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Thermal Arc Plasma Treatment of Waste Electrical and Electronic Equipment: A Review

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Abstract: Waste electrical and electronic equipment (WEEE) is increasing at an alarming rate due to technological advancement and upgrade in consumer electronic goods. There is a continuous production of new version while the old ones are discarded. These led to the accumulation of large quantities of WEEE. Thermal arc plasma provided the needed benign technology that safely treats the waste and reclaims the metallic part. A review of thermal arc plasma treatment of WEEE is presented in this study. Products from the treatment technique are flue gas, molten metals, vitreous slag and fly-ash. The flue gas is mostly CO, CO_2 and O_2 obtained from pyrolysis of plastics and other organic parts of the waste. Copper is the dominant metal in the ingot as it was the dominant metal in the electronic waste. Precious metals are recovered from the ingot through other purification processes. Large volume reduction of electronic waste is achieved after thermal arc plasma treatment. Partitioning of precious metal into solid product (ingot) is achieved through plasma temperature regulation not above the boiling point of the metals concerned. However, this will affect the quality of flue gases generated from decomposition of the organic part of the electronic waste, obnoxious gases are formed at low temperatures. It is therefore recommended to use an integrated plasma system comprising of two units, one of low temperature to separate precious metals from electronic waste and the other of high temperature to treat flue gases exiting the first unit.

Key words: Electronic waste, flue gases, ingot, metal recovery, thermal plasma,

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1. INTRODUCTION

Product development and technological innovations in the electrical and electronic industry coupled with consumerism has led to a fast growth of waste electrical and electronic equipment (WEEE) [2, 3]. The lifespan of electrical and electronic products has been shortened drastically, the lifespan of most mobile phones is around 1 year while that of personal computers is between 2 to 5 years[4]. The quest for newer versions, with more inbuilt facilities, of electrical and electronic consumer goods has increased[5]. Older/outdated versions are continuously being replaced[6]. This has led to the generation of large volume of obsolete discarded electrical and electronic equipment (EEE)[7].

According to Widmer, et al. [8], WEEE account for 8% of municipal waste. About 100 million mobile phones and 17 million personal computers were discarded annually. Within the EU countries alone, WEEE has grown from 6.7 million tons in 2006 to 12 million tons in 2015. The UN has put the global production of WEEE at 20 to 50 million tons per year [4, 9, 10]. In 2008 Sweden, Britain and Austria, respectively collected 16.7, 8.2 and 6.5 kg/capita of WEEE[11]. Fig. 1 depicts the pace of WEEE growth in Eastern (EA) and western (WE) Europe.

First twenty (20) leading nations in the electronic waste generation and the corresponding per capita generation is shown in Table 1. USA, China, Japan and Germany are the leading nations is the electronic waste generation. While the USA, Japan and Germany have the large per capita generation, China with a low per capita generation of 9.7 is among the first four due to its large population. UK has the largest per capita generation of 51.8 followed by USA and France with per capita generation of 48.7 each. The Asian countries of Taiwan and Thailand are among the 20 leading nations in the WEEE generation. WEEE has become a global problem not only because of growth in volume and mass but also due to the presence of toxic materials like mercury, lead, nickel, palladium, beryllium, brominated flame retardant (BFRs) and cadmium[12, 13].

EU legislative restricts the use of hazardous substances in EEE (Directive 2002/95/EC) such as lead, mercury, cadmium, chromium and flame retardants: polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) and also promotes the recovery, reuse and recycling (RRR) of such equipment (Directive 2002/96/EC)[10]. The European Parliament and the Council Directive of 2003 on WEEE(Directive 2002/96/EC) set the following objectives[14].

- Collect annually at least 4 kg/habitant of WEEE from private households
- Ensure an annual rate of recovery and recycling according to a set guideline as shown in Table 2
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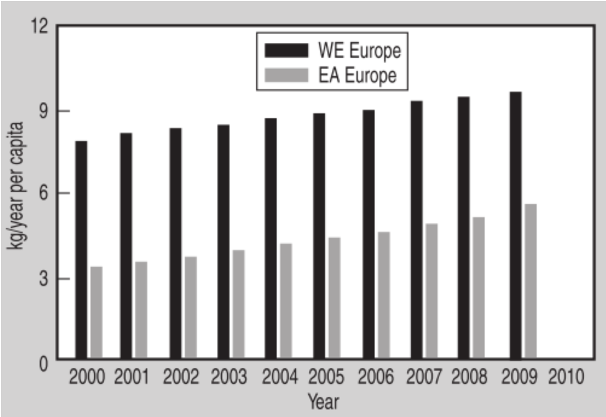

Fig. 1: Increase in the WEEE amount in European countries [1]

Table 1: World major producers of electronic waste in 2014 (adopted from Bodamer [15])

Position	Country	Population (1000,000)	E-waste generation (tons)	Rate (lb/ inhabitant)
1	US	300	7, 795, 000	48.7
2	China	1, 300	6, 650, 000	9.7
3	Japan	127	2, 430, 000	38.1
4	Germany	81.6	1, 950, 000	47.6
5	India	1, 260	1, 810, 000	2.9
6	UK	64	1, 670, 000	51.8
7	France	64	1, 560, 000	48.7
8	Brazil	200	1, 560, 000	15.4
9	Russia	143	1, 360, 000	19.2
10	Italy	61	1, 190, 000	38.8
11	Mexico	117	1, 050, 000	18.1
12	Spain	46	900, 000	39.0
13	Rep. of Korea	50	886, 000	35.1
14	Indonesia	251	821, 000	6.6
15	Canada	35.5	799, 000	45.0
16	Iran	78	640, 000	16.3
17	Turkey	77	554, 000	14.3
18	Australia	23.3	516, 000	44.1
19	Taiwan	23.5	483, 000	41.0
20	Thailand	65	462, 000	14.1

Other regulations on the generation of WEEE include WEEE directives and Restrictions on Hazardous Substances (RoHS) [16].Despite all the environmental regulations on WEEE only one-third of the waste are collected and appropriately recycled in the European countries; two-thirds of the waste is sent to landfills and inappropriate treatment sites[10]. Majority of the WEEE end-up in open-land-dumping and landfill. This practice endangers the environment by leaching out toxic chemicals to the ground[17, 18] or releasing harmful chemicals into the air[19]. This paper covers, a review of thermal arc plasma treatment of WEEE

2. CHARACTERISTICS OF ELECTRICAL AND ELECTRONIC WASTE

Electronic waste (E-waste) is a terminology applied to business and consumer goods (electrical and electronic equipment) that is broken, malfunction, unwanted or near the end of its useful life [20]. It is also referred to WEEE. It is a complex waste with a wide variety of mechanical devices and highly integrated component units

[21]. Precisely, electronic waste includes waste from discarded mobile phones, computers, electrical and electronic office equipment, household appliances and electronic entertainment devices [22]. Electronic waste account for about 8% of the global municipal solid waste (MSW) [8].

Electronic waste is hazardous due to the presence of heavy metals (e.g., mercury, cadmium, lead), flame retardants (e.g., Penta-bromophenol, poly-brominated-diphenyl-ethers (PBDEs), tetrabromo-bisphenol-A (TBBPA), etc.) and other substances [23]. Cathode ray tubes (CRTs), for example, is reported by Kang and Schoenung [12] as one of largest sources of lead in municipal waste. According to Yuan, et al. [24], printed circuit board (PCB) contain about 30% metals, 37% inorganics and 31% organics. Cell phones were reported to contain mercury (Hg), cadmium (Cd), lead (Pb) and arsenic (As) [14]. These substances in cell phones can pollute the air, soil and water. They persist in the environment through bioaccumulation via the food chain. An estimate by Basel Action Network (BAN) put a number of materials in 500 million computers in the world at 2.87 billion kilograms of plastics, 716.7 million kilograms of lead and 286,700 kilograms of mercury [13]. The material composition of WEEE from two different sources is given by Jarosz, et al. [1] as shown in Fig. 2. Components of electronic waste containing hazardous substances and material composition of PCB are shown in Table 3 and Table 4 respectively.

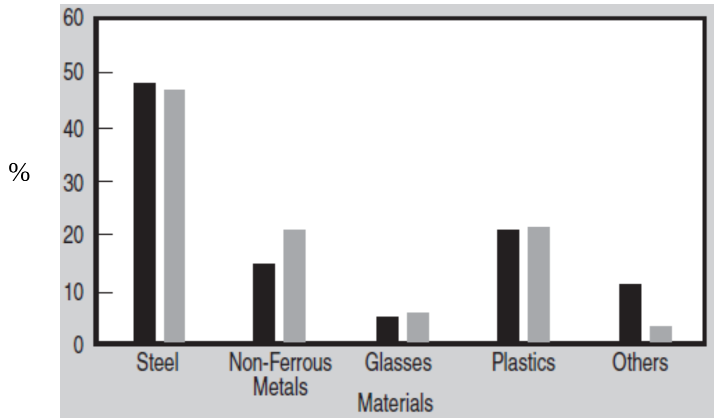

Fig. 2: Material composition of WEEE according to Jarosz, et al. [1]

Table 2: The RRR of components, materials and substances in EEE [14]

Category of e-waste	Rate of reuse (%)	Rate of the reuse and recycle (%) (from the average weight of the component)
Large household appliances	80	75
Small household appliances	70	50
Information & telecommunication components	75	65
Consumer electronic	75	65
Electric & electronic machines (except large stationary industry machines)	70	50
Machines for monitoring and control	70	50

3. TECHNOLOGIES FOR TREATMENT OF WEEE

Methods for treatment of WEEE include incineration, pyrolysis, mechanical treatment, hydrometallurgical process and pyrometallurgical smelting. Incineration is a widely used treatment method adopted for solid waste, it has the advantage of complete waste destruction and volume reduction[25]. However, incinerating WEEE is a dangerous practice. Heavy metals and compounds of chloride are found in ashes which posed environmental challenges[20]. Obnoxious chemicals (dioxins and furans) are released from incineration of brominated flame retardants (BFRs) even at low temperature due to the catalytic action of copper[23, 26]. Incineration of WEEE in EU countries accounts for emissions of 36 tons per year of mercury and 16 tons per year of cadmium[27].

Pyrolysis of WEEE allows separation and concentration of metals in combination with carbon from the organic parts of the waste. However, liquids and gaseous products from pyrolysis of WEEE contain a significant amount of toxic brominated hydrocarbons[28, 29]. Mechanical processing of WEEE is based on mechanical milling of the feedstock into fine powder followed by multi-step segregation of the powder materials. The process allows recovery of materials like aluminum, brass, ferrous metals, glass, plastics and dust. However, there is the loss of precious metals and the recovered metals need to be purified through a hydrometallurgical or pyrometallurgical process[30].

Table 3: Major components of electronic waste containing hazardous substances[23]

Components	Equipment	Hazardous substance
Cathode ray tubes	Old TV set, PC monitors, oscilloscopes	Pb in cone glass, Ba in electron gun getter, Cd in phosphors
Printed circuit boards	Ubiquitous, from beepers to PCs	Pb and Sb in solder, Cd and Be in contacts, Hg in switches, BFRs in plastics
Batteries	Portable devices	Cd in Ni-Cd batteries, Pb in lead-acid batteries, Hg in Hg batteries
Gas discharge lamps	Backlights LCDs	Hg in phosphors
Plastics	Wire insulators, plastics housing, circuit boards	BFRs

Table 4: Material composition of PCB

Metals	Weight percent				
	[36]		[32]	[30]	
Cu	27.99	25.24	18.5	14.6	24.61
Al	0.47	0.69	1.33	NA	NA
Pb	2.17	2.22	2.66	2.96	0.63
Zn	2.01	2.05	NA	NA	NA
Ni	1.23	0.93	0.43	1.65	0.11
Fe	1.18	0.98	2.05	4.79	0.22
Sn	3.26	3.17	4.91	5.62	2.31
Cr	NA	NA	NA	356 ppm	250 ppm
Au	440 ppm	890 ppm	86 ppm	205 ppm	76 ppm
Pt	57 ppm	17 ppm	NA	NA	NA
Ag	1490ppm	1907ppm	694 ppm	450 ppm	242 ppm
Pd	50 ppm	47 ppm	97 ppm	220 ppm	< 27ppm

Waste treatment and metals recovery using hydrometallurgical techniques are based on acid leaching[31], cyanide lixiviation[32] and a combination of supercritical water (SCW) pre-treatment and acid leaching[33]. Hydrometallurgical techniques allow segregation, refining and recovery of metals from waste. However, application of hydrometallurgy to metal recovery from WEEE on an industrial scale is limited due to the large volume of liquid waste that is generated from the process[30]. The prerogative of any waste treatment technique, especially to WEEE, is for high efficient metal recovery from the feedstock combine with less production of secondary waste. That is the reason behind the choice of pyrometallurgical processes for treatment of WEEE over other processes.

Pyrometallurgical processing is a high-temperature treatment of waste where the organic components are incinerated while the inorganics and metals presents are smelted into slag and ingot[34]. The smelted metals, like Cu, are used as collectors to bond together certain groups of metals, like Ag and Au. Subsequently, those concentrates are further treated to recover pure metals [11, 35]. High-temperature pyrometallurgical process based on a thermal arc plasma technology overcomes the problem of gaseous emission from incineration. The plasma technology is an alternative to the centralized smelting technologies of the pyrometallurgical process. It is a promising technology in the treatment of WEEE.

There is a rapid growth in the use of thermal arc plasma technology in waste treatment[36, 37]. The plasma treatment technique has the advantage of producing less harmful by-products coupled with large waste volume reduction [38]. The organic portion of waste is converted to synthetic gas while the inorganic is vitrified into an economically viable solid [39]. Thermal arc plasma has been adopted for highly efficient processes like thermal cracking and oxidation of hazardous wastes [20, 40]. In waste management, plasma technology has found applications in the treatment of municipal solid waste [36, 41-48], treatment of medical waste [49-54], treatment of incinerator ashes [39, 55-64], treatment of industrial and wastewater sludge [38, 65-71] and in treatment of electrical and electronic waste[1, 11, 20, 30, 72-76].This paper reviews thermal arc plasma treatment of WEEE. The paper looked into the characteristics and composition of WEEE, described nature and generation of thermal arc plasma, compared process variables and performances in different novels thermal arc plasma treatment of WEEE and proffer suggestions for improvement.

4. THERMAL ARC PLASMA TECHNOLOGY

Plasmas contain a lot of energetic species, such as electrons, ions and radicals which can enhance chemical reactions. It is categorized into thermal and non-thermal arc plasmas. The former is an atmospheric pressure plasma characterized by high temperature and enthalpy, the temperature ranges from 1,500 to 10,000 K. The latter is the non-equilibrium low-pressure plasma characterized by high electron temperature and low ion and neutral temperature[77]. A thermal arc plasma is generated using plasma torch, a device that utilizes two electrodes, cathode and anode, and neutral gas to create a high-density electric arc[78]. There are basically two types of plasma torches, transferred arc torch and non-transferred arc torch[79, 80]. In non-transfer arc torch, the two electrodes are located within the water-cooled body of the torch[81, 82]. High density and a high-temperature arc are generated in between the electrodes. The pressure of the flowing gas stream pushes the plasma out of the torch through a nozzle creating a plasma jet[80]. This type of torch has a lower power consumption and a lower electrode degradation[83], it produces less noise and less vibration resulting to a more stable operation, and it has a low heating efficiency of between 50 and 75%.

In the case of transferred arc torch, only the cathode is located within the torch casing, the anode is usually the material to be treated or a metal container that holds the material to be treated [67, 69, 84]. This electrodes arrangement allows the plasma to be generated in the space between the water-cooled torch and the material thereby generating plasma with high heating efficiency[85]. Transfer arc torch is characterized by relatively large electrodes separation that ranges from a few centimeters up to a meter[81]. The cathode is either a consumable material, like graphite, or a water-cooled metal, while the anode is usually a metal with high thermal conductivity like copper or silver[83].

5. THERMAL ARC PLASMA TREATMENT OF ELECTRONIC WASTE

A number of studies on the treatment of WEEE using thermal arc plasma technology have been documented in the literature. Whereas most of the studies were solely targeted at protecting the environment through benign treatment options[20], some have in addition, recovering of precious metals present in the waste[72-74].Tippayawong and Khongkrapan [20] investigated the physical characteristics of a 20 kW non-transferred DC air plasma reactor as well as its application to electronic waste treatment. Using power rating of 12-20 kW and gas flow-rate of 300 L/m, the researchers' discovered that the torch can produce a high-temperature plasma of the order of 1200 K with a large volume of flames. Using the generated plasma they were able to achieve a thermal decomposition and waste volume reduction of 80% within two minutes of treatment. Schematic diagram of the thermal arc plasma system used by Tippayawong and Khongkrapan [20] is shown in Fig. 3.

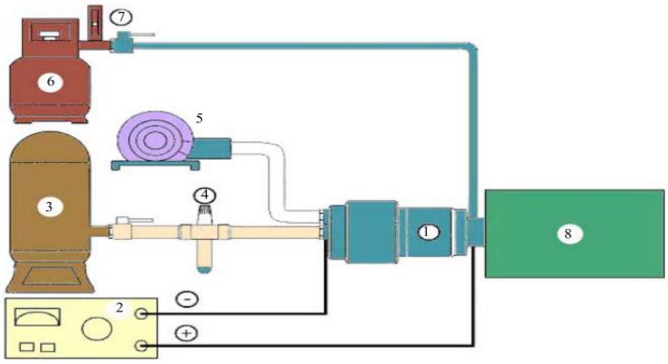

Fig. 3: Schematic diagram of thermal arc plasma system. (1) Plasma torch, (2) DC power supply, (3) air tank, (4) air flow regulator, (5) blower for cooling air (6) LPG tank, (7) gas flow regulator and (8) furnace module

A previous study on the recovery of precious metals from WEEE indicates that low boiling point metals like As and Cd are volatilized in both oxidizing and reducing environment even at a temperature of 880^{o}C [3]. For this reason, precious metal recovery using plasma is regulated at a temperature below the boiling point of the metal concern. An investigation of valuable metal recovery from assorted electronic waste using transferred thermal arc plasma reactor was reported by Rath, et al. [74]. The transferred arc reactor, shown in Fig. 4, is made of a zircon coated graphite crucible furnace enclosed in a water-cooled steel casing. The cathode is a vertical graphite electrode with an axial hole for passage of the plasma forming gas. A horizontal graphite electrode serves as the anode. One kilogram of assorted electronic waste consisting of plastics, PCBs, batteries and cardboard were melted in the 35kW DC extended transferred arc plasma reactor. Two products, metals and nonmetals mainly ash, were obtained in the ratio of 80:20. In their findings, Cu was leached out from the plasma product whereas Al and

Fe were obtained as an alloy. They also observed an increase in weight reduction with treatment time up to a maximum of 60% at the end of 20 minutes treatment. Concentrations of obnoxious elements in the flue gas were reported to be well below their permissible limits.

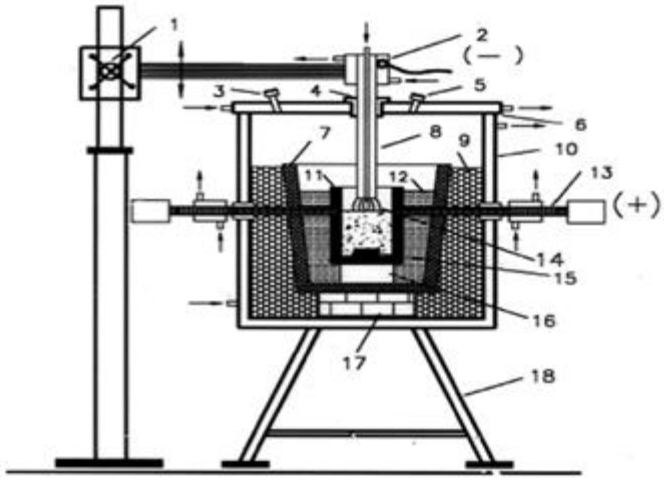

Fig. 4: Schematic diagram of an extended arc plasma reactor. 1-rack & pinion, 2-hole for cooling water, 3-gas exhaust outlet, 4-alumina bush with graphite sleeve, 5-view port, 6-steel cover, 7-salamander hearth, 8-graphite electrode, 9-bubble alumina, 10-water-cooled steel casing, 11-graphite crucible, 12graphite wool, 13-graphite electrode, 14-plasma stream, 15-graphite block, 16-magnesia block, 17-alumina block, 18-support.

More studies on the recovery of valuable metals from electronic waste were reported by Mitrasinovic, et al. [73] and [72]. Using a DC arc plasma reactor designed and built at the Centre for Advanced Coating Technology (CACT), the University of Toronto, Mitrasinovic, et al. [72] were able to recover valuable precious metals from WEEE. The reactor, shown in Fig. 5, is equipped with a 30kW non-transferred torch. The torch is a button type water-cooled electrode with a 7 mm nozzle diameter for passage of plasma gas. Using a mixture of molecular gases (CH_4 and CO_2) the researchers were able to generate high enthalpy plasma with high thermal conductivity which was used to recover copper from a simulated electronic waste. In an earlier investigation, the research team were able to recover 91wt.% of copper at plasma temperature lower than the boiling point of pure copper [73].

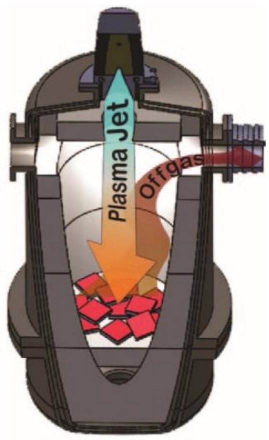

Fig. 5: Laboratory size batch-type reactor for thermal arc plasma treatment

Similar investigations of recovery of metals from WEEE using thermal arc plasma technology were conducted by a polish team. A high-temperature-pyrometallurgical non-transferred thermal arc plasma reactor for treatment of PCB was designed and constructed at the Industrial Research Institute for Automation and measurements, Poland. The reactor which is designed to neutralize PCB waste and recover precious metals is equipped with three plasma touches. The system can process PCB without shredding, and the power consumption is 2kWh/kg of PCB processed[11].

The equipment setup is shown in Fig. 6. Two products (molten metals and slag) were obtained from treatment of 18kg of PCB at the rate of 0.55kg/min. In yet another investigation, Szałatkiewicz [30] reported a high-efficiency recovery of about 76% for each of, Ag, Au, Pd, Sn and Pb. According to the researchers, the novel reactor can treat 100% PCB with no generation of toxic byproduct.

Fig. 6 Thermal arc plasma reactor (1) plasma reactor, (2) plasma torch, (3) molten product collector), (4) fume exhaust chimney, (5) waste conveyor, (6) plasma energy source, (7) PLC automation and data collection apparatus cabinet and (8) waste feeder.

The effect of melting sorted electronic scraps in plasma furnace was investigated by Jarosz, et al. [1]. Three types of materials (PCBs, cables and windings) were dismantled and segregated from WEEE and treated batch-wise in a 50kg/h capacity transferred thermal arc plasma furnace. Nitrogen gas was used to generate the transferred thermal arc plasma between vertical carbon electrodes. Four products (alloy metals, slag, dust and gases) were obtained from the treatment of the sorted electronic scraps. The three sorted WEEE show similarities in the composition of the recovered alloy metals were Cu is the dominant metal in the alloys with traces of Fe, Sn, Sb, Ba, Pb and Ag.

Further investigations on the treatment of WEEE in thermal arc plasma reactor were reported by Ruj and Chang [75]. Under reduced atmosphere, plastic and other non-metallic components of mobile phone waste were decomposed into combustible reformed gases (H_2, CO and CxHy), while the metal components were concentrated into solid byproduct. Variation with time, of the concentration of CO, CxHy and H_2 for display-magnetic (dm), display-nonmagnetic (dnm), non-display-magnetic (ndm) and non-display-nonmagnetic (ndnm) components of mobile phones are depicted in Fig.7. Toxic gases (NOx and H_2S) and greenhouse gas (CO_2) were not detected. The nature of the WEEE, weather dm, dnm, ndm or ndnm, does not affect the composition of the H_2 in the flue gas. However, nature of waste affects the CO and CxHy compositions in the flue gas. The product of dm contained more CO than CxHy while dnm contained more CxHy than CO.

In yet another investigation on the treatment of WEEE in a thermal arc plasma reactor, discarded computer equipment mixed with dolomitic limestone in the ratio 71.43:28.57, were treated at an average temperature of 1410^{o}C[14]. Four products, metal-alloy, slag, flue-dust and syngas were obtained. The composition of the three solid products can be seen in Table 5 [14]. Stable slag-forming oxides, (SiO_2, Al_2O_3, CaO and MgO) concentrated at the bottom of the reactor in the slag form. Less-stable oxides with high boiling point and low vapour pressure of metals (Cu_2O, Fe_2O_3, NiO, SnO_2, CdO, ZnO and PbO) are reduced by the high-temperature plasma into their metal elements (Cu, Fe, Ni, Sn, Cd, Zn and Pb). Heavy metals with lower boiling points (Hg, Cd and Zn) are concentrated in the synthesis gas and reduced to fly ash in cleaning facilities. An average generation of synthetic gas was 0.498 m^3/kg of waste, and the average composition of the synthetic gas is as follows; 0.15% CH_4; 47.50% H_2; 0.28% O_2; 15.70% N_2; 0.43% CO_2; 36.00% CO; 0004% C_2H_4; $\leq$ 0.001% C_2H_6; 0008% C_2H_2; 0003% C_3-C_8 hydrocarbons. Ellamparuthy, et al. [76] have shown that exhaust gas from the recycling of WEEE contained heavy metals (Cu, Al, Fe, Sn, Pb, Zn, Ni), hazardous metals (Sb, As, Cd), and precious metals.

Operating conditions for treatment of WEEE and chemical compositions of product alloys from several investigations are shown in Tables 6 and 7 respectively. It is evident that most of the studies on recycling of precious metals from WEEE using thermal arc plasma technology duel on the evaluation of the product solid. Only a few of the investigations evaluated the flue gas with the goal of analyzing the components, the environmental safety of the gas and the energy derivable from it.

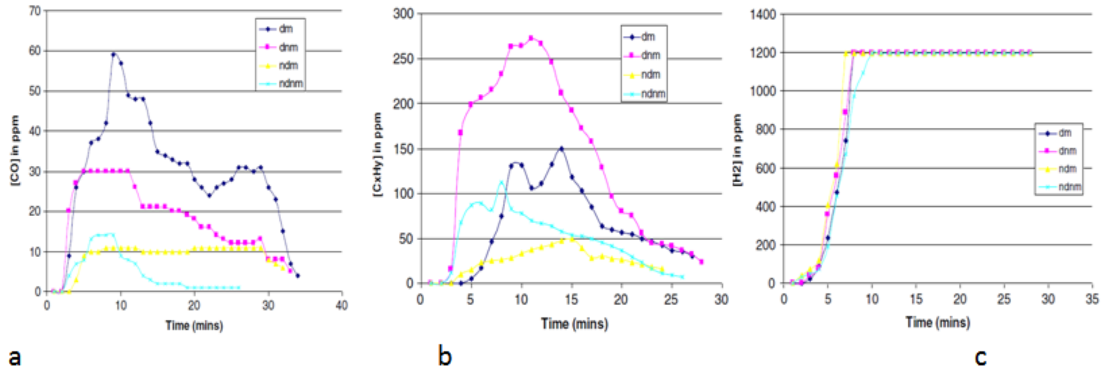

Fig 7: Concentrations of, (A) CO in flue gas (B) CxHy in flue gas and (C) H_2 in flue gas, with time during thermal arc plasma decomposition of mobile phone waste [2]

Table 5: Composition of three product solids (metal alloy, slag, flay ash)

Metal Alloy		Slag		Fly ash	
Metal	% Composition	Compound	% Composition	Compound	% Composition
Cu	80.5	CaO	46.71	C	40.02
Al	4.21	Al_2O_3	31.16	CaO	16.04
Si	4.89	SiO_2	3.27	MgO	10.35
Sn	3.91	MgO	0.12	SiO_2	5.60
Fe	2.44	Cu	13.03	Cu	6.13
Ni	0.316	Fe total	0.55	Pb	3.90
Cr	0.157	Sn	0.132	Zn	1.45
Ag	0.0563	Zn	0.071	Fe total	0.19
Au	0.0163	Pb	0.028	Cd	0.01
S	0.0095	Ag	0.0046	Humidity	3.55
Cd	0.00046				
Te	> 0.144				
C	> 0.0732				
Zn	< 0.003				
Pb	< 0.05				

6. CONCLUSION

Thermal arc plasma has proven to be an efficient technology for the treatment of electronic waste. Products from plasma treatment of WEEE are flue gas, molten metals and slag. The flue gas is mostly CO, CO_2 and O_2 formed from either pyrolysis or incineration of plastics and other organic components of the electronic waste. Copper is the dominant metal in molten products, this is because copper is the dominant metals in the electronic waste used by most of the investigations documented. Precious metals are recovered from the ingot through other purification processes. A large mass or volume reductions of electronic waste were achieved in most of the references considered in this review. Recovering precious metals in form of ingot were achieved through plasma temperature regulation not above the boiling point of the metals concern. However, this will affect the quality of flue gases generated from decomposition of the nonmetallic part of the electronic waste.

7. RECOMMENDATION

To produce syngas with little/no toxic gases (NOx and H_2S) and greenhouse gas (CO_2), high-temperature plasma is required. On the contrary, recovering of precious metal requires plasma at a temperature not above the melting/boiling point of the metal. An integrated plasma system comprising of two units, one of low temperature to separate precious metal from electronic waste and the other of high temperature to treat flue gases exiting the first unit is recommended.

Table 6: Review of operating conditions adopted for different investigations on plasma treatment of WEEE

Type of waste material	Operating condition	Product/outcome	Reference
Electronic waste	Torch Mode: Non-transferred Arc power: 12-20 kW, Plasma Gas: Air, Gas flowrate: 300 L/min, Temp.: 1200 K, Treatment time: 2½ minutes	Weight lost: > 50%	Tippayawong and Khongkrapan [20]
Cu-clad plates simulated for circuit board	Power: 30 kW, Electrodes gap: 30 cm Plasma gas: CO_2& CH_4, Flowrate: 30L/min	Not available	Mitrasinovic, et al. [73]
Printed circuit boards (PCBs)	Arc voltage: 135 V, Arc current: 300 A, Electrodes gap: 30 cm, Plasma gas: CO_2 and CH_4, Gas flowrate: 30 L/min, Temp.: 800 ºC	Weight loss: 14.4% Product gas: CO, CO_2 and O_2	Mitrasinovic, et al. [72]
Sorted PCBs, cables and windings	Torch Mode: Transferred Arc power: 80 kW, Plasma Gas: Nitrogen	Products: Metal alloy, slag, dust and gases.	Jarosz, et al. [1]
Printed circuit boards (PCBs), CRT monitor scraps, PC main board scraps	Torch model: Transferred, Voltage: 50-60 V, Current: 250 – 260 A Plasma gas: Argon, Flowrate: 1.01 L/min, Temp.: 1400 – 1600 ºC, Time: 20 min.	Weight loss: 60% Product gas: CO and very small quantities of NOx and SO_2	Rath, et al. [74]
Mobile phone	Torch Mode: Non-transferred Arc power: 1.5 kW, Electrodes gap: 5 cm, Plasma Gas: Argon, Gas flowrate: 35 L/min, Temp.: 1950ºC, Treatment time: 30 minutes	Weight loss: 7% Product gas: CO, H_2&CxHy	Ruj and Chang [86]
Printed circuit boards (PCBs)	Torch power: 20 kW, Efficiency: 70% Plasma Gas: compressed air. Air flowrate: 11 Mm^3/h Temp.: 1492-1560 ºC Energy consumption: 2.06-4.99 kWh/kg	Weight loss: 61 - 81%	Szałatkiewicz [30] and [11]
Printed circuit boards (PCBs)	Temp.: 1500ºC, Treatment time: 30 minutes	Particulate: heavy metals (Cu, Al, Fe, Sn, Pb, Zn, Ni), hazardous metals (Sb, As, Cd) and precious metals.	Ellamparuthy, et al. [76]
Computer part and dolomite in ratio 71.43:28.57	Energy consumption: 3 kWh/kg Plasma Gas: Nitrogen, Temp.: 1410 ºC Treatment time: 73 minutes	Products: Metal alloy, slag, dust and gases.	Lázár, et al. [14]

Table 7: Chemical composition of product alloy metals obtained from thermal arc plasma treatment of WEEE

Waste type	Component in slag									Source
	Cu	Fe	Sn	Sb	Ba	Pb	Ag	Ni	Zn	
PCB	97.2	0.60	1.2	0.03	0.20	0.07	0.20	NA	NA	Jarosz, et al. [1]
Cables	99.0	0.05	0.1	0	0.05	0.05	0.05	NA	NA	Jarosz, et al. [1]
Windings	98.6	0.70	0.1	0	0.10	0.10	0	NA	NA	Jarosz, et al. [1]
PCB	90	1.1	5.3	0.29	NA	1.1	0.06	0.76	NA	Szałatkiewicz, et al. [11]
PCB	76.41	6.77	10.66	NA	NA	1.06	0.18	1.44	0.85	Szałatkiewicz [30]
Computer part and dolomite in ratio 71.43:28.57	13.03	0.55	0.132	NA	NA	0.028	0.0046	NA	0.071	[14]

NA: Not available

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