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Assessment of toxic metals in waste personal computers

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ABSTRACT

Considering the enormous production of waste personal computers nowadays, it is obvious that the study of their composition is necessary in order to regulate their management and prevent any environmental contamination caused by their inappropriate disposal. This study aimed at determining the toxic metals content of motherboards (printed circuit boards), monitor glass and monitor plastic housing of two Cathode Ray Tube (CRT) monitors, three Liquid Crystal Display (LCD) monitors, one LCD touch screen monitor and six motherboards, all of which were discarded. In addition, concentrations of chromium (Cr), cadmium (Cd), lead (Pb) and mercury (Hg) were compared with the respective limits set by the RoHS 2002/95/EC Directive, that was recently renewed by the 2012/19/EU recast, in order to verify manufacturers' compliance with the regulation. The research included disassembly, pulverization, digestion and chemical analyses of all the aforementioned devices. The toxic metals content of all samples was determined using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The results demonstrated that concentrations of Pb in motherboards and funnel glass of devices with release dates before 2006, that is when the RoHS Directive came into force, exceeded the permissible limit. In general, except from Pb, higher metal concentrations were detected in motherboards in comparison with plastic housing and glass samples. Finally, the results of this work were encouraging, since concentrations of metals referred in the RoHS Directive were found in lower levels than the legislative limits.

1. Introduction

Due to the significant technological development during the last decades, Electrical and Electronic Equipment (EEE) has become an integral part of human life. Modernization of EEE caused a constant increase in standards and, consequently, a decline in its lifespan. As a result, nowadays, Waste Electrical and Electronic Equipment (WEEE), also known as "*e*-waste", is one of the largest and fastest growing waste streams. The importance of WEEE is not restricted only to its amounts, but also to its content. WEEE contains a variety of hazardous material, such as toxic metals and Brominated Flame Retardants (BFR) and any lack of proper treatment could cause important environmental concern (Cui and Forssberg, 2003).

The most widespread device of EEE is the personal computer, mainly because of its applications in a vast range of activities, such as work, entertainment and communication. Having a lifetime between 2 and 5 years, it is estimated that approximately 17 million personal computers become obsolete every year (Yamane et al., 2011). Considering the high percentage of waste computers in WEEE, any research regarding the composition of the main parts that constitute a personal computer is considered necessary. A personal computer consists of a large number of components of various sizes, shapes, functions and composition, two of which, the monitor screen and the motherboard, were examined in their metal content within the framework of this study.

Motherboard is the main and largest printed circuit board inside a desktop computer. A typical printed circuit board of a personal computer is composed of 27 wt.% polymers, 28 wt.% ceramics and 45 wt.% metals (Yamane et al., 2011), the significant percentage of which are toxic metals that could cause contamination of air, soil and ground water, if disposed inappropriately. Furthermore, an incomplete incineration of printed circuit boards could result in liberation of dioxins and furans, jeopardizing public health (Owens et al., 2007; Bi et al., 2010; Hadi et al., 2013). However, a waste printed circuit board contain not only toxic metals but also a lot of valuable materials such as gold, silver and palladium, which can be recovered using various recycling methods (Veit et al., 2005; Park and Fray, 2009; Guo et al., 2010). The most common type of a printed circuit board used in personal computers is the FR-2, which is a single layer of fiberglass or cellulose paper reinforced phenolic resin, coated with a copper layer (Yamane et al., 2011). However, Hall and Williams (2007) demonstrated a mixture of FR-2 and

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FR-4 in computer boards. The FR-4 type is made of glass fibre reinforced with epoxy resin.

The most widely produced computer monitors are Cathode Ray Tube (CRT) and Liquid Crystal Displays (LCD) monitors.

CRT screens were produced until the beginning of the 21th century and are considered a major item in WEEE treatment because of their volume, high recycling cost, toxicity and disposal restrictions (Kang and Schoenung, 2005; Nnorom et al., 2011). This type of screens consists of two parts: the glass components (funnel glass, panel glass, solder glass, neck) and the non-glass components (plastics, steel, copper, electron gun, phosphor coating). The present study focused on the examination of three of the aforementioned components: the panel glass, which represents approximately two-thirds of a CRT weight, the funnel glass, which represents almost one-third of a CRT weight (Nnorom et al., 2011) and the plastic housing. These three parts contain several hazardous substances, especially lead (Santos et al., 2010; Nnorom et al., 2011), which require proper handling in order to avoid any undesirable implications with the environment.

In the mid-1990s a new type of desktop computer monitors, the LCD, appeared. The rapid advances and falling prices of the LCD flat panel technology has been the main reason for becoming the primary technology used in desktop computers. Although the replacement of CRT monitors with LCD reduced the overall average mass of a desktop (Robinson, 2009) and its content in Pb (Ravi, 2012), LCD contains many other hazardous substances, such as Hg in cold cathode fluorescent lamps (CCFL) (Li et al., 2009), hence its toxic metal content should not be considered negligible. Since LCDs are present in several variants, such as thin film transistor liquid crystal displays (TFT-LCD) and/or touch screen LCDs, their development is considered still in progress. In this study, the LCD examination regarded the plastic housing and the panel glass.

In order to regulate the treatment of WEEE, the European Union has introduced two Directives, the 2002/96/EC and the 2002/95/EC. The first is known by the title "Directive on Waste Electrical and Electronic equipment" (WEEE Directive) and its main objective is the prevention of WEEE and the promotion of WEEE's recycling (European Commission, 2003b). The 2002/95/EC "Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment" (RoHS Directive) specifies maximum concentration limits for six restricted materials, came into force on the 1st of July, 2006 and was recently renewed by the 2012/19/EU recast, presenting the same concentration limits. These maximum concentrations are: 1000 ppm for Polybrominated Biphenyls (PBB), Polybrominated Diphenyl Ethers (PBDE), Lead (Pb), Mercury (Hg) and Hexavalent Chromium (Cr^{6+}) and 100 ppm for Cadmium (Cd) (European Commission, 2003a).

The aim of this study was the quantification of the main toxic metals (Al, Cr, Fe, Ni, Cu, Zn, As, Cd, Sn, Hg, Pb) found in a personal computer's monitor glass, monitor plastic housing and motherboard. In addition, samples were divided into two different streams; one with release date before 2006, and the other after 2006. Choosing this year was mainly done so as to examine whether manufactures have complied with the RoHS Directive limits or not, regarding the aforementioned metals, and for comparing the overall metal composition of the computers of the two streams.

2. Materials and methods

2.1. Sample determination

The samples used in the present study were chosen, as mentioned, according to their release dates. More specifically, at least one sample of each computer component was used with a release date before 2006 and at least one after 2006. The reason to follow this method was to compare toxic metal content of samples before and after 2006, when the RoHS Directive came into force. Computer screen material consisted of: two CRT screens, a HITACHI and a SONY, with release dates 2002 and 2000 respectively, three LCD screens, two produced by LG and one by SAMSUNG with release dates 2007, 2008 and 2006, respectively and one LG LCD touch screen, which went on market in 2008. Samsung LCD screen was classified in the "after 2006" category. The touch screen was examined separately from the other LCD screens so as to examine whether significant difference in its composition would occur. The quantification of toxic metals in funnel glass (for CRT), panel glass and plastic housing was also investigated. Motherboard devices included: three samples with release dates before 2006 (ECS, GIGABYTE, ASUS) and four after 2006 (three GIGABYTE and one ASROCK). Finally, the following 24 samples were established and examined: mixed plastic housing (<2006), HITACHI plastic housing (<2006), SONY plastic housing (<2006), mixed plastic housing (>2006), LG plastic housing (>2006), SAMSUNG plastic housing (>2006), LG touch screen plastic housing (>2006), mixed panel glass (<2006), HITACHI panel glass (<2006), SONY panel glass (<2006), mixed funnel glass (<2006), HITACHI funnel glass (<2006), SONY funnel glass (<2006), mixed panel glass (>2006), LG panel glass (>2006), SAMSUNG panel glass (>2006), LG touch screen panel glass (>2006), mixed printed circuit boards (<2006), GIGABYTE printed circuit board (<2006), ECS printed circuit board (<2006), ASUS printed circuit board (<2006), mixed printed circuit board (>2006), GIGABYTE printed circuit board (>2006), ASROCK printed circuit board (>2006). It should also be noted that motherboard samples were labeled as "printed circuit boards", because the motherboard was regarded as a representative sample of printed circuit boards of personal computers.

2.2. Sample collection

Some of the aforementioned devices were collected from the School of Electronic and Computer Engineering of Technical University of Crete, which handles all kinds of *e*-waste. Others were collected from the Recycling Department of the Municipality of Chania, while the rest of them from various electronic stores in Chania and Athens. All devices and their parts were non-functional.

2.3. Sample preparation

All computer screens were disassembled in order to separate the panel glass, the plastic housing and the funnel glass (regarding CRT) using screwdrivers and pliers (Fig. 1a). Thereafter, the aforementioned material and motherboards were cut into pieces of dimensions approximately 1 cm $\times$ 1 cm with the use of hammer, screwdrivers and pliers (Fig. 1b). The samples were then pulverized by the use of a solid sample homogenizer (Pulverisette 19, Fritz) with a grid of 0.5 mm openings, followed by a cyclone (Nabertherm) (Fig. 1c). In order to avoid cross contamination between samples, before each one's pulverization, the homogenizer and the cyclone were switched on and left operating for a few seconds without having any sample. After that, a small quantity of the next sample was milled but without collecting the product. Finally, all removable components of the homogenizer were washed with soap and de-ionized water.

2.4. Sample microwave digestion and chemical analysis

After each sample's preparation, as described above, they were digested in a microwave reaction system. The device used was a MARS 6 Microwave Reaction System by CEM Corporation. Different