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Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays

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ABSTRACT

Display devices such as cathode-ray tube (CRT) televisions and computer monitors are known to contain toxic substances and have consequently been banned from disposal in landfills in the State of California and elsewhere. New types of flat panel display (FPD) devices, millions of which are now purchased each year, also contain toxic substances, but have not previously been systematically studied and compared to assess the potential impact that could result from their ultimate disposal. In the current work, the focus is on the evaluation of end-of-life toxicity potential from the heavy metal content in select FPD devices with the intent to inform material selection and design-for-environment (DfE) decisions. Specifically, the metals antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel, selenium, silver, vanadium, and zinc in plasma TVs, LCD (liquid crystal display) TVs, LCD computer monitors and laptop computers are considered. The human health and ecotoxicity potentials are evaluated through a life cycle assessment perspective by combining data on the respective heavy metal contents, the characterization factors in the U.S. EPA Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), and a pathway and impact model. Principal contributors to the toxicity potentials are lead, arsenic, copper, and mercury. Although the heavy metal content in newer flat panel display devices creates less human health toxicity potential than that in CRTs, for ecological toxicity, the new devices are worse, especially because of the mercury in LCD TVs and the copper in plasma TVs.

1. Introduction

In recent years, there has been a tremendous rate of product redesign and replacement in consumer electronics. The replacement of cathode-ray tube (CRT) televisions (TVs) with flat panel display (FPD) devices such as plasma TVs and liquid crystal display (LCD) TVs, is particularly notable, with millions of new devices now being sold each year, as illustrated in Fig. 1. This rapid replacement is similar to that for CRT computer monitors by LCD monitors and laptop computers, which began several years ago (also shown in Fig. 1). Devices with FPDs are currently the highest volume product within the market for consumer electronic devices [1,3]. An unintended outcome of this rapid display device replacement is the generation of millions of units of CRT waste [2]. Because of the heavy metal content in CRTs [4], lead (Pb) in particular, the potential for waste CRTs to impact the environment has been studied previously and various waste management initiatives have been put into place. For instance, the leachability of heavy metals has been assessed to simulate the hazard from landfilled electronic devices [5–7], and the heavy metal content in CRT glass has been characterized to facilitate recycling [4]. The findings from these studies indicate that CRTs contain substantial amounts of Pb, as well as many other heavy metals, and that under standard leaching test procedures, CRTs do indeed represent a potential environmental burden. As a result of these and other findings, the disposal of CRTs in California landfills was banned in 2001 [8]. The U.S. EPA considers CRT glass to be hazardous waste under RCRA (Resource Conservation and Recovery Act, 1976), but in January 2007, implemented policy to streamline management of CRTs if destined for recycling [9].

As LCD computer monitors began to replace CRTs, researchers asked the questions: will these new devices also represent an environmental burden at their end-of-life, and can they be better designed to reduce this potential impact? In the late 1990s, an important study was conducted as part of the U.S. EPA's Design for Environment Program. Called the Computer Display Partnership [10], this effort entailed collaboration between industry and researchers at the University of Tennessee to use life cycle assessment (LCA) methods to analyze the environmental impacts, performance, and cost of both CRT and LCD desktop computer monitors. The results of this endeavor are provided in an extensive U.S. EPA report published in 2001 [11] and summarized in Ref. [12]. The findings of this study indicated that although LCD dis-

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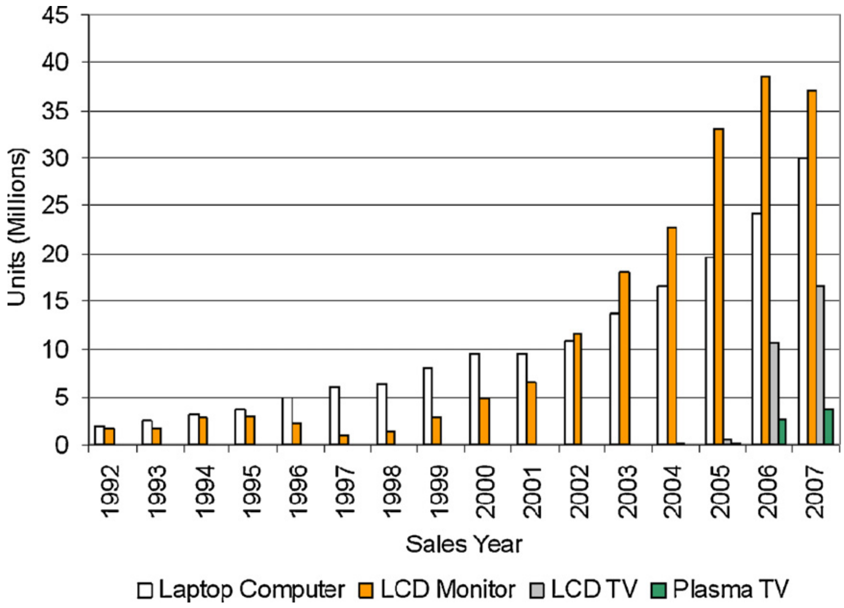

Fig. 1. Sales volume for electronic devices with flat panel displays (FPDs) in the United States. These data were adapted from Refs. [1,2]; the market shares for LCD and plasma TVs for years 1999–2003 were assumed to be the same as those in year 2004.

plays produced less environmental impact potential than the CRTs in almost all impact categories, there were still areas of concern such as potential for aquatic toxicity and eutrophication. Uncertainty related to many aspects of the study, including data sources, were considered in detail. The findings from this study also highlighted the need to better design LCD displays (and other novel devices) to minimize their toxic substance content and reduce their potential for negative environmental impacts throughout the life cycle. Because this study was a comprehensive LCA, the specific effects of material selection in these products is difficult to extract from among the trade-offs that also account for other factors such as energy consumption. Furthermore, this study focused only on CRTs and LCDs, as used for computer desktop displays. Thus, the current work is designed to complement the U.S. EPA study by highlighting the effects of heavy metal content in display technologies and to consider additional display technologies in light of the growing demand for FPD TVs, so as to inform design-for-environment (DfE) decisions. It is recognized that other types of hazardous substances such as brominated flame retardants, liquid crystals, Plexiglas^{TM}, polyoxymethylene, polyvinyl chloride, and phthalates are also contained in the devices with FPDs [3], but these are beyond the scope of the present work. The focus of this work is on human health and ecotoxicity potential, rather than the more comprehensive list of impact categories considered in the U.S. EPA study, because this shorter list of impact categories represent those for which the presence of heavy metals have a more direct effect. In addition, the focus is on end-of-life management, because of the large volumes of waste FPDs that will be generated in the future, consideration of which has not been previously studied. Because details on future end-of-life of these devices is highly uncertain, various assumptions are employed and a pathway and impact model is developed to estimate the distribution of the heavy metals in air and water, after the devices are discarded in landfills and/or incinerated. The U.S. EPA Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) is used as the source of characterization factors, because it is U.S. centric and includes heavy metals in its dataset [13]. It is important to note that this study is, therefore, a comparative evaluation in the context of life cycle assessment, rather than an absolute evaluation in the context of risk assessment [14]. The toxicity potentials over time in the United States are also estimated. This study can contribute to DfE of the devices, to their market-driven improvement by assisting customers in purchasing and insisting upon greener devices [15], and to the development of appropriate e-waste management policy and regulations.

2. Methods

2.1. Pathway and impact model for heavy metals

A pathway and impact model for the heavy metals in e-waste (see Fig. 2) is developed here so that an upper bound on the amount of heavy metals can be estimated. Heavy metals in e-waste treated in incineration facilities are distributed into flue gas, fly ash and bottom ash [16–18]. Volatile metals are enriched into fly ash, and lithophilic metals are deposited into bottom ash [16]. Some lithophilic and volatile metals are included in the flue gas and emitted into the air [16]. The distribution of heavy metals in municipal solid waste into the flue gas, bottom ash, and fly ash is presented in Table 1, which shows average values derived from the literature [16,17]. Note that although the distribution ratio is affected by waste composition, physico-chemical properties of heavy metals, and incinerator operating conditions [17], the data in Table 1 can be used to estimate the amount of heavy metals in the pathways because in the U.S. e-waste is most commonly disposed of together with municipal solid waste. The heavy metals in flue gas are ultimately deposited into water. It is assumed that all the heavy metals in the fly and bottom ashes are landfilled for final disposal [18,19] and that they ultimately leach into water. It is recognized that this is an extreme assumption, and that it is inconsistent with the public perception of landfills as storage containers. This assumption can, however, avoid many uncertainties related to complex and diverse reactions and transformations in landfill facilities. Furthermore, this assumption recognizes that disasters can occur, and that although a proper landfill liner system should contain the metals for the short-term, the long term scale for landfill treatment is on the order of 1000 years, and therefore landfill treatment can ultimately return the constituents of waste to the ecological cycle through chemical, physical, and biological reactions and transformation [19]. This very long term perspective is consistent with the "Egalitarian Perspective," as defined by cultural theory [20] and applied to LCA within the commonly used European LCA tool Eco-

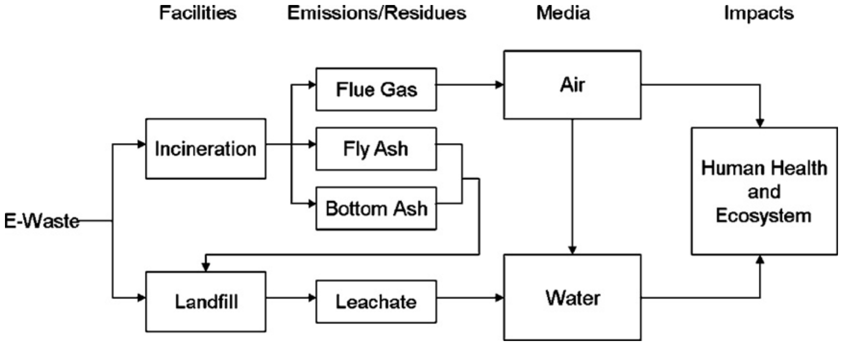

Fig. 2. Pathway and impact model for heavy metals in e-waste.

indicator 99™ [21,22]. Various studies have highlighted the need to consider the Egalitarian Perspective in LCA [23–25], while others have built their case studies around this perspective, such as the assessment by Brambilla Pisoni et al. on the environmental impact of waste transport [26]. For the purpose of comparison among the different display devices, such as in the current study, this assumption is the most appropriate approach. Thus, it is assumed that all of the heavy metals included in e-waste have the potential to impact human health and the ecosystem through water medium, as translated by the characterization factors described below. It is further noted that in this study the toxicity potentials from heavy metals in flue gas are double-counted for toxicity potentials for both water and air.

2.2. Evaluation of toxicity potentials from each device

Human health toxicity (cancer and non-cancer) and ecotoxicity potentials from each device were evaluated on the basis of the pathway and impact model by using the heavy metal content and the respective toxicity potential characterization factors. Metrics for toxicity potential were first defined by Guinée and Heijungs in 1993 [27] in an effort to develop characterization factors equivalent to those used for other ecosystem effects such as global warming potential and ozone depletion potential, recognizing that while the latter effects contribute to only one mechanism of environmental impact, human health and ecological toxicity effects contribute to more than one mechanism. The method combines information on exposure and effect, and compares the combined result for a given substance relative to a reference substance. ‘Toxicity potential’ thus “represents the potential contribution of a unit amount of a given substance to [e.g.,] human toxicity ... relative to a unit amount of a reference substance [27].” This approach has been widely accepted and further expanded upon by others, including Hertwich et al. [28] who expanded the list of substances and distinguished between cancer and non-cancer effects in humans, and Huijbregts et al. [29] who developed methods to distinguish between five ecotoxicity categories. Quite recently, an effort has been made to develop a consensus model for evaluating toxicity potential. The product of this effort, which is being coordinated by the United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC), called UseTOX, will provide an important tool to the LCA community, but at present it does not include any data on metals [30].

One method that derives from the early studies described above is TRACI. TRACI is a set of metrics developed by the U.S. EPA in a program that was initiated in 1995, with the goal of creating a U.S. centric tool for consistent decision making based on life cycle thinking [13], noting that the characterization factors developed by Guinée and Heijungs derive from European standards. During the development of TRACI, select environmental impact categories were investigated and the best available approach was applied to each category. For the categories of human health toxicity potential (cancer and non-cancer) and ecotoxicity potential, the characterization factors represent the “potential of a chemical released into an evaluative environment to cause human cancer effects/human non-cancer effects/environmental harm [13].” These characterization factors are derived on the basis of sophisticated multi-media models and exposure models, relying heavily on CalTOX, which is a widely accepted generic fate and exposure model [31]. The reader is encouraged to read Ref. [13] for complete details. It should be noted that for the human health categories (cancer and non-cancer potential) the characterization factors represent a U.S. geographical average, because sensitivity to toxicity and cancer potency was determined to be orders of magnitude more significant than regional sensitivities [13]. The units on the TRACI characterization factors reflect the extension of Guinée and Heijungs’ method to compare toxicity to a reference substance, rather than in absolute terms: grams of benzene equivalent for human health, cancer; grams of toluene equivalent for human health, non-cancer; and grams of 2,4-dichlorophenoxyacetic acid equivalent for ecotoxicity. The TRACI tool has been widely used, including its application to industrial ecosystem design in the Lower Mississippi River Corridor [32], to the comparison of in situ and ex situ treatment scenarios for remediation of a diesel-contaminated site [33], and to the comparison of crop-based, fossil-based and electric fuels [34]. Moreover, TRACI is one of the few data sets that attempt to characterize the effects of heavy metals [35]. Thus, TRACI, with its U.S. centric metrics [36], is an appropriate data source for the current work. It should be noted that this application of TRACI, as well as the pathway and impact model, do not take into account occupational exposure.

Table 1
Distribution of heavy metals into flue gas, fly ash, and bottom ash incurred in incineration facilities for municipal solid waste.

	Sb[a]	As[b]	Cd[b]	Cr[b]	Co[c]	Cu[b]	Pb[b]	Hg[c]	Ni[c]	Se[a]	Zn[b]
Flue gas (%)	1	1	4	0	0	0	1	74	0	0	1
Fly ash (%)	66	42	84	8	10	5	38	24	8	22	45
Bottom ash (%)	33	57	12	92	90	95	61	2	92	78	54

[a] Data source: [16].
[b] Data sources: [16,17].
[c] Data source: [17].

Laptop computers, LCD monitors, LCD TVs, and plasma TVs were employed to represent waste electronic devices with FPDs and were compared to CRT TVs. The heavy metal content of waste electronic devices with FPDs was obtained from the literature to calculate the weight of each metal in each device [37]: four representative laptop computers, seven LCD monitors, four LCD TVs, and four plasma TVs. These data were assumed to be simple random samples and their populations were assumed to be normally distributed, in order to calculate the margin of error for a 95% confidence interval. The data for CRT TVs were derived from recycling facilities [38]. The screen sizes for these representative FPDs were 12.1–13.3 in. for laptop computers, 15–17 in. for LCD monitors, 26–37 in. for LCD TVs, 42–50 in. for plasma TVs, and 20–21 in. for CRT TVs. The heavy metals consist of Sb, As, Ba, Be, Cd, Cr, Co, Cu, Pb, Hg, Mo, Ni, Se, Ag, V, and Zn.

The toxicity potentials for air from Ba, Be, Mo, Ag, and V were not evaluated because data on their distributions into flue gas were not available. Inspection of their respective weights and characterization factors, however, indicates that their toxicity potentials would be negligible even in the extreme case, because even if 100% of these metals is assumed to be emitted to the air, their evaluated toxicity potentials for air are still negligibly small when compared to those of the other metals.

2.3. Estimation of toxicity potentials over time in the United States

Human health toxicity and ecotoxicity potentials in the U.S. were estimated on the basis of the pathway and impact model by using the average toxicity potentials, sales volume over time, product weights, lifetimes of each device, and the fraction of devices landfilled and incinerated. The sales volume data were presented in Fig. 1. Average product weights were used for laptop computers and LCD monitors [2]. Representative weights were used for LCD and plasma TVs by converting the representative screen sizes into weights through product specifications [1]. The fraction of devices that are landfilled and incinerated relative to total waste devices was set at 0.85 through year 2005 and at 0.82 from year 2006 [39]; the remaining fraction represents recycled devices. The fraction of devices treated in incineration facilities to total waste devices was set at 0.02 [40]. Although it would be interesting to compare the toxicity potential as a function of disposal route, such a comparison is beyond the scope of the present work. The average lifetimes were set at 7 and 9 years for laptop computers and LCD monitors, respectively [2]. For LCD and plasma TVs, a lifetime of 15 years was assumed, which is the average lifetime for CRT TVs [2]. Note that in order to minimize uncertainty the temporal estimation did not take into account changes in recycling fraction in the future, which could reduce toxicity potentials. Furthermore, the temporal estimation results assumed static product composition and technology.

3. Results and discussion

3.1. Weights of heavy metals included in each device

The heavy metals in the devices with FPDs consisted mainly of Cu and Pb, as shown in Fig. 3. The total weight of heavy metals in these devices was less than that in the CRT TVs. It is also noted that the amount of Cu and Pb is much less in the new devices than in the CRT TVs, with the exception of the Cu in the plasma TVs. The Cu in these devices is used primarily as the conducting material in the printed wire boards (PWBs) and cables [3]. The Pb is used in the PWBs as solder (in metallic form) [3], in the dielectric layers of plasma TVs to prevent the deformation of the glass substrates (in oxide form) [41], and in the glass components of CRT TVs (i.e., panels, funnels, necks, and frits) to shield X-rays generated in the CRTs and to reduce the forming temperature of the glass (in oxide form) [5]. Arsenic is added to the glass in its oxide form during the melting process to improve the optical clarity of the glass panels in LCDs [42], and could be present in III–V semiconductors on the PWBs in the form of GaAs and InAs [43]. Mercury is found in the backlights of LCD panels, i.e., in cold cathode fluorescent lamps (CCFLs) that use mercury-containing bulbs, which are energy-efficient and cost-effective [3]. Although the absolute quantity of heavy metals provides some valuable information, the toxicity of these metals is relatively different and should be taken into account in comparing the potential impact of these devices in the waste stream.

3.2. Human health and ecological toxicity potentials from each device

3.2.1. Cancer potentials

Pb and As in the devices with FPDs are the only contributors to cancer potentials for water and for air, except for Cd in CRTs,

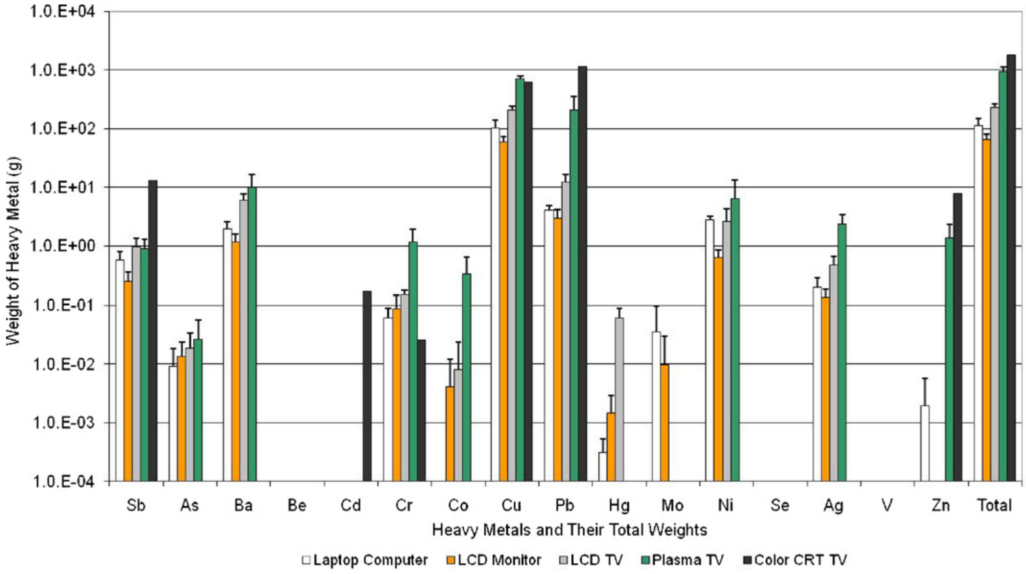

Fig. 3. Heavy metal content in waste electronic devices with flat panel displays (FPDs) and in cathode-ray tube (CRT) TVs. The error bars show the positive margin of error for a 95% confidence interval.

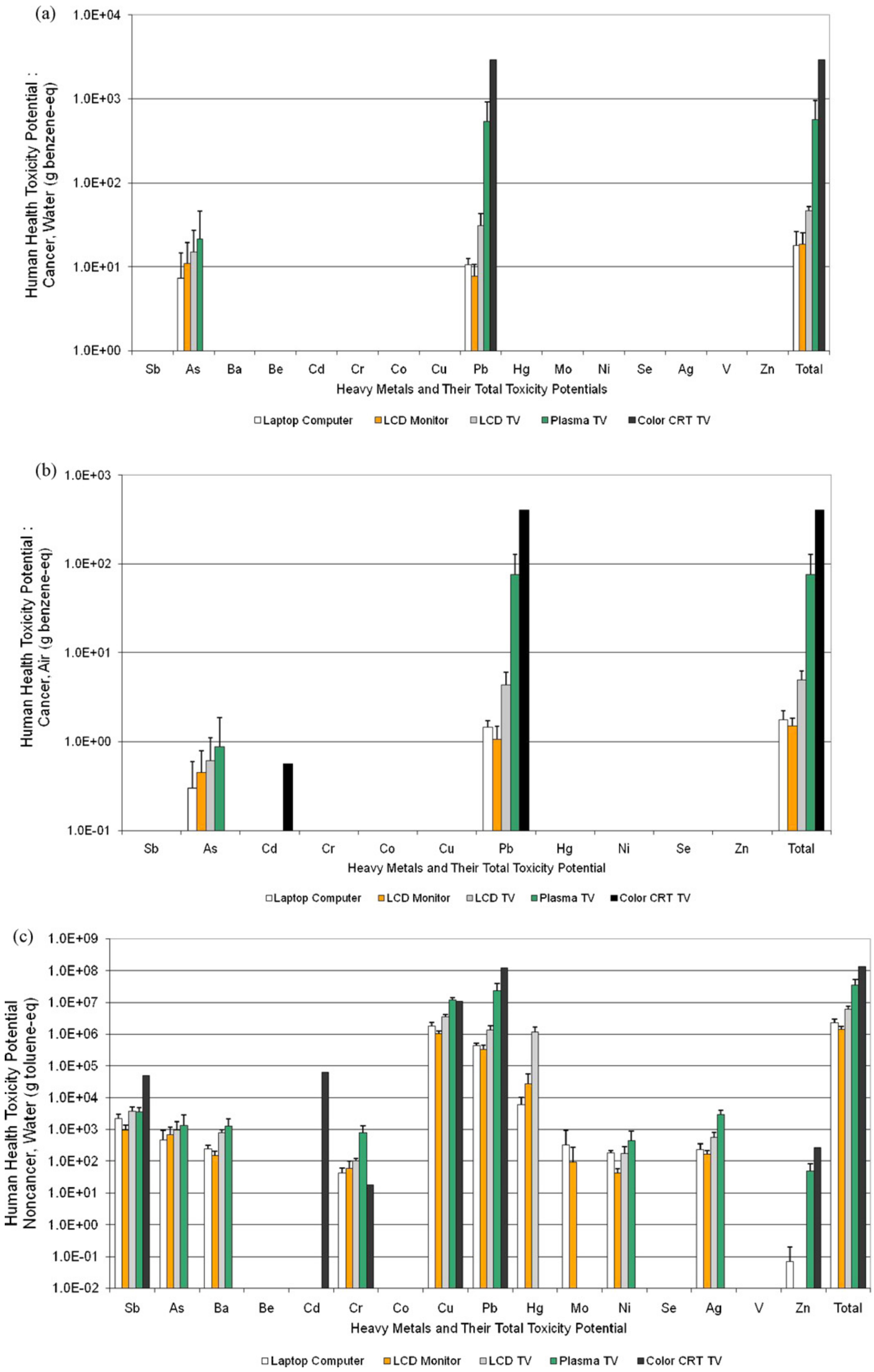

Fig. 4. Human health and ecotoxicity potentials from heavy metals in waste electronic devices with flat panel displays (FPDs) and in cathode-ray tube (CRT) TVs: (a) cancer potentials for water; (b) cancer potentials for air; (c) non-cancer potentials for water; (d) non-cancer potentials for air; (e) ecotoxicity potentials for water; and (f) ecotoxicity potentials for air. The error bars show the positive margin of error for a 95% confidence interval.

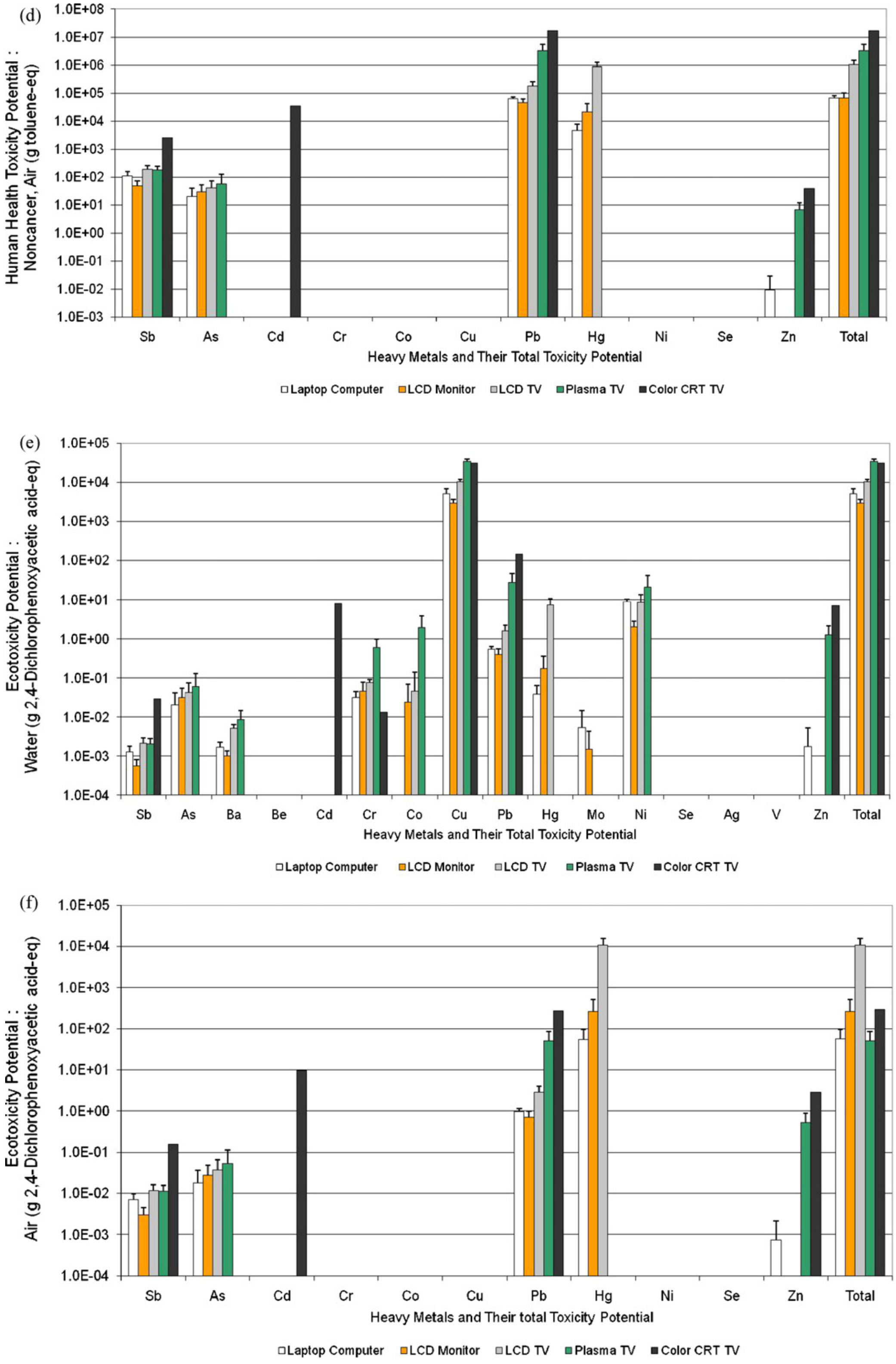

Fig. 4. (*Continued*).

as shown in Fig. 4(a) and (b). Although the contents of Pb and As in the devices are different by several orders of magnitude (see Fig. 3), their toxicity potentials are on the same order, especially in the laptop computers and LCD monitors. It should also be noted that, although Pb in electronics is regulated by the EU-RoHS (Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment) Directive [44] and the California Electronic Waste Recycling Act (CEWRA) [45], arsenic is not. In addition, although In was not taken into account in this study because its characterization factor from TRACI is not available, In compounds, such as InAs and InP semiconductors and indium tin oxide (ITO), which is used as a transparent and conductive thin film in LCDs [46], have the potential to incur lung disease and cancer.

The devices with FPDs exhibit lower cancer potentials than the CRT TVs, and the plasma TVs exhibit higher cancer potentials than the LCD TVs, primarily because of the differences in Pb content.

3.2.2. *Non-cancer potentials*

Major contributors to non-cancer potentials for water in the devices with FPDs are Cu, Pb and Hg; and those for air are Pb and Hg, as shown in Fig. 4(c) and (d). The different results between water and air media result from the fact that Cu is thermodynamically a lithophilic metal and so it is distributed mainly to bottom and fly ash [16]; as a result, Cu has no impacts through air but only through water. The non-cancer potentials for water from the other heavy metals are, in general, at least one order of magnitude less than those for Cu, Pb and Hg, although the toxicity potentials from Sb, As, Ba, Cr, Mo, Ni, Ag and Zn should be noted. For air, only Sb, As and Zn generate notable levels of toxicity potential, although still orders of magnitude less than from Pb and Hg.

The devices with FPDs exhibit lower non-cancer potentials than the CRT TVs, and the plasma TVs exhibit higher non-cancer potentials than the LCD TVs. The Pb is the major contributor to the high non-cancer potentials from the CRT TVs, as in the comparison of the cancer potentials. The differences in the non-cancer potentials between the plasma TVs and the LCD TVs result primarily from the presence of Pb rather than from Cu and Hg.

3.2.3. *Ecotoxicity potentials*

A major contributor to ecotoxicity potentials for water from the devices with FPDs is Cu in the PWBs; for air the major contributors are Hg in the CCFLs for the devices with LCDs and Pb for the plasma TVs, as shown in Fig. 4(e) and (f). The different results between water and air media were derived from the different volatile characteristics of the metals. It is interesting to note that for the ecotoxicity potentials for water, Pb, Ni, and Hg are on the same order, although noticeably lower than for Cu. Zn, Co, Cr, and As also demonstrate ecotoxicity potentials, but several orders of magnitude less than for Cu. In air, only Zn, As, and Sb lead to ecotoxicity potentials.

The devices with FPDs exhibit lower ecotoxicity potentials for water than the CRT TVs, with the exception of the plasma TVs, and lower ecotoxicity potentials for air, with the exception of the LCD TVs; and the plasma TVs exhibit higher ecotoxicity potentials for water than the LCD TVs but lower ecotoxicity potentials for air. The Cu is the major contributor to the high ecotoxicity potentials for water from the plasma TVs, and the Hg leads to the high ecotoxicity potentials for air from the LCD TVs.

3.2.4. *Implications*

DfE and e-waste management policy for devices with FPDs should focus on Pb, As, Hg, and Cu with priority to effectively reduce their toxicity potentials. Manufacturers should replace these heavy metals in the devices with non-toxic materials, which can relieve consumers' concerns and persuade them to purchase their greener devices. The implementation of RoHS in the EU and of CEWRA in California will drive the removal of Pb and Hg, as well as Cd and Cr, from these products. Thus, future efforts should focus on As and Cu; several other heavy metals are of secondary importance: Sb, Ba, Co, Mo, Ni, Ag and Zn. Revolutionary, not evolutionary, changes in technology and materials are needed to eliminate the use of these heavy metals. Unless such changes become realistic in the short- to mid-term future, e-waste management policy and regulations should be established to eliminate and/or recycle the heavy metals to prevent their release into the environment. Furthermore, the toxicity potentials of nanoscale materials and devices, including As-containing materials such as GaAs and InAs, should be further investigated as the electronics industry continues to develop nanotechnology to enhance the performance of electronic devices. The size, structure, and physical/chemical properties of nanoscale materials and devices can incur greater impacts on human health and ecosystems under certain conditions [47,48].

The ecological performance of LCD and plasma TVs should be improved to protect ecosystems. Although display technology development from CRT TVs to FPD TVs would contribute to improving human health due to less cancer and non-cancer potentials of FPD TVs than for CRT TVs, waste LCD and plasma TVs would have more significant impact potentials on ecosystems in the near future than CRT TVs because CRT TVs have been dramatically replaced with LCD and plasma TVs. Therefore, manufacturers of LCD and plasma TVs should endeavor to decrease the use of Hg and Cu, respectively, to reduce ecotoxicity potentials.

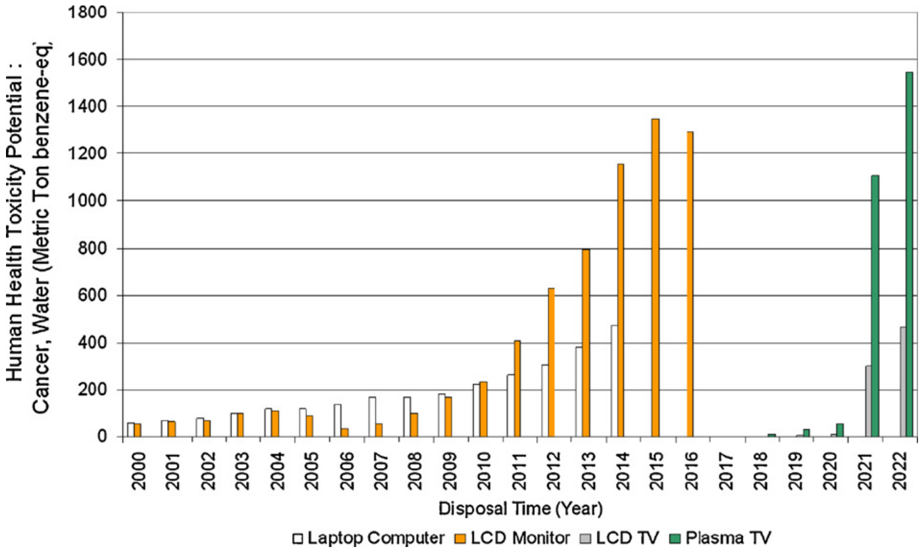

Fig. 5. Variation over time in cancer potentials for water in the United States from heavy metals in waste electronic devices with flat panel displays (FPDs). The projection results for the other human health and ecotoxicity potentials are available in Supplementary Material: cancer potentials for air; non-cancer potentials for water; non-cancer potentials for air; ecotoxicity potentials for water; and ecotoxicity potentials for air. The toxicity potentials from laptop computers and LCD monitors were estimated until years 2014 and 2016, respectively, and those from LCD and plasma TVs were estimated from year 2014, because of the time lags between their sales and anticipated disposal.

3.3. Toxicity potentials over time in the United States

3.3.1. Temporal variation of toxicity potentials

The cancer potentials are projected to dramatically increase over the next few years, as shown in Fig. 5. The cancer potentials from laptop computers and LCD monitors are projected to significantly increase starting in years 2009 and 2011, respectively. LCD monitors exhibit a larger increase in cancer potentials than laptop computers because of the rapid replacement of CRT monitors with LCD monitors since year 2002 (see Fig. 1). A dramatic increase in cancer potentials from LCD and plasma TVs is projected to begin in year 2021 because of the even more rapid replacement of CRT TVs with LCD and plasma TVs since year 2006 (see Fig. 1). It is anticipated that after year 2023, the high impacts from LCD and plasma TVs will continue to grow due to increased sales volume, data for which are not yet available. Some of this growth in toxicity potential (as well as those for non-cancer and ecotoxicity) will, however, be mitigated through the implementation of RoHS and CEWRA, which will force the decreased use of Pb, Hg, Cd, and Cr in these products.

The non-cancer potentials are projected to increase rapidly over time in the same manner as the cancer potentials, as shown in Supplementary Material. It is interesting to note, however, that whereas the cancer potentials from the plasma TVs rapidly surpassed the cancer potential from the LCD monitors and laptops, the non-cancer potentials for water remain higher, especially for LCD monitors. In air, the new TVs (both plasma and LCD) both rapidly outpace the LCD monitors for non-cancer potential, especially for the LCD TVs because of mercury's contribution.

The ecotoxicity potentials are also projected to increase over time, as shown in Supplementary Material. It is noted, however, that the ecotoxicity potentials for water from both LCD and plasma TVs are, for this toxicity category, lower than those from laptop computers and LCD monitors. In contrast, the ecotoxicity potentials increase dramatically for air with the introduction (and disposal) of the LCD TVs.

3.3.2. Implications

E-waste management policy and regulations should be established to prevent significant environmental and human health threats from what will soon be a rapidly growing waste stream of electronic devices with FPDs. In addition to targeting the heavy metal content of these devices, it is important for waste management organizations and regulatory bodies to prepare for the potentially large quantities of potentially toxic devices. This preparation should entail not only legislative initiatives, but also the development of appropriate recycling, recovery and collection technologies, especially for the large LCD and plasma TVs.

4. Conclusions

Electronic devices with FPDs contain significant amounts of a wide variety of heavy metals, which, when disposed of by landfill or incineration, can lead to potential human health toxicity and ecotoxicity. With millions of these devices now being sold each year in the U.S. as replacements for the conventional CRT displays, there is a need to select less toxic materials for use in these products. This study highlights not only the heavy metal content in these new devices, but also the toxicity potential associated with them. By incorporating TRACI characterization factors, a comparative life-cycle based assessment is provided. The results indicate that although from a human health toxicity perspective the new FPDs are better than the CRTs they replace, these new devices still contain substantial amounts of toxic heavy metals. When considering ecotoxicity, the new devices (specifically plasma TVs and LCD TVs) are not better than the CRTs. The heavy metals of greatest concern include, not surprisingly, lead (Pb) and mercury (Hg), which are now being phased out by law. Other metals, however, are also highlighted in the results of this study, especially copper and arsenic. Also of concern for select impact categories are indium, nickel, antimony, barium, chromium, cobalt, molybdenum, silver and zinc. It is important to note that some of these substances, although used in very small quantities, represent significant toxicity potential. The results of this study can contribute to improved decision making for material selection and design for environment of new devices. These findings also can provide consumers with appropriate toxicity information, which can motivate changes in e-waste management policy and regulation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2009.12.025.

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