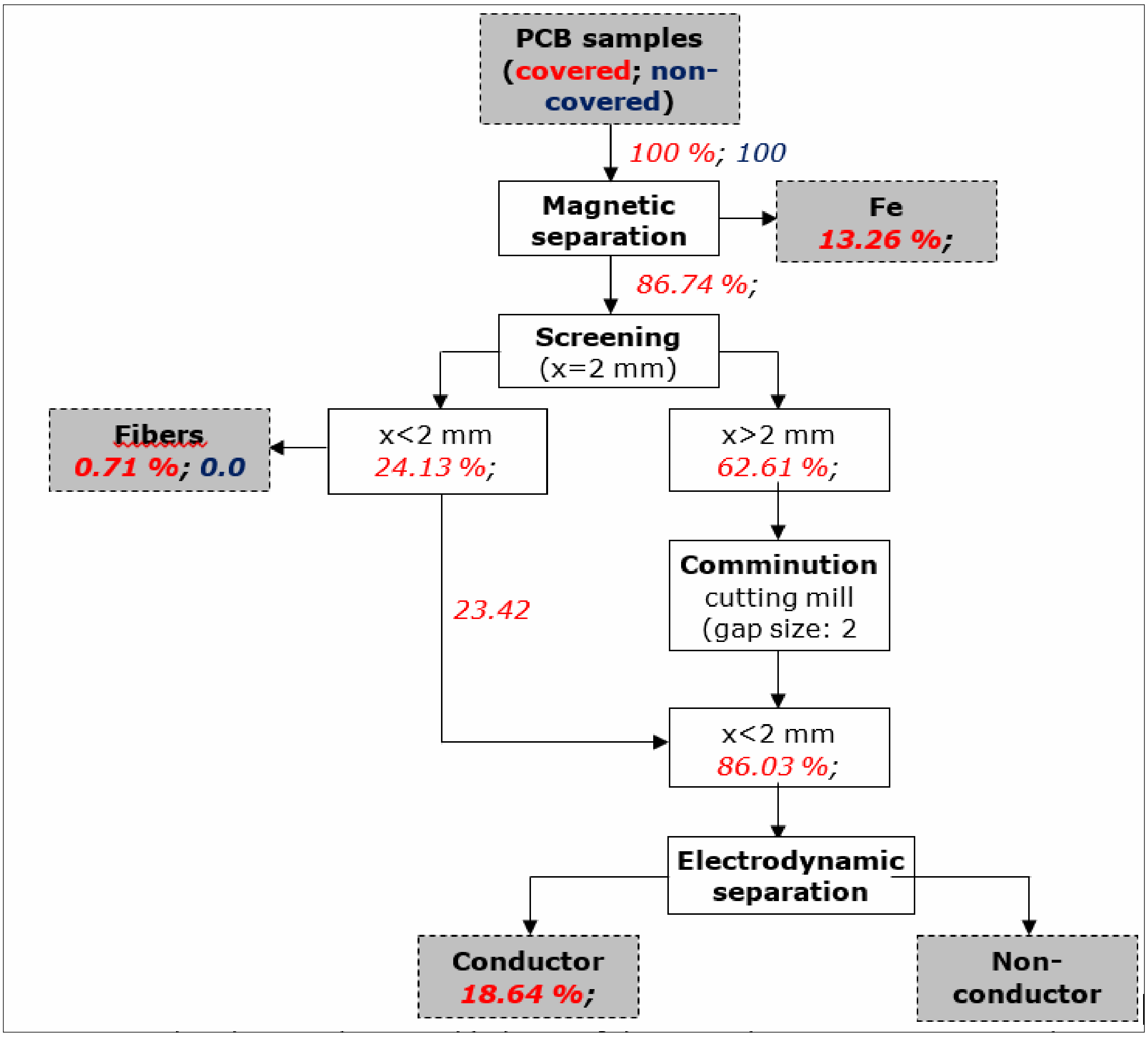

Figure 4. Flowsheet and material balance of the second separation test carried out on < 2 mm sample.

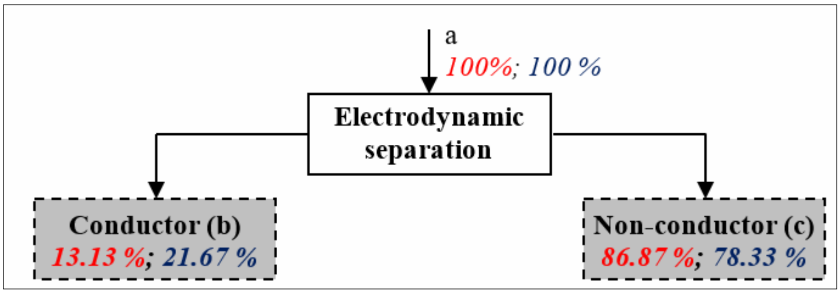

Figure 5. Flowsheet and material balance of the second separation test carried out with only an electrodynamic separator.

Products of separation tests were sent to chemical analysis to the Hungarian Academy of Science, Research Center for Natural Sciences. The results are indicated in Tables 2 and 3.

Table 2

Chemical elements in a corresponding group

| *Groups* | *Chemical elements* |
|---|---|
| Base metals | Cu; Zn; Pb; Sn; Sb; Ni; Co |
| Rare metals | Be; Ta; Ga; Ge; Nb; V; Te; Tl |
| Rare earth elements | Ce; Pr; Nd; Pm; Sm; Eu; Gd; Tb; Dy; Ho; Er; Tm; Yb; Lu |
| Precious metals | Au; Ag; Pt; Os; Ir; Pd; Rh; Ru |
| Critical elements | Sb; Be; Co; F; Ga; Ge; In; Mg; Nb; Pt; Os; Ir; Pd; Rh; Ru; Y; Sc; La; Ce; Pr; Nd; Pm; Sm; Eu; Gd; Tb; Dy; Ho; Er; Tm; Yb; Lu; Ta; W |

Table 3

Yields and recovery rates of different elements in the products of electrostatic separation

| *Groups / Elements* | *$m_b$. yield conductor [%]* | *$m_c$. yield non-conductor [%]* | *b. amount in the conductor [mg kg$^{-1}$]* | *c. amount in the non-conductor [mg kg$^{-1}$]* | *a. amount in the feed [mg kg$^{-1}$]* | *$k_b$. recovery rate in the conductor [%]* | *$k_c$. recovery rate in the non-conductor [%]* |
|---|---|---|---|---|---|---|---|
| Base metals | 13.13 | 86.87 | 729621.00 | 182404.40 | 254253.94 | 37.68 | 62.32 |
| | 21.67 | 78.33 | 806400.30 | 178108.80 | 314259.57 | 55.61 | 44.39 |
| Rare metals | 13.13 | 86.87 | 43.10 | 29.80 | 31.55 | 17.94 | 82.06 |
| | 21.67 | 78.33 | 22.10 | 36.60 | 33.46 | 14.31 | 85.69 |
| Rare Earth elemnts | 13.13 | 86.87 | 11.90 | 56.80 | 50.90 | 3.07 | 96.93 |
| | 21.67 | 78.33 | 23.30 | 105.80 | 87.92 | 5.74 | 94.26 |
| Precious metals | 13.13 | 86.87 | 902.10 | 2399.00 | 2202.46 | 5.38 | 94.62 |
| | 21.67 | 78.33 | 1967.00 | 629.60 | 919.41 | 46.36 | 53.64 |
| Critical elements | 13.13 | 86.87 | 4289.00 | 3057.30 | 3219.02 | 17.49 | 82.51 |
| | 21.67 | 78.33 | 1026.10 | 3122.10 | 2667.90 | 8.33 | 91.67 |
| Gold | 13.13 | 86.87 | 5.70 | 3.50 | 3.79 | 19.75 | 80.25 |
| | 21.67 | 78.33 | 18.20 | 28.50 | 26.27 | 15.01 | 84.99 |
| Silver | 13.13 | 86.87 | 887.00 | 2390.00 | 2192.66 | 5.31 | 94.69 |
| | 21.67 | 78.33 | 1940.00 | 592.00 | 884.11 | 47.55 | 52.45 |

Note: results indicated in red originates from covered PCB while results indicated in blue originates from non-covered PCB feed.

**Conclusions**. After the sample preparation, the products were divided into size fractions by using standard sieves. In the different fractions, the precious metals were enriched by eddy current and electrostatic separator successfully. The density analysis showed that the liberation of metal parts is appropriate under the particle size of 2 mm, therefore the samples were crushed and the enrichment experiments were carried out with this fraction again. Based on the results of electrostatic separator, the non-ferrous and precious metals are enriched in the conductive product, while the majority of the critical elements were concentrated in the non-conductive product.

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