UNIVERSITÀ DEGLI STUDI DI PALERMO, ITALY
Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali
DICAM

Dottorato di Ricerca in Ingegneria Civile e Ambientale – XXVI Ciclo

TREATMENT OF WEEE – WASTE OF ELECTRIC AND ELECTRONIC EQUIPMENTS – BY MICROWAVE - INDUCED PYROLYSIS

TRATTAMENTO DI RAEE – RIFIUTI DA APPARECCHIATURE ELETTRICHE ED ELETTRONICHE – MEDIANTE PIROLISI INDOTTA DA MICROONDE

Thesis Submitted in Fulfilment of the Requirements for the Degree of
Doctor of Philosophy
in *Civil and Environmental Engineering*

by

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January 2016

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Extended Abstract

Any hypothesis of beneficial treatment of the “motherboards” (MB) of end-of-life electronic appliances (European Waste Catalogue: Classes 16 02 ZZ and 20 01 ZZ) must deal with the fact that they make a complex and composite – though potentially valuable – waste.

The extraordinary mechanical and electrical properties of MBs arise from the association of completely different materials, as metals and plastic materials (thermo-plastic and thermo-setting) are.

One process chain possibly suited for materials and energy recovery from these wastes consists of the following line:

- A thermal process to char the plastics and make them brittle, and
- An electrochemical process of dissolution – deposition to extract and recovery the metals.

Pyrolysis and gasification of the E-waste described above, carried out at moderately high temperatures (about 800 °C) promit to

- Recovery the *plasmix* (a blend of plastics, mostly thermo-setting: such as epoxydic resins), at least as heating value;
- Produce a significant gaseous fraction, with minor amounts of liquid by-products (*tar*);
- Entrap the metals from MBs in a non-oxidised form, in a porous, incoherent matrix (the *char*) that lend itself to downstream recovery for the more valuable ones.

The variant of feeding to the thermal reactor a non-inert process gas (such as the simple steam) would shift the pyrolysis towards gasification, and should help in orienting the process towards the preferred products.

The use of microwaves (MWs) as a heating means allows also:

- To shorten process residence times;
- To attain a more uniform distribution of temperatures throughout the reactor.

Developing a program of realistic scientific and technological research in this field requires the capacity of attaining and maintaining levels of unit power input of the order of thousands W/kg waste; for comparison one should think that a kitchen MW oven or a MW sterilization plant does not exceed few hundred W/kg.

The pilot plant built within this PhD Thesis work was designed and assembled for operation in this whole range of power, and can be modified without confronting the constraints associated with marketed oven models (either conceived for home or laboratory uses). The plant was set up in the "S-07 Lab" at the Physics and Chemistry Department's historical wing, Palermo, via Archirafi ***(see Acknowledgements at the end).***

Thanks to the expertise and skills of the Researchers in Physical Sciences, the core plant with its strictly necessary accessories costed less than ten thousand euros; to this amount are to be added the value of the expended time, and the investments made in the measurement and analysis equipment that stay around and in the background.

The preparation work of this Thesis ended with a test of the plant operation with small quantities of waste. Its forthcoming development shall consist in:

- The chemical analysis of the products from the pyrolysis of MBs;
- The correlation of the results with the operation parameters (e.g., MW field power; temperature attained; residence time; nature and rate of flow of the process gas).

In a broader perspective the process deserves being applied and verified in several and diverse applications in Environmental Engineering; for instance the following.

- Contaminated soils depollution (EWC 17 05 00)
- Waste treatment
    - Pyrolysis of: Sludges; EoL Tyres (EWC 16 01 03); Packaging waste such as multi-layer food containers including an Al foil ("Composite Packaging": 15 01 05); Engine, Gear and Lubricating Oils (13 02 00) and Leachate from waste landfill (19 07 02) (adsorbed onto a granular activated carbon bed).
- Regeneration of Activated Carbon saturated with Volatile Organic Compounds (19 01 10*).
- Sterilization of Health Care Waste.
- Materials treatment
- Sintering of Asbestos fibers and of Asbestos-containing Materials (EWC 17 06 05*).

We believe that the plant described in this Thesis is versatile enough – both on the physical and on the chemical side – to support research projects on thermal treatment of waste of even very diverse kinds, such as the ones listed above.

Sommario esteso

Le schede – madri degli apparecchi elettronici a fine vita sono un rifiuto composito complesso e potenzialmente pregiato (Classi C.E.R. 16 02 e 20 01, più disciplina propria: D.Lgs. 14/3/2014 n. 49 “Attuazione della direttiva 2012/19/UE sui rifiuti di apparecchiature elettriche ed elettroniche (RAEE)”).

Le loro straordinarie proprietà meccaniche ed elettriche nascono dal’associazione di materiali completamente diversi, quali sono le materie plastiche termo-plastiche e termo-indurenti, e i metalli.

Uno degli schemi di processo adatti per recuperare materia ed energia da questi rifiuti è la sequenza di

- un processo termico per carbonizzare e fragilizzare la plastica, e di
- un processo elettrochimico di dissoluzione – deposizione per estrarre e recuperare i metalli.

La pirolisi e la gassificazione dei RAEE del Raggruppamento R4 ad alte temperature (prossime a 800 °C) promettono di

- recuperare il *plasmix* (miscela di materie plastiche in massima parte termo-indurenti: resine epossidiche) almeno come energia;
- ottenere una consistente frazione gassosa, con minori sottoprodotti liquidi (*tar*);
- catturare i metalli delle piastre madri in forma non ossidata, in una matrice porosa e incoerente (il *char*) favorevole al recupero a valle, p.es. elettrolitico. L’introduzione di un gas di processo non inerte (quale il semplice vapore d’acqua) sposterebbe la pirolisi verso la gassificazione, e dovrebbe aiutare a orientare il processo verso i prodotti preferiti.

Il riscaldamento del reattore con MO consente anche di:

- ridurre i tempi del processo;
- uniformare le temperature di reazione.

Il lavoro di ricerca scientifica e tecnica in questo campo richiede che si possano realizzare livelli di densità di potenza dell’ordine del migliaio di W/kg rifiuto; per confronto si pensi che in un forno da cucina o in un impianto di sterilizzazione la densità di potenza resta nell’ordine delle centinaia di W/kg.

Nel corso di questa Tesi è stato progettato e costruito un impianto pilota che può funzionare in tutto questo arco di potenza, e può essere modificato senza i vincoli associati a un forno commerciale (che sia costruito per uso di

cucina o di laboratorio). L’impianto è stato allestito nel Laboratorio S-07 del Dipartimento di Fisica e Chimica in via Archirafi, Palermo (***vedi Riconoscimenti alla fine***).

Grazie alla competenza e all’abilità dei Ricercatori di Scienze Fisiche, l’impianto con gli accessori strettamente indispensabili è costato meno di diecimila euro; a questo importo vanno aggiunti il valore del tempo dedicato, e quello dell’investimento negli apparecchi di misura e di analisi che stanno al contorno.

Il lavoro per questa Tesi si è concluso col collaudo dell’impianto con piccole quantità di rifiuti. Il suo sviluppo immediato consisterà nell’analizzare i prodotti della pirolisi delle schede-madri, e correlare i risultati con i parametri operativi (potenza del campo di microonde, temperatura raggiunta, tempo di permanenza nel reattore, natura e flusso del gas di processo).

In un prospettiva più ampia il processo può essere applicato e verificato per diverse altre applicazioni in Ingegneria Ambientale:

- Bonifica di suoli contaminati (C.E.R. 17 05 00)
- Trattamento di rifiuti
    - Pirolisi di: Fanghi, Pneumatici usati (16 01 03), Rifiuti da imballaggio quali laminati plastica/Al (“poli-accoppiati”: 15 01 05), Oli lubrificanti usati (13 02 00) e liquido percolato di discarica (19 07 02) (su letto di carbone attivo).
- Rigenerazione di: Carbone attivo saturo di Composti Organici Volatili (19 01 10*).
- Sterilizzazione di Rifiuti sanitari.
- Trattamento di materiali
- Sinterizzazione di fibre di amianto e di rifiuti di materiali contenenti amianto (C.E.R. 17 06 05*).

Noi riteniamo che l’impianto sia abbastanza versatile - sia nella sua parte fisica che in quella chimica – per supportare ricerche sui trattamenti termici di rifiuti anche fra loro molto diversi, come quelli elencati sopra.

Chapter 1

Introduction

1.1. The E-waste issue

In the last twenty five years electric and electronic equipment (EEE) requirements is growing worldwide due to the development of technology, with the design of components with more and more high performances and new functions and design, as well as to the development of society, which is affected by a marketing more and more invasive.

The increase in production of new EEE causes the rapid obsolescence and leads to the replacement of appliances in spite of their good state of functionality. Advancements in electronics, compatibility issues, and attractive consumer designs are the main causes in shortening the lifespan of the most electronic goods. For example the lifespan of a consumer notebook was 4 years in 2000 decreasing to 2 years in 2010.

Due to the short turnover a huge quantity of electronic waste (E-waste) is generated; so causing management problems and environmental burdens. Figure 1.1 shows examples of E-waste: namely, some components from PCs.

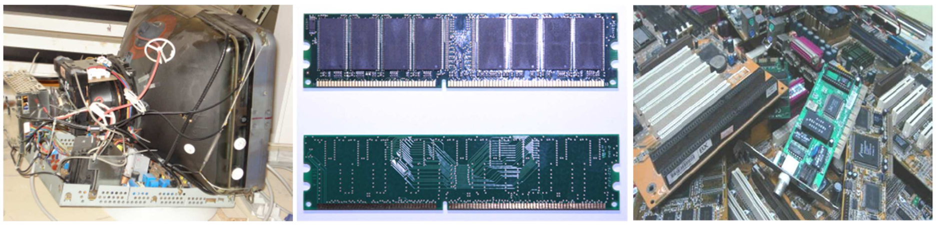

Figure 1.1 Some examples of E-waste: PC Monitor; RAM memories; motherboards and other PC devices

E-waste – more rigorously named Waste of Electric and Electronic Equipment (WEEE) – must be managed and disposed of in accordance with national regulations. WEEE includes a wide range of products mainly - household or business - appliances with electrical components with power or battery supply. A basic classification of EEE and consequently of E-waste refers to six categories:

- Large equipments: e.g. kitchens, ovens, washing machines, PV panels.
- Small equipments: microwave ovens, toasters, electric shavers, small electrical and electronic tools, electrical and electronic toys.
- Small IT and ITC equipments: e.g. mobile phones, PCs, printers, notebooks.
- Temperature exchange equipments: e.g. refrigerators, freezers, air conditioners, heat pumps.
- Screens: e.g. CRT and LCD monitors, TVs.
- Lamps: e.g. fluorescent and LED lamps.

This variety of End-of-Life (EoL) products implies different material compositions, different economic values, and different technologies for recycling each category. E-waste contains a wide range of recyclable materials but also hazardous substances like heavy metals (Pb, Cd, Hg), CFCs, brominated flame retardant (BFR) and others potentially toxic. Inappropriate recycling can led to serious environmental and health problems.

Valuable materials from E-waste are mainly metals, plastics and glass. Valuable metals are for example Cu, Fe, Al, Sn, Pb, Zn and nobles metals like Au, Ag, Pt, and Pd.

There are also smaller amounts of the so-called Rare Earths used for example to convert the kinetic energy of an electron beam to light on the interior of CRT screens (Y, Eu) but also in LEDs (Ce, Y), LCD backlights and plasma screens (Eu, Tb, Y) (Binnemans et al., 2013).

Plastics content in WEEE is about 30 % (mainly thermo-hardening), and recycling systems should deal also with it.

Toxic substances can affect human health in terms of direct impacts on workers in the primitive recycling systems, mainly in developing countries, by direct exposure to these substances and through food chain (Kiddee et al., 2013).

In fact, in developing countries E-waste and electronic goods are usually imported from developed countries. These WEEE are usually treated with poor or no safely processes and dispose of with no advanced technologies (Hicks et al., 2005).

All treatments technologies to recovery these materials include mechanical and chemical processes in different proportions. Difficulties arise because of E-waste are made up of mixed materials and usually it is not easy to separate the single substances found in the components of them.

This issue has contributed to develop processes and technologies focusing in recovering the energy content of of plastics in EoL appliances, instead of the matter. It is recognized, though, that the milder and more sophisticated processes of breaking down plastics into oligomers make for the best mid-term strategy (Grause, 2014).

In the short term, *thermal treatments* - like pyrolysis and gasification - aim mainly to recover fractions useful to replace natural gas, light and heavy fuel oil thanks to their energy content in the form of heating value.

In 2011 about 10 million tonnes of new EEEs were placed on the EU-27 market and about 9 million tonnes of WEEE were generated. Prevision made by European Commission - DG Environment in 2009 estimates a WEEE generation rate per year of about 12 million tonnes by 2020.

These figures shows that recycling of WEEE is an important problem and potential resource as well. Therefore, E-waste management must be considered with special attention not only from a technical point of view but also from economic policy aspects. Decisions makers in all countries ought to be aware of the possibility of energy and materials recovery from WEEE, and of the reduction in the same time of environmental pollution as well as of human health risks.

EU has recognized the importance of the E-waste issue and since 2002 has issued Directives on recycling in terms of energy and materials recovery, aiming to reduce WEEE quantities stocked or improperly disposed of.

To reach this goal regulations aim to encourage: *reuse* of an EEE item or parts of it (components, accessories); *disassembling* to use components in the manufacturing of new product; *dismantling* to recover materials (Figure 1.2).

Important components of EEE, contained in nearly all appliances, are printed circuit boards (PCBs) that account for about 3-6% of the total weight of E-waste and are the most difficult parts to dispose of (Hadi et al., 2015; Sun et al., 2011).

The PCB mechanically supports and electrically connects the electronic components, so represents an integral component of any electronic equipment. The basic structure of the PCBs consists in a copper-clad laminate of glass-reinforced epoxy resin in which some metallic components are grafted above (Ghosh et al., 2015).

Disassembly means to manually break down E-waste into individual components either for re-sale or re-use or to sort for further recycling.

For example *thermal treatments* - like pyrolysis and gasification - aim mainly to recover fractions useful to replace natural gas, light and heavy fuel oil thanks to their energy content in the form of heating value.

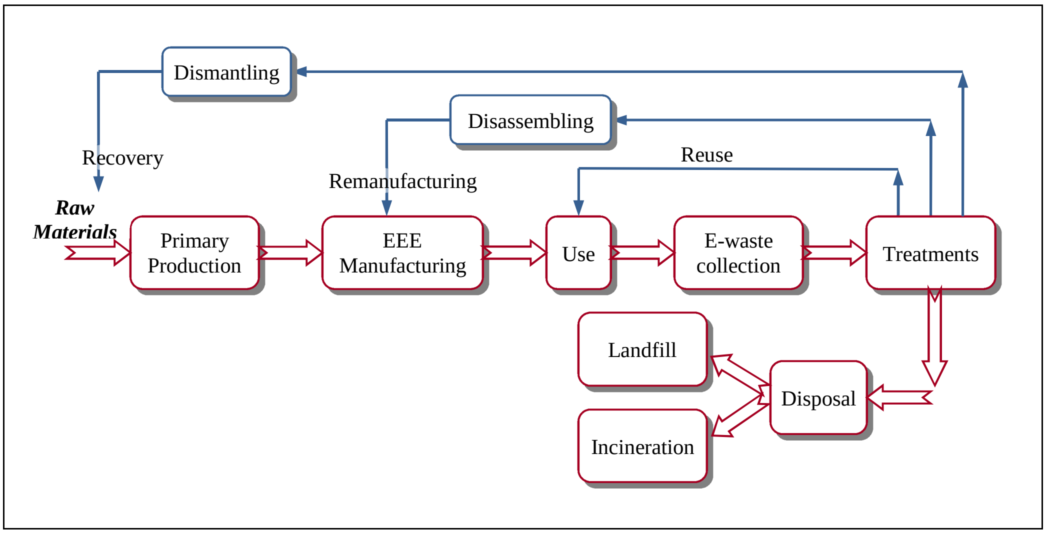

Figure 1.2 E-waste generation and management

PCBs contains 28 up to 40 % (w/w) of metals, 30 % organics, 30 % ceramics (Gosh et al., 2015; Huang et al., 2009; Zeng et al., 2012). The high metal content, including valuable non-ferrous metals (such as copper, lead, tin, zinc, nickel, aluminium) and precious metals, makes the recovery of material from PCBs among WEEE an interesting operation for its economic benefits (Oliveira et al., 2009).

In general, PCBs are manufactured in three basic varieties that are: single-sided, double-sided and multi-layered. The spatial requirement and the circuitry complexity determine the type of board produced. The choice of manufacturing materials used for PCBs also depends on the application.

Examples of PCBs are PC desktop or laptop motherboards (MBs). Figure 1.3 shows a MB taken off from an Asus PC desktop in which RAM modules , CPU fan and backup battery were previously separated. Various elements are grafted on the MB: CPU socket, slots for RAM modules, slots for expansions cards, input and output connectors, condensers, inductive elements and other components.

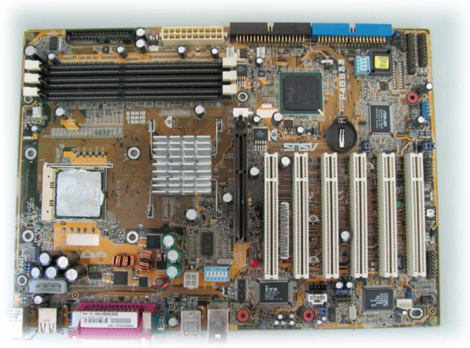

Figure 1.3 A motherboard from an Asus PC desktop.

Uncontrollable incineration of waste PCBs produces potentially hazardous by-products - like dioxins, furans, polybrominated organic pollutants and polycyclic aromatic hydrocarbons - caused by chemical transformations of BFR, epoxy resins and plastics during combustion.

The materials containing BFR are precursors to polybrominated dibenzo-p-dioxins and dibenzofurans (PBDDs, PBDFs), that are classified as persistent organic pollutants (POPs) by the Stockholm Convention (UNEP, 2012), an international treaty aiming to protect human health and the environment (Huang et al., 2009).

This means that uncontrolled disassembly, improper disposal of discarded PCs, and of course open burning can cause a variety of environmental as well as health problems.

1.2. Scope and objectives

Material composition of EEE depends from type of appliance as well as from manufacturing process at the factory. A physical mean composition is shown in Table 1.1. The coexistence of different materials, with different properties, makes separation and recovery treatments difficult.

Thermal treatments, such as pyrolysis, seem suitable for recovery of metals and plastics in WEEE and, in particular, in EoL motherboards; and to produce a gas fraction with a valuable heating value (say, 18 000 kJ / m^3).

Among thermal treatments, an innovative technology and process is microwave - induced pyrolysis (MIP). Indeed, MIP has various advantages on traditional heating processes, also economical.

This PhD Thesis work aimed at building and testing a pilot system to process through MIP several waste materials such as: MBs in powder; rubber;

and others. The maximum target temperature at this stage is about 800-900 °C, which in the technical area of pyrolysis is defined high.

The pilot system was entirely designed and set up during the Thesis work.

We believe that the built and tested pilot system will be used for further experiments in which parameters, like temperature; inert or reacting gas flow rate; and residence time inside the reactor, can be varied and correlated to product gas composition.

Gas analysis will be made in a gas-chromatograph of the laboratory of *Ingegneria Sanitaria* of this University thanks to a recent enhancement of the instruments.

Table 1.1 EEE material composition

Material	Percentage
Ferrous	38
Non-ferrous	28
Plastics	19
Glass	4
Wood	1
Other	10

Chapter 2

Background and current status of the E-waste management

2.1. Generation and management of WEEE

The WEEE stream generated covers a large number of products. This, in addition to the estimated generation rate growth of 4 to 5 % in following years, has posed a significant challenge to waste management in both developed and developing countries. Principal factors causing the growing amount of e-waste are connected to the fast technology innovation and to every day reduced product lifespan (Baldé et al., 2014).

The global E-waste generation calculated for year 2014 was about 41.8 millions of tonnes that correspond to 5.9 kg per capita (Baldé et al., 2014). Quantities associated to the six categories are graphically reported in Figure 2.1.

In Italy in year 2014 almost 232 kt of WEEE were collected by the *Collective Systems* (Sistemi Collettivi) with an increment of 2 % over 2013. The mean value of generation rate is 3.81 kg/capita with differences between Nord 4.84 kg/capita, Centre 3.78 and Sud including Islands 2.37 (Rapporto Annuale 2014, CdC RAEE). *Collective Systems* are constituted by EEE manufacturers registered to the *WEEE Coordination Centre* (Centro di Coordinamento RAEE, CdC RAEE). There are 17 Collective Systems managing “home-generated” E-waste.

Every typology of WEEE is collected in Collections Centres separately considering five categories or groups:

- **R1** Cold and Climatization: air conditioners, refrigerators, heat pumps;
- **R2** Large white: washing machines, dishwashers, drying machines;
- **R3** Tv and Monitor;
- **R4** Little household appliances, CE (consumer electronics), ICT, lighting equipments (without lamps) and others;

- **R5** Lamps.

Every group has peculiar characteristics to easy dismantling, separating and processing the E-waste collected. This five groups are defined by Italian Decree n. 185 of the 25 September 2007.

WEEE collected in Italy by *Collective Systems* are reported in Figure 2.1 for each group and for year 2014.

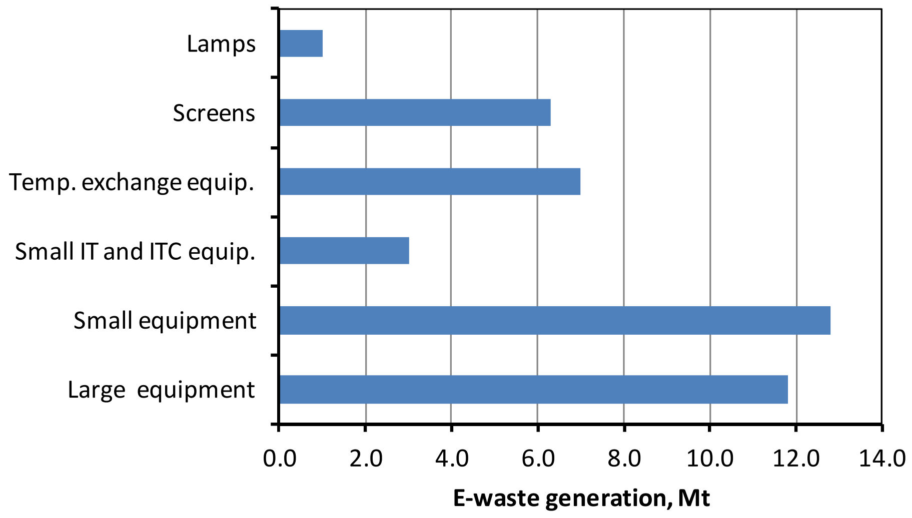

Figure 2.1 Global E-waste generation for single category in year 2014

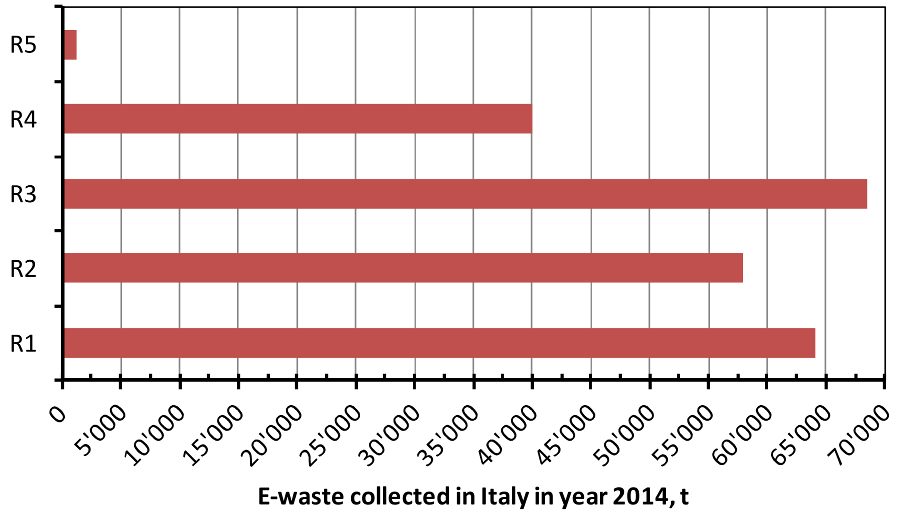

Figure 2.2 E-waste collected in Italy by *Collective Systems* in year 2014

European Union regulations related to E-waste aims to “preserve, protect and improve the quality of the environment, protect human health and utilize natural resources prudently and rationally” (EU - WEEE Directive, 2003). The WEEE Directive (2003) adopted regulations for EEE product design, E-waste collection, recovery, treatment and treatment financing, and EEE user awareness. The Directive focused on the recovery, recycle and reuse of E-waste. It also aimed to raise awareness of end-of-life factors during product design. Actions considered are: dismantling of parts and recyclability of materials, proper collection systems that support separate collection of E-waste to reduce disposal in common municipal waste streams, and best practices for treatment, recovery and recycling of WEEE (Kahhat et al., 2008).

According to last regulations, retailers of electronic products serve as a collection agency and consumers can bring old electronic equipment to a retailer when they purchase new electronic equipment. The active participation of the retailer is essential for this method of collection to be successful (Kang, 2005).

In U.S., for example, several original equipment manufacturers (OEMs) have established a ‘take-back’ collection systems for collecting used electronic products from consumers independently of the brand of the EoL appliance.

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.

2.2. Legislative aspects

The first WEEE Directive was the Directive 2002/96/EC entered into force in February 2003. The Directive provided for the creation of collection schemes where consumers return their WEEE free of charge, aiming to increase the recycling and reuse of WEEE.

The last WEEE Directive was the Directive 2012/19/EU entered into force on 13 August 2012 and became effective on 14 February 2014.

In addition, the European Union Restriction of Hazardous Substances (RoHS) Directive (2002/95/EC) restricts (beginning July 2006) the use of six hazardous compounds: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE), commonly found in EEE (Kahhat et al., 2008). In 2011 EU published the RoHS Recast Directive (RoHS 2) – Directive 2011/65/EU – a revised form that: extends the field of application to medical devices and monitor and control instruments; introduces changes in the procedures for product conformity. The aim of RoHS Directives according to Article 1 is: *This Directive lays down rules on the restriction of the use of hazardous substances in electrical and electronic equipment (EEE) with a view to contributing to the protection of human health and the environment, including the environmentally sound recovery and disposal of waste EEE* (Directive 2011/65/EU).

European Standardization Organizations developed standards for the treatment of WEEE. Among these the most relevant are:

- EN 50419 on the marking of electrical and electronic equipment.
- EN 50574 on the collection, logistics and treatment requirements for end-of-life household appliances containing volatile fluorocarbons or volatile hydrocarbons.
- EN 50625-1: Collection, logistics and treatment requirements for WEEE - Part 1: General treatment requirements.

In European waste regulation WEEE belong to Classes 16 02 and 20 01 (E.W.C.).

In Italy Legislative Decree 3/4/2006 n. 152 *Norme in materia ambientale* (“Regulations on environment”) that is the reference regulation on environment, in its Part IV “Regulations on waste management and contaminated soils remediation” mentions national and European regulations on WEEE.

In particular WEEE have a specific regulation: Legislative Decree14/3/2014 n. 49 *Attuazione della direttiva 2012/19/UE sui rifiuti di* *apparecchiature elettriche ed elettroniche (RAEE)*, that implements European Directive on WEEE.

Italian and European regulation underlines the importance of E-waste treatment processes and aims to recover secondary raw materials with economical value through a correct reuse, recycling and recovering.

In the WEEE regulation Electric and Electronic Equipments (EEE) are defined as: equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1 000 volts for alternating current and 1 500 volts for direct current, as defined Decree 49/2014.

Regulations differentiate WEEE in “household” and “professional”: the first are E-waste generated at home and E-waste generated from commercial, industrial and other activities that are for typologies and quantities similar to those generated at home; the second are E-waste generated from administrative and economical activities different from those coming from home.

In turn, household and business WEEE can be differentiate in relation to their production date: “historical WEEE” are those put on the market before 2006 August 13 and “new WEEE” those put on the market after 2006 August 13.

2.3. Alternative processes for recycling WEEE

WEEEs are diverse and complex, in terms of materials and components makeup. Selective disassembly is an indispensable process in the practice of recycling of WEEE.

For maximum separation of materials, WEEE should be shredded to small particles, generally below 10 mm.

Mechanical/physical processing, based on the characterization of WEEE, provides an alternative means of recovering valuable materials.

2.3.1. Mechanical recycling

Mechanical processes, such as screening, shape separation, magnetic separation, Eddy current separation, and density-based separation, are widely utilized in recycling industry.

Screening is used to prepare a uniformly sized feed. The primary method of screening in metals recovery uses the rotating screen, or *trommel*, a unit which is widely used also in municipal solid waste processing.

Shape separation techniques is mainly used to control properties of particles in the powder industry. This method is based on principles such as the particle velocity on a tilted solid wall or the particle settling velocity in a liquid and others.

Magnetic separation is used for the recovery of ferromagnetic metals from non-ferrous metals and other non-magnetic wastes. Low-intensity drum separators are widely used in this technique.

Eddy current separators are widely used to separates materials of different electric conductivity (or resistivity). The physical principle is based on the different electric conductivity of different materials.

Density-based separation is used to separate heavier materials from lighter ones. The difference in density of the components is the basis of separation.

2.3.2. Chemical recycling: metals recovery

In this type of recycling, the E-waste, in particular printed circuit boards (PCBs), are depolymerised into smaller useful molecules by several techniques, such as pyrolysis and gasification.

Valuable products obtained are fuels and gases that are subsequently refined by conventional approaches. The metallic fraction are treated by metallurgical approaches.

In EEE precious metals are used as contact materials due to their high chemical stability and their good conducting properties. To recover precious as well non-ferrous metals from E-waste *pyrometallurgical* process has been used for years.

In this process, the scraps are burned in a furnace or in a molten bath to remove plastics, and the refractory oxides form a slag phase together with some metal oxides. A subsequent electrorefining is need to recovery metals.

Pyrometallurgical process has some limitation. One is that only partial separation of metals can be achieved, resulting in a limited upgrading of the metal value. Furthermore, electrochemical or *hydrometallurgical* processing are subsequently necessary and precious metals are obtained only at the end of the process.

A better process for recovery of metals from electronic scraps is recovering precious metals by hydrometallurgical techniques. Comparing with the pyrometallurgical processing, hydrometallurgical method is more exact, more predictable, and more easily controlled.

Hydrometallurgical processing consist of a series of acid or caustic leaches of solid material. The solution obtained is then subjected to different separation and purification procedures such as precipitation of impurities, solvent extraction, adsorption and ion-exchange to isolate and concentrate the target metals. At last, for recovery the metal, the solutions are treated with techniques such as electro-refining, chemical reduction, or crystallization.

The first step in a hydrometallurgical process is *leaching* that is the process of extracting a soluble constituent from a solid by means of a solvent. In the recovery of precious metals compounds used in leaching are usually cyanide, halide, thiourea, and thiosulfate.

2.3.3. Chemical recycling: plastic recovery

The most common type of PCB used in computers and communication equipment is made from glass fibre reinforced epoxy resin but televisions and home electronics predominantly use PCBs made of cellulose paper reinforced phenolic resin (Hall and Williams, 2007).

Pyrolysis is a thermal recycling technique suitable for recycling PCBs and recovering both the organic and non-organic fractions. Pyrolysis has been widely researched as a method of recycling synthetic polymers including those mixed with glass fibres.

Pyrolysis of polymers leads to the formation of gases, oils, and chars which can be used as chemical feedstocks or fuels.

The combination of the removal and recovery of the organic fraction of PCBs and the removal of the solder (if temperature is high enough) should aid the separation of the metal components from the organic material.

2.4. Pyrolysis of WEEE: Conventional vs. Microwave heating

Pyrolysis can be described as a chemical process and thermal decomposition of organic components in an oxygen-free atmosphere to yield char, oil and gas.

Two types of the heat sources can be provided: conventional heat source and microwave.

Conventional and MW heating are quite different respect to their heating mechanism.

2.4.1. Conventional heating

Conventional heating usually involves the use of a furnace or oil bath which heats the walls of the reactors by convection or conduction. The core of the sample takes much longer to achieve the target temperature.

2.4.2. Microwave heating

Microwave penetrates inside the material and heat is generated through direct microwave-material interaction.

The advantages of microwave heating over conventional methods are moreover:

- volumetric heating,
- reaction rate acceleration,
- higher chemical yield,
- lower energy usage,
- different reaction selectivity
- no direct contact between the heating source and the heated material.

With microwave heating no energy is wasted in ‘bulk heating’ the sample, thus it is very efficient in the selective heating of materials. This is a fundamental advantage over conventional methods (bulk heating in furnaces).

Moreover, materials like plastics can’t be directly heated by MW. In fact, mixing plastics have a very high transparency to microwaves but when are mixed with carbon, or other MW absorbent materials, the energy absorbed from the microwaves is transferred to the plastics by conduction, providing a very efficient energy transfer and a highly reducing chemical environment.

Chapter 3

Microwaves: Fundamentals and Applications

3.1. EM Waves

Microwave radiation is the term associated with any electromagnetic (EM) radiation in the microwave frequency range of 300 MHz – 300 GHz. Domestic and industrial microwave ovens generally operate at a frequency of 2.45 GHz corresponding to a wavelength of 12.24 cm.

In the electromagnetic spectrum (Figure 3.1) they are embedded between the radio frequency range at lower frequencies and infrared and visible light at higher frequencies. Thus, microwaves belong to the non-ionising radiations.

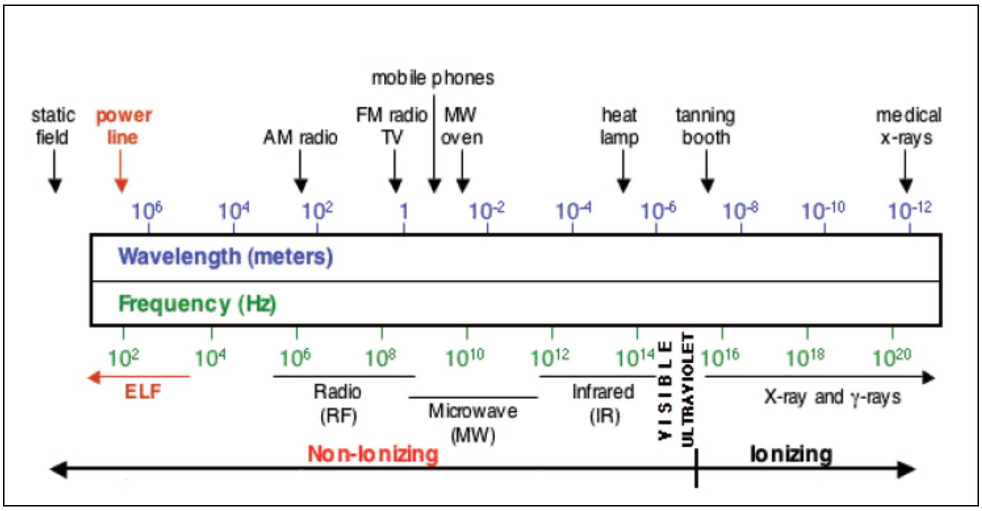

Figure 3.1 Electromagnetic spectrum (ELF = extremely Low frequency)

Microwave energy is transferred to the material by interaction of the electromagnetic field at the molecular level.

MWs are electromagnetic waves and consist of two perpendicular components, namely electric (E) and magnetic (H) fields, as shown in Figure 3.2. The MW propagation direction is perpendicular to both E and H, the horizontal line in the Figure.

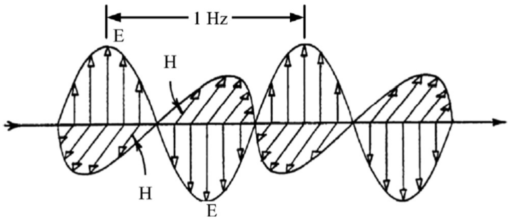

Figure 3.2 Electric and magnetic field in microwaves

In microwave heating as source of MWs magnetrons are generally used due to their easy availability and low cost. The size and configuration of a cylindrical magnetron is much suited for microwave ovens as well as for other applications of microwave heating.

The basic structure of a cylindrical magnetron is showed in Figure 3.3. It consists of a number of identical cavity resonators arranged in a cylindrical pattern around a cylindrical cathode.

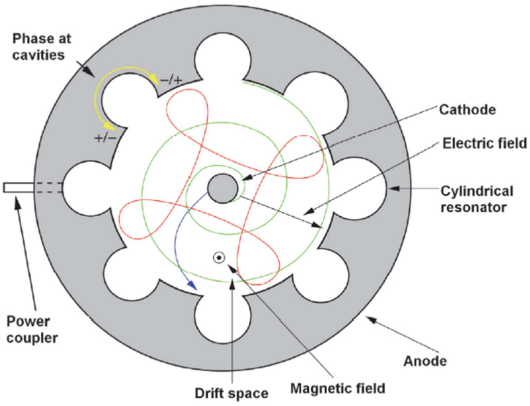

Figure 3.3 Schematic structure of a magnetron

Two large pole pieces of permanent magnets are used to produce a strong magnetic field normal to the plane of cavities. The electrons emitted from the central cathode are accelerated towards the anode but the presence of transverse magnetic field exerts a torque which causes the electrons to move in a curved path in the drift space. Interaction between electrons and electromagnetic field induced in the cavities generates energy which is the loss electrons energy.

3.2. Microwaves interactions with materials

Materials can may be classified into three categories depending of their behaviour when interact with MWs:

- Conductors – MWs are reflected;
- Insulators – these materials are transparent to MW;
- Absorbers – MW are partially or totally absorbed.

This classification is illustrated in Figure 3.4.

In metals MW penetrates only in a thin skin, on the order of 1 µm, so they can be considered to be opaque to MW, in other words they are good reflectors of MW.

Microwave absorbers are materials which interact with microwaves to produce heat. Materials that absorb microwave radiation are called dielectrics, thus, microwave heating is also referred to as dielectric heating. Dielectric have heating is due to interaction of charged particles with the electric field component of electromagnetic radiation.

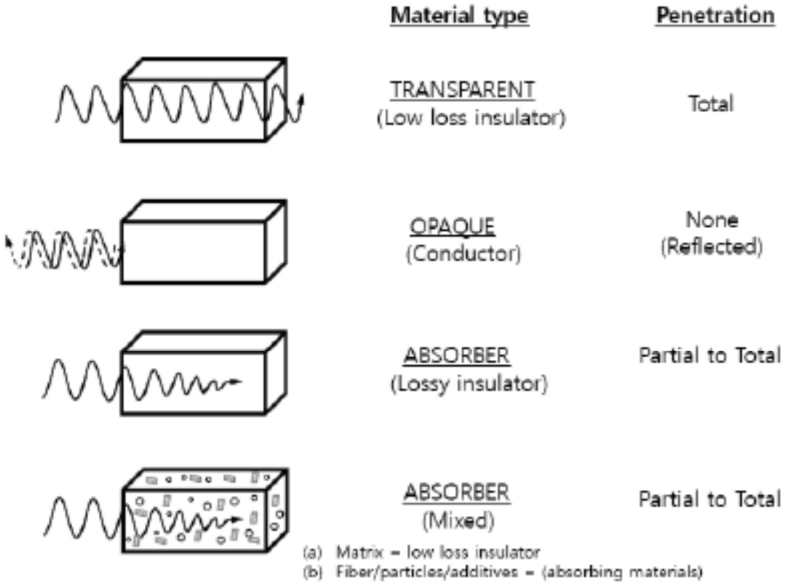

Figure 3.4 Microwave interaction with materials

Microwave absorbers are materials which interact with microwaves to produce heat. Materials that absorb microwave radiation are called dielectrics, thus, microwave heating is also referred to as dielectric heating. Dielectric have heating is due to interaction of charged particles with the electric field component of electromagnetic radiation.

The heat resulting from this interaction is mainly due to two different effects:

- Dipolar Polarization
- Maxwell-Wagner Polarization.

The first effect (Dipolar Polarization) occurs in the case of polar fluids, such as water, in which the electric field component of the microwaves causes rotation of both permanent and induced dipoles because polar molecules try to align themselves with the alternating field (frequency 2.45 GHz). This molecular movement generates friction among the rotating molecules causing energy dissipation as heat. The first effect is the more important.

The second effect (Maxwell-Wagner Polarization) occurs in the case of some dielectric solid materials (composite materials) in which charged particles movement are limited in a restricted area (for example π-electrons in carbon materials). MWs induce in this materials a current traveling in phase with the electromagnetic field and as consequence that the electrons cannot couple to the changes of phase of the electric field, energy is dissipated in the form of heat.

Some ceramics, such as Al_2O_3, MgO and SiO_2, are transparent to MW at room temperature but above a critical temperature they become absorber and begin to couple with microwave radiation.

Another phenomenon that can occur during MW heating is the formation of the so-called “hot-spot”. It consists of local super-heating, with very high rising in temperature, caused by reflection of radiation by the surface of a body, such as metals, inside irradiated matter with microwave constructive interferences.

Microwave interaction with materials is widely used for heating absorbing materials but also insulators if mixed with additives. Microwave heating is a volumetric heating and the temperature profile of material processed is quite different respect of that caused by conventional heating. Figure 3.5 illustrates the different temperature gradient within samples heated with conventional an MW heating.

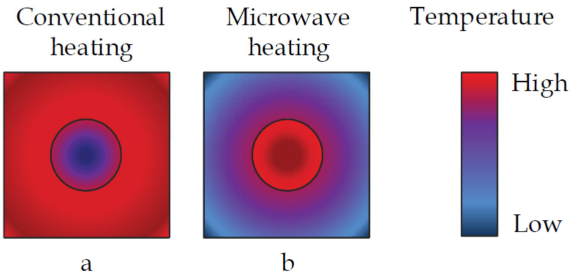

Figure 3.5 Comparison of temperature profile within samples heated by (a) conventional heating and (b) microwave heating.

3.3. Wave guides

Waveguides are used to couple the microwave power from the magnetron to the main chamber of the oven. The conducting walls of the guides / resonators confine the electromagnetic fields and couple the power from magnetron to the cavity of the oven. In other words, waveguides drive the MWs from the source (magnetron) to the chamber where the material will be processed (resonant cavity).

A number of distinct field configuration or "modes" can exist in waveguides. Considering a conductor with its boundary parallel to z-axis that is also the propagation direction of the microwaves, the modes are:

- Transverse electric mode (TE)
- Transverse magnetic mode (TM)
- Transverse electromagnetic mode (TEM)

In general electromagnetic field is the combination of an electric field (E) and a magnetic field (H), each field has component in x-, y-, and z-axes. Transverse electric waves – also referred to as H-waves – are characterized by $E_z = 0$ and $H_z \neq 0$. Transverse magnetic (TM) waves – also referred to as E-waves – are characterized by $E_z \neq 0$ and $H_z = 0$. Transverse electromagnetic waves are characterized by $E_z = H_z = 0$.

Inside the waveguide either TE or TM modes can propagate but not TEM. This because waveguides often consist of a single conductor. Thus, they may support transverse electric and/or transverse magnetic waves, characterized by the presence of longitudinal magnetic or electric field components as mentioned above.

TEM waves, characterized by the lack of longitudinal field components, may be supported by transmission lines that consist of two or more conductors.

Rectangular waveguides are waveguides with rectangular cross section and generally their mode is TE mode (Thostenson and Chou, 1999; Pozar, 2012;).

3.4. Microwaves applications in environmental engineering

Microwave has been used in food industry for the last fifty years. Innovative processing methods and new applications using MWs has been emerging in the last twenty years according to scientific literatures: Clark and Sutton, 1996; Thostenson and Chou, 1999; Jones et al., 2002; Acierno et al., 2003; Acierno et al., 2004; Zhang et Hayward, 2006; Das et al., 2008; Sun et al., 2011; Fernández and Menéndez, 2011; Beneroso et al., 2015. Some of these cited publications are “review” articles: it means that MW processing research is riding high.

Some MWs environmental engineering applications are briefly recalled below.

Contaminated soil remediation

Microwave-assisted soil remediation applies to the in situ remediation of sites contaminated with volatile compounds (e.g. polycyclic aromatic hydrocarbons, polychlorinated biphenols, etc.) as well as non-volatiles (e.g. heavy metals).

Waste treatment

Microwave heating can be applied to a variety of waste treatment processes. Among these there are: waste volume reduction; rapid heating; ability to treat wastes in situ; compactness and maintainability of process equipment; ease of control.

Among waste treatments, MW heating has been applied to:

- Sterilisation of healthcare waste
- Processing of packaging wastes
- Sludge treatment processes
- Processing Printed Circuit Boards (PCBs).

Other fields of application of MW processing are: the sintering of Asbestos fibres and of Asbestos-containing Materials; synthesis of ceramics, ceramic and metal nanopowders, nonotubes, etc.

3.5. Microwaves hazards

High frequency (HF) is generally considered encompass the frequency range from 100 kHz to 300 GHz. HF field exposure causes heating in living tissues, and therefore is obviously harmful for human body. This has been established without doubts (Saxena and Chandra, 2011; www.icnirp.org).

MWs fall in the range of HF, thus exposure to MW radiation can produce serious health problems: continuous exposure to feeble radiation can cause sleep disturbance, but higher doses can induce melatonin reduction and cancer in many parts of the body. Acute illnesses and serious damages – like burnings, early cataract, blindness – can stem from short, intense exposures.

Effects of microwave radiation on the human biochemistry and physiology depend therefore upon frequency, intensity and duration of exposure of radiation. According to ICNIRP guidelines, the safe limit for microwave radiations is ~ 2.5 mW/cm^2 or less (Saxena and Chandra, 2011). Other relevant parameters are: electric field intensity (V/m) and specific absorption rate (W/kg).

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Chapter 4

A pilot System for MIP at laboratory scale

4.1. Strategies in laboratory research on MIP

Generally speaking, three are the instrumental strategies developed by scientists for Microwave – Induced Pyrolysis at laboratory scale.

One is using a brand MW lab muffle with few, but necessary, modifications: first of all, input for inert gas and output for gaseous products with the possibility to connect condensing line to recover condensable gases (Heyerdahl and co-workers, Zhang et al., 2011).

Such muffles are produced by a small number of Firms in diverse Countries: among others, in France, Popular Republic of China, United Kingdom and United States. . Examples are the MW ovens shown in Figure 4.1 and Figure 4.2.

Figure 4.1 Microwave oven for pyrolysis by Milestone (Connecticut, USA), model PYRO XL (left) and by CEM (North Carolina, USA), model Phoenix (right)

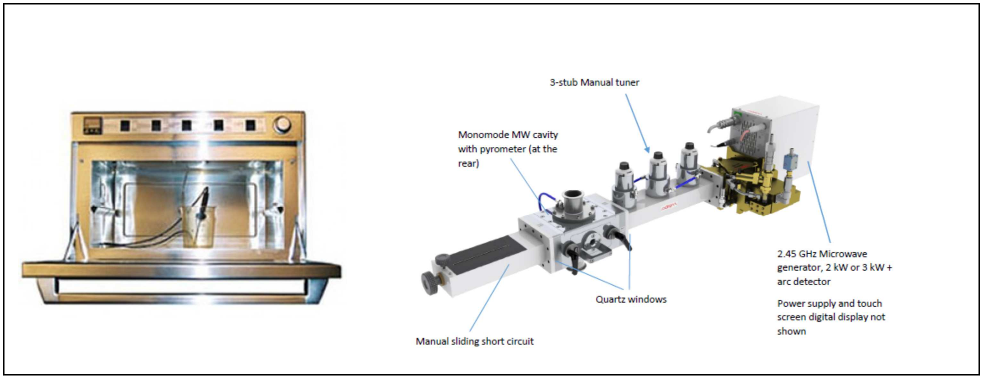

Figure 4.2 Microwave oven for pyrolysis by LADD Research Industries (Vermont, USA) (left) and by SAIREM (FR) (right)

Incidentally, *Milestone Pyro XL* has been bought at *Dipartimento DICAM* of the University of Palermo to set up a parallel line of MW pyrolysis.

Another strategy is to profoundly modify the inner structure of a commercial MW oven, originally conceived for food heating or cooking; putting in it a quartz cylinder with connections for a process gas input and for the exit of gaseous products.

Examples of this are the research works of Sun et al. (2011), Lam et al. (2010), Gedam and Regupathi (2012).

The third strategy is starting from single components to design and build an original laboratory scale apparatus. The principal components are: magnetron, waveguides, quartz reactor, refrigeration system, temperature monitoring instruments, recovery or venting line for gaseous products.

All these experimental setups have in common the input line for inert gas and the condensation/recovery system for the gaseous products downstream.

The advantages and the drawbacks of the three strategies above are summarized in Table 4.1 below.

Table 4.1 Features of the three research strategies

Instrumental setup strategy *Feature*	Brand MW lab muffle	Commercial MW oven, modified	Own design and construction
Process gas I/O	If provided by the Producer	Usually difficult to add, due to compact, crowded construction	At will
Cooling	Provided by the Producer	Could be inadequate at high power feed rates	At will
Power focusing	Provided by the Producer	Multi-mode	To be properly designed
Resonance frequency	Tuned by the Producer	Original resonance freq. could change because of the modifications	Adjustable by stubs, mobile walls, etc.
Temperature monitoring and control	Assured	Holes in the walls for thermocouple and pyrometer	Pyrometers, thermocouples

At *DICAM - Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale e dei Materiali,* the second strategy was discarded after a preliminary evaluation.

The first one has been pursued purchasing and setting up an appropriate, tailored laboratory instrumentation; this makes up a parallel path that will not reported on in this Thesis.

The practical development of the last strategy is the subject of the experimental work made within the Candidate’s Doctorate attendance.

4.2. The pilot system: from magnetron to the quartz reactor

In tight cooperation with Researchers in Physics of EM Fields at *Università di Palermo*, a pilot system at laboratory scale was built. Its core are two rectangular waveguides, fastened in series at the flanges, in which a quartz reactor can be placed and receive a microwave flux from a magnetron.

The system is a mono-mode (or single-mode) cavity that can be tuned turning three stubs placed in one of the two rectangular waveguide. Mono-mode cavity is a resonant cavity in which no MW reflection occurs except, eventually, those due to the presence of sample.

The stubs are three metallic screws that partially enter into wave guide cross section modifying electromagnetic field. Turning the three screws permits to set the resonance frequency of the cavity to 2450 MHz, that is the magnetron own working frequency.

Household MW oven are multi-mode cavity and have a chamber with a volume of 20-30 litres. Mono-mode applicators have a resonant cavity in which the reactor is limited to few millilitres.

The advantage of single-mode cavity is that can generate a much higher intensity of EM field than the multi-mode cavity, therefore is more favourable for fast heating processes. Furthermore, in single-mode cavity the electromagnetic field distribution of the initiated stationary wave (mode) is theoretically predictable.

The principal component of the systems are:

- commercial microwave ovens.
- rectangular wave guides.
- digital thermometer with thermocouples probes.
- IR thermometer
- digital manometer
- refrigeration pipeline
- quartz reactor
- Liebig refrigerator

A general overview of the prototype system is shown in Figure 4.3.

The commercial microwave ovens used as a source of components are two: Fimar mod. ME1630 and Panasonic mod. NN-E201WM. All uses and modifications of parts of them have been made after the judgment and under the responsibility of the research team only, and of course they do not entail any license, advice and liability of the Producers.

Figure 4.3 An overview of the prototype

The Fimar ME1630 has a useful volume of 30 liters and a rated power of 1600 W. The oven uses one magnetron Toshiba as MW generator and a rectangular wave guide to direct MW flux into the resonant cavity. It has five working power levels (Figure 4.4).

Figure 4.4 The Fimar ME1630 oven

The Panasonic NN-E201WM is smaller, featuring a useful volume of 20 liters and a nominal power of 1100 W. The oven uses one magnetron Witol as MW generator with its antenna directly pointing to the resonant cavity. It too has five working power levels (Figure 4.5).

Figure 4.5 The Panasonic NN-E201WM oven

The main difference between the two ovens is that the Fimar model has a waveguide from magnetron's antenna to the resonant cavity (the heating chamber) and Panasonic model hasn't (Figure 4.6). In fact, as mentioned before, Panasonic's antenna points directly on the resonant cavity with its tip positioned close to a later wall of the chamber.

The consequence of the different positions of the antennas is that, to achieve uniform heating, the Panasonic model has to be fitted with a turning plate on which the material to be heating is placed, and Fimar hasn't to. The Fimar oven has a metal disk with some openings turning under the top, inside the chamber, at the waveguide exit (Figure 4.7). It's a sort of metal blade fan to stir MWs uniformly in all the directions.

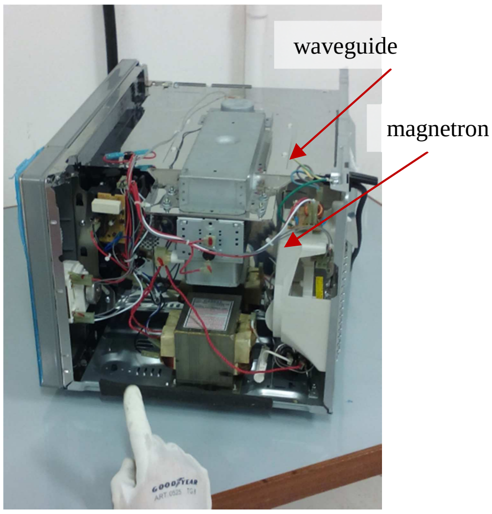

Figure 4.6 The magnetron and the waveguide inside the Fimar ME1630 oven

Figure 4.7 The metal turning disk and its plastic protection cover removed from the Fimar oven

The magnetron removed from Panasonic oven is a Witol 2M219J and is shown in Figure 4.8: the antenna is visible at the top.

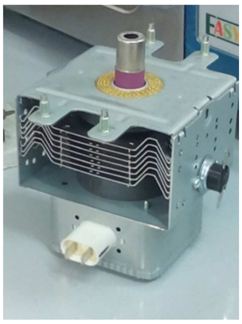

Figure 4.8 The magnetron Witol

Two rectangular wave guides A-Info Straight WG (300 mm length each) with end flanges were connected in series and fastened. Their working frequency is in the range 2.2 – 3.3 GHz and have a length of 300 mm each (Figure 4.9).

Figure 4.9 One of the two rectangular wave guides A-Info Straight WG

The digital thermometer is a Testo 992 with a range from -50 to +1000 °C. It’s a 2-channel instrument and has two input ports for connecting two thermocouple probes. It can display simultaneously the 2-channel temperatures and the calculated differential temperature Its rated precision is: ±(0,5 °C +

0,3%) in the range -40 – 900 °C and ±(0,7 °C + 0,5%) in the range 900 – 1000 °C (Figure 4.10). The thermocouple probes are K- type (Cr-Ni) (Figure 4.11).

Figure 4.10 The digital thermometer Testo 992

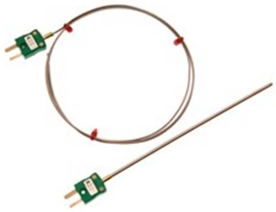

Figure 4.11 Thermocouple probes K- type

The infrared (IR) digital thermometer is the Amprobe IR-750 with a working range from -50 to +1550 °C and a precision of ±1,8 %. Its response time is 250 ms (Figure 4.12). It can be connected, via USB cable, to a PC where a specific software shows graphically temperatures values vs. time and records data.

Figure 4.12 The IR thermometer Amprobe IR-750

The digital manometer is a Druck DPI 705 with a measuring range from 0 to 20 bar and a precision of ±0,1 % (Figure 4.13)

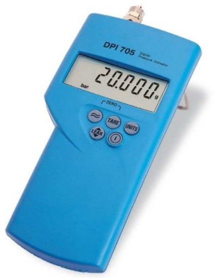

Figure 4.13 The digital manometer Druck DPI 705

The quartz reactor was designed specifically for the pilot system. It has an outer diameter of 25 mm an is placed vertically into a hole milled in the waveguide (Figure 4.14). Its length is 151 mm, including a part of 32 mm length (see Figure) for connection with a Liebig condenser fitted onto it. The bottom of the reactor is joined to a quartz tube with O.D. 8 mm and length 81.5 mm for input of the inert gas flow. The two part were manufactured to make up a single piece in operation.

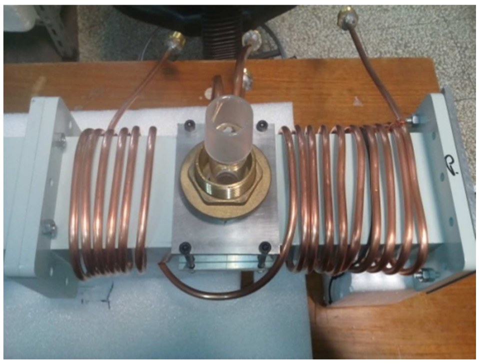

Figure 4.14 The quartz reactor placed inside the waveguide of the prototype

Before modifying the waveguides a full scale model was built with sheets. Some preliminary controls (measurements, holes position, etc.) were made on the model. After this the two waveguide were modified and connected together.

The prototype was first brought in the MW laboratory to measure the resonant frequencies of the cavity (Figure 4.15).

Spectra measurements were carried on with a Hewlett Packard Network Analyzer 6719D (Figure 4.16) in order to identify the resonance frequencies characteristics of the prototype.

Figure 4.15 The prototype in the MW laboratory

Several measurements were done: in the quartz reactor were added for every measurements small pieces of graphite, of recycled rubber from used tires, and of motherboards reduced in powder. The spectrum showed no appreciable changes compared to the tests made on empty reactor.

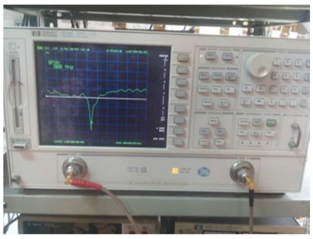

Figure 4.16 The HP Network Analyzer 6719D

The temperature monitoring of the system is shown in Figure 4.17. The pyrometer *Amprobe* monitors via IR the temperature inside the quartz reactor; it can simultaneously receive a temperature signal from a thermocouple. The digital thermometer *Testo* simultaneously monitors, with two K thermocouples, the temperature at the base of magnetron and that of the quartz reactor wall.

Another thermocouple is connected to the pyrometer for spot measurement along waveguides walls.

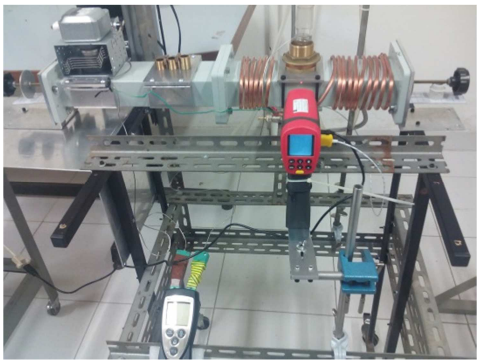

Figure 4.17 Temperature monitoring

The magnetron was placed into the waveguide of the prototype with its antenna inside the cavity near the three stub tuners Figure 4.18). Electrical cables connect the magnetron with the circuits in the oven assuring power supply.

Figure 4.18 The magnetron placed into the waveguide

A radial fan was placed near the magnetron to dissipate by forced convection the heat generated during operation (Figure 4.19).

Figure 4.19 Radial fan for cooling the magnetron

For security reasons the prototype was earthed connecting the different components with electric cables (Figure 4.20) and to the oven metallic structure.

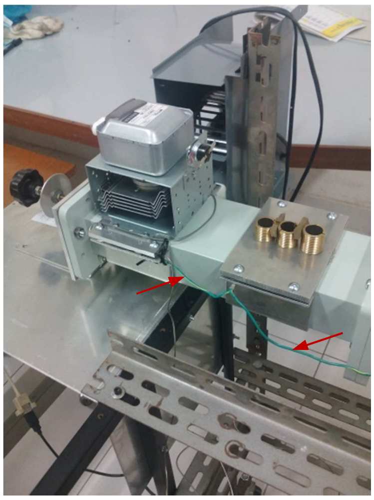

Figure 4.20 Electric cables connecting the different part of the prototype

To cool the waveguide near the reactor a copper pipe was rolled around it. (Figure 4.21). The cooling water used come from a centralize circuit and has a temperature of about 12 °C.

The same cooling water is used in the condenser fitted above the reactor. The hydraulic connections of the system are showed in Figure 4.22.

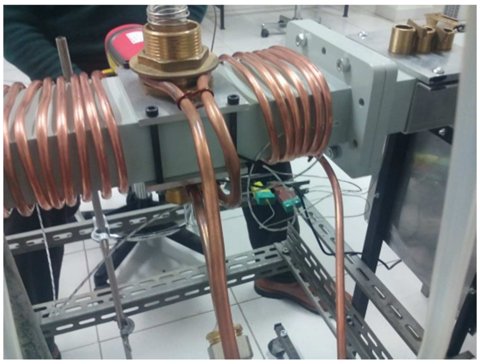

Figure 4.21 Cooling coils in the area of the reactor

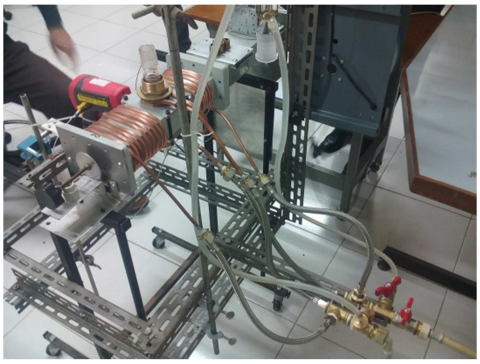

Figure 4.22 Cooling water connections

The system block diagram is shown in Figure 4.23. The prototype system is part of a more complex pilot system.

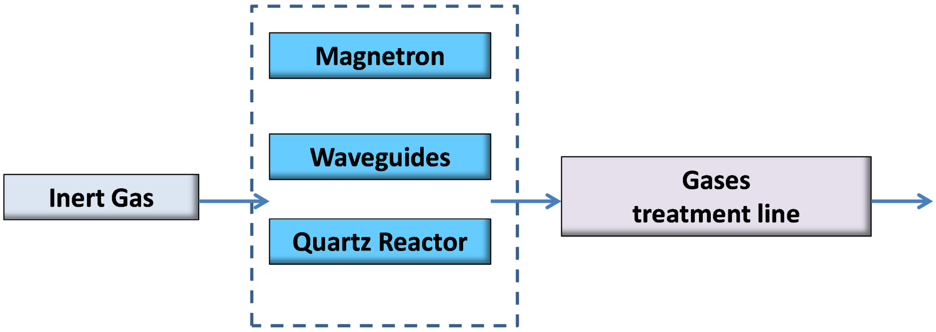

Figure 4.23 The prototype system

The complete scheme of the pilot system is illustrated in Figure 4.24.

For safety reasons some metal sheets with 5 mm holes were bought to create a protection screen between prototype and operators. It wasn't necessary to use these sheets because the prototype was well designed and manufactured.

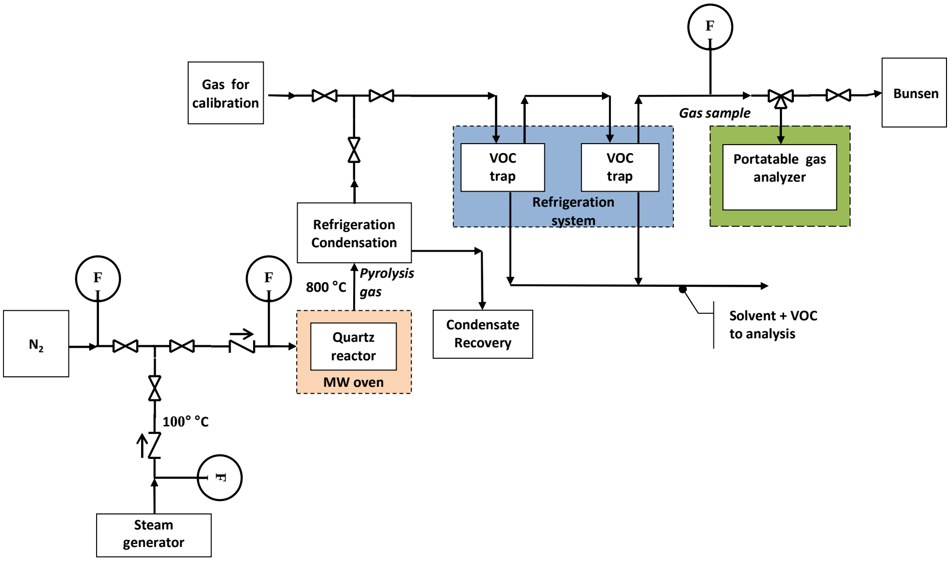

Figure 4.24 The complete pilot system

4.3. The pilot system: the gas line

The gas line involves refrigeration and condensation of the gaseous products. Air sampling bags are suitable to sample the gases for subsequent gas-chromatographic analysis.

4.4. Sample preparation

A main board ASUS model P5LD2-X/1333 was used as WEEE sample. Its form factor was ATX and dimensions 30.5x18.3 cm (Figure 4.25).

Before MB shredding, with the aid of forceps and tongs, some components were manually separated, such as:

- the central process unit (CPU);
- the CPU socket;
- the northbridge chipset;
- the southbridge chipset.

The weight of MB, without these components, was 470.5 g.

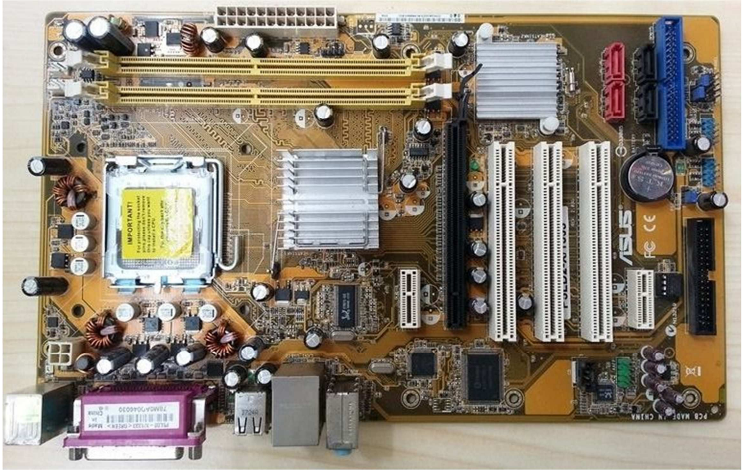

Figure 4.25 The Asus MB used sample preparation

Some removed components are showed in the following Figures (Figure 4.26, Figure 4.27) In the first CPU socket lever can be seen, in the seconds inductive and capacitive components.

Figure 4.26 Bulky components removed from the MB

Figure 4.27 Capacitive and inductive components and others removed from the MB

Stripped of these components, the weight of our MB was now 411.5 g.

The MB was then reduced manually into pieces of 2-3 cm (Figure 4.28) and weighted: 410.5 g. A quantity of 1 g was lost in this operation.

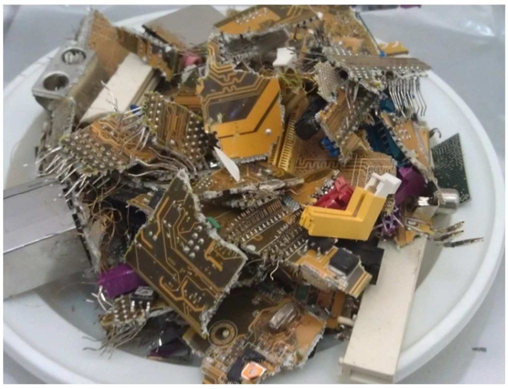

Figure 4.28 The MB manually reduced in pieces of 2-3 cm

A hammer mill was used as shredder; it essentially consists of an array of rotating hammers and a perforated screen that controls the product size (Figure 4.29). The sieve used was a 5 mm size.

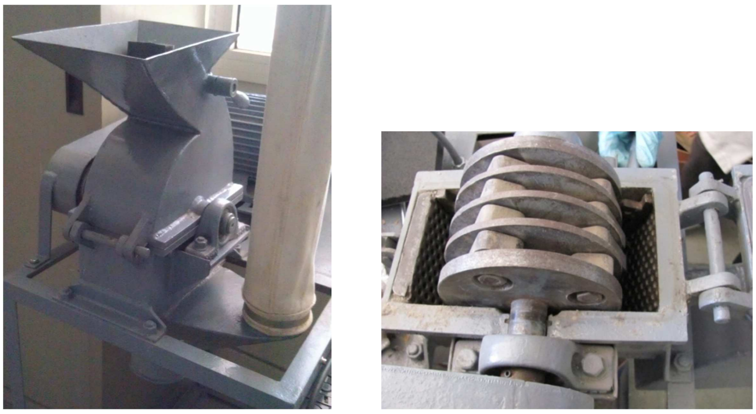

Figure 4.29 The hammer mill used to crush the motherboard.

Materials exiting from hammer mill was screened: the two fraction obtained are shown in Figure 4.30.

Figure 4.30 The two sample fraction output from the hammer mill

To prepare dust free, more uniformly sized samples a screening was carried on with a 1.5 mm sieve (Figure 4.31).

Figure 4.31 The two sample fraction after screening with 1.5 mm sieve

4.5. The output gaseous mixture from MIP experiments

The main gaseous compounds in the output gaseous mixture formed during pyrolysis have the following composition:

Table 4.2 Volumetric composition of the output gas

Compound	Range, vol. %
H_2	46 ÷ 53
CO	14 ÷ 38
CO_2	6 ÷ 11
CH_4	3 ÷ 18
C_2H_4	1 ÷ 4
C_3H_6	1,5 ÷ 2,0
CH_3Br	0,5 ÷ 1,5

The gaseous mixture has a mean LHV of 18 000 kJ/m^3.

Chapter 5

Conclusions

Microwave pyrolysis of WEEE, and in particular of PCBs, seem to be an economic and environmental friendly E-waste treatment process for energy and mass recovery.

In the course of this thesis a pilot plant was designed and built, which can operate in a wide range of power and can be modified at will, without the constraints associated with a commercial oven.

The work was concluded with the testing of the system with small quantities of mainboards reduced in powder and of other wastes.

During functionality tests, the pilot system has operated properly with the expected rise of temperature in the reactor zone. The cooling water circuit was able to maintain external temperature of waveguide at security level.

Its immediate development will be to analyse the products of pyrolysis of MBs and correlate the result with operating parameters (power of the microwave field, temperature, resident time in the reactor, the nature and flow of process gas).

An advantage of a single-mode cavity is that the distribution of electromagnetic field is predictable. The rectangular geometry, as all simple shapes, allows easy simulation of the EM field distribution with simulation software packages like COMSOL’s Multiphysics and others.

A current critical issue of such system is that it can process very little amounts of material; and the scale-up of the prototype to industrial scale could be difficult. Moreover, it is a batch system, while for industrial applications a continuous – feed arrangement would be more suitable.

In spite of all that, results and indications obtained from this system could be useful to design, for example, a MW system made up of parallel waveguides, each connected with a magnetron (MW generator), focusing together on a conveyor screw or belt.

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Acknowledgements

Warm thanks to:

- Dr Aurelio Agliolo Gallitto, Associate Professor at the Department of Physics and Chemistry, for theoretical and practical support to this research.
- Vito Mazzola, Doctor in Physical Sciences, for his invaluable help in the design and set-up of the prototype system.
- Mrs. Rosa D’Addelfio (*Funzionario Tecnico*, University of Palermo), for taking constantly care of the consistence, continuity and serviceability of the lab supplies required.

Funds for instruments, apparati, glassware etc. – only partially shown here - were provided by the Projects:

- PON “SIGLOD - SIstema intelligente di supporto alla Gestione e alla LOcalizzazione delle Discariche e di Impianti di gestione dei rifiuti” - 2012-NAZ-0053; led by INGV and UniNetLab, Palermo.
- PO FESR Regione Siciliana 2007-13 “INTEP - Innovazione tecnologica e di processo per il settore manifatturiero”.

List of Acronyms/Abbreviations

BFR	Brominated Flame Retardant
CE	Consumer Electronics
CRT	Cathode Ray Tube
EEE	Electrical and Electronic Equipment
EHS	Environment, Health and Safety
EoL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
EWC	European Waste Code
FR	Flame Retardant
ICNRIP	International Commission on Non-Ionizing Radiation Protection
ICT	Information and Communication Technology
IT	Information Technology
LCA	Life Cycle Assessment
LCD	Liquid Crystal Display
LCIA	Life Cycle Impact Assessment
LED	Light-emitting Diode
LHV	Low Heating Value
MB	Motherboard
OEM	Original Equipment Manufacturer
PAH	polycyclic aromatic hydrocarbons
PBDD	polybrominated dibenzo-p-dioxin
PBDF	dibenzofuran
PCB	Printed Circuit Board
RAM	Random Access Memory
RoHS	Restriction on the use of Hazardous Substances (EU Directive)
SAR	Specific absorption rate (W/kg)
UNEP	United Nations Environmental Programme
US EPA	Environmental Protection Agency (United States)
WEEE	Waste Electrical and Electronic Equipment
WPCB	Waste of Printed Circuit Board

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