TCLP Heavy Metal Leaching of Personal Computer Components

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Abstract: Electronic waste (E-waste), including all obsolete electronic products, has become the fastest growing component in the solid waste stream. Personal computers (PCs)—the most significant component in E-waste stream—were studied for their potential leaching toxicity of contaminants. All the components in a PC that are composed of, or contain printed wire boards (PWBs) including the motherboard, various expansion cards, disk drives, and power supply unit were tested by the toxicity characteristic leaching procedure (TCLP). The total contents of eight heavy metals including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver in the PWBs and their TCLP leaching from the PWBs were examined. Among these eight heavy metals lead was found to be the predominant element that causes the toxicity characteristic of the PC components. The lead concentrations in the TCLP extracts of the vast majority of the PWBs ranged from 150 to 500 mg/L, which are 30–100 times the regulatory level of 5 mg/L for classifying a waste as hazardous. The motherboard in a PC contributed 50–80% of the total lead that could leach out from all the PWBs in the PC under the TCLP test conditions. The contents of barium and silver were found to be high in some components, but they were not leachable under the TCLP test conditions. The contents of other five elements in all the PC components were hardly detectable. They would not have the potential to cause toxicity characteristic leaching concern.

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Introduction

The U.S. Environmental Protection Agency (USEPA) has found electronic waste (E-waste) to be the fastest-growing component in the American solid waste stream and it already constitutes 1% of the municipal solid waste (EPA 2003). Although the recycling and reuse of the obsolete electronic products is strongly encouraged, only 9% is recovered for recycling and the vast majority ends up in landfills. More importantly, huge amounts of obsolete electronic products, especially personal computers (PCs) and televisions (TVs), are stored in people's homes and offices, waiting for disposal. In California, it is estimated that some 6 million obsolete PCs and TVs are stored in people's homes and another 10,000 are joining them every day (Murray 2004).

E-waste contains a complex array of hazardous substances that can threaten human health and the environment if not handled or disposed of properly. The cathode ray tubes (CRTs) in computer monitors and TVs contain about 8% lead (Pb) by weight (Smith et al. 1996). They also contain small amounts of other toxic substances including barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn) (Lee and Hsi 2002). The Pb leaching toxicity of CRTs has been studied by a research team led by Dr. Tim Townsend at the University of Florida (Townsend et al. 1999) using the EPA standard toxicity characteristic leaching procedure (TCLP). The study found an average Pb concentration of 22 mg/L in the TCLP extracts for most color CRTs, which exceeded the 5 mg/L regulatory level for characterization as hazardous waste. Based on this finding, EPA has proposed a rule on the proper handling of CRTs (EPA 2002). Massachusetts and California have banned disposal of CRTs in landfills effective 2000 and 2002, respectively, and Minnesota and Maine's legislatures have passed a ban that will take effect in 2005 and 2006, respectively.

PCs constitute the second largest component next to CRTs in the E-waste stream and are growing most rapidly. PCs also contain the largest amount of printed wire boards (PWBs) among electronic products. PWBs have been known to contain many types of heavy metals and brominated flame retardants (BFRs) which are toxic to human beings and the environment (Schmidt 2002; SVTC 2004), but the study on the leaching characteristics of the toxicants in PWBs has been very limited. An earlier study in Taiwan (Yang 1992) examined only three PWBs separated from three TVs. The study tested the leaching of heavy metals nickel (Ni), Cu, Zn , Cr, Cd, and Pb by the TCLP method. A recent study (Jang and Townsend 2003) compared the leaching of Pb from PC motherboards in the TCLP extracts to the leaching in landfill leachates obtained from eleven Florida landfills. The motherboards were size reduced to approximately 50 mm as

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Table 1. Identifications of PC Samples

Identification number	Make	Model	CPU
PC-1	IBM	PS/2 50z	286
PC-2	DTK	—[a]	486 Sx
PC-3	Dell	Dimension 433 DM	Intel 486 Dx
PC-4	Nyma	—	486 Dx2
PC-5	HP	Vectra VL	Pentium
PC-6	Dell	OptiPlex G1	Pentium II
PC-7	Compaq	Desk Pro	Pentium III

[a]Not available.

opposed to 9.5 mm and smaller as mandated by the TCLP method.

The objectives of this study were (1) to examine the existence and contents of toxic heavy metals in different PC components; (2) to determine the leaching toxicity characteristics of the heavy metals in the components by the TCLP method; and (3) to identify the components which could fail the TCLP test and cause environmental hazards when being discarded or co-disposed with municipal wastes in landfills. Eight heavy metal elements including As, Ba, Cd, Cr, Pb, mercury (Hg), selenium (Se), and silver (Ag) were examined. They are mostly likely to be found in PCs (SVTC 2004) and are on the EPA list (D list) of the toxicity characteristic substances for TCLP (EPA 1999).

Samples and Methods

Computer Samples

The computer samples used in this study were desktop PCs obtained from the Computer Recycling Project at Jackson State University (JSU), Miss. The PCs with a wide range of models and manufacturers were included in the samples. This paper presents the results for seven desktop PCs ranged from the early 1980 models with an Intel 80286 microprocessor or central processing unit (CPU) to the 21st century models with a CPU of Intel Pentium III. The PC samples contained the housing and everything inside; the peripherals such as the monitor, keyboard, speakers, and mouse were not included. Sample identification numbers from PC-1 to PC-7 were given to these PCs. Their corresponding makes, models, and CPU types are given in Table 1.

Composition Analysis of PCs

A weight-based composition analysis of the PCs was conducted. The PCs were separated into the following major components in the analysis: (1) housing: steel and/or plastic pieces that form the case of a PC; (2) frame: steel structure supporting all the components inside the housing; and (3) motherboard (MB): the largest PWB connecting all the devices inside a computer. A motherboard typically included a big piece of board on which the following components were fixed: (1) CPU; (2) integrated circuit (IC) packages including random access memory (RAM) cards, basic input/output system (BIOS) chips, controller chips, etc.; (3) various slots, connectors, and sockets for interfaces, drives, and devices to plug into; and (4) expansion cards: connected to the motherboard to provide added functions such as the video card (VC), sound card (SC), network card (NC), modem card, and serial/parallel interface card. For some newer PCs, these expansion cards were built directly into the motherboard; (5) power supply unit (PSU); and (6) disk drives including hard disk drive (HDD), floppy disk drive (FDD), compact disk drive (CDD), and/or digital video disk (DVD) drive. Other components included fans for ventilation, integrated drive electronics (IDE) cables, and small speakers.

Composition Analysis of Motherboards

The motherboard is the largest and the most complex PWB in a PC. In this study, the motherboards were separated into the following components for testing and analysis: (1) the board: consisting of a plastic board, interconnecting wires, and solder; (2) IC packages: containing IC chips, the polymer encapsulant, and metal pins; (3) CPU: the largest IC package on the motherboard; (4) CPU radiator; (5) CPU socket or housing if any; (6) slots: including the industry standard architecture (ISA), peripheral component interconnection (PCI), accelerated graphics port (AGP), and dual inline memory module (DIMM) slots for connecting various expansion cards and RAM cards; (7) RAM cards; (8) connectors: including the peripheral connectors, IDE cable connectors, and the internal power connectors; (9) timer battery; and (10) other small elements: including capacitors, resisters, and some unidentified small items.

Analysis of Heavy Metal Contents

The total contents of eight heavy metals in the motherboards were analyzed. Since the acid digestion method (EPA 1996a) requires a small solid sample size (1–2 g), the samples must be carefully selected in order to be representative. Due to the heterogeneous nature of the PC components, not all components could be reasonably sampled in such a small size. Therefore, only the boards, IC packages, and CPUs of the seven motherboards were tested for the heavy metal contents. For the board samples, about 50 g of the well mixed, size-reduced particles as prepared for the TCLP test (see the "TCLP Test" subsection) were taken. The particles were further cut and ground into particles less than 2 mm using heavy duty hand shears and a durable iron mortar and pestle set. Triplicate samples of 2 g were taken from the ground particles for acid digestion and heavy metal analysis. For the IC packages, about 20 g of the well mixed, size-reduced particles as prepared for the TCLP test were taken and further ground into particles smaller than 2 mm using the mortar and pestle set, then 2 g samples in triplicate were taken. For the CPUs, each one was entirely cut and ground into particles smaller than 2 mm using the hand shears and the mortar and pestle set, then triplicate of 2 g samples were taken. All the samples were sent to Environmental Hazards Services, L.L.C. (EHS) of Richmond, Va. for the total heavy metal analysis. EHS is an analytical testing laboratory specializing in the analysis of environmental samples. EHS used EPA Method 3050B (EPA 1996a) to digest solid samples and to prepare aqueous samples for the analysis of As, Ag, Ba, Cd, Cr, Pb, and Se by the inductively coupled plasma-atomic emission spectrometry (ICP-AES) as specified in EPA Method 6010B (EPA 1996b). The content of Hg was analyzed according to the EPA Method 7471A for cold-vapor atomic absorption (EPA 1994).

TCLP Test

The EPA standard TCLP method (EPA 1992a) was employed to test all the PC components that contain PWBs. The samples included the motherboards, VCs, SCs, NCs, HDDs, FDDs, CDDs, and PSUs. The motherboards were separated into the following ten groups of components and tested separately: (1) the board; (2) IC packages; (3) CPU; (4) ISA slots; (5) PCI slots; (6) DIMM slots; (7) AGP slots; (8) RAM cards; (9) connectors and sockets; and (10) other small elements including capacitors, resisters, and other unidentified small components. The CPU radiator, CPU housing, and battery were not included in the TCLP samples. Testing these groups separately made it possible to quantify the contributions of different components to the leaching of the toxic constituents in the TCLP extraction.

The VCs, SCs, and NCs were much simpler than the motherboards. Each card consisted of a board, a small amount of IC packages, some small electronic devices, and one or two peripheral connectors. No further separation of the cards was made for the TCLP test. Since not all of the seven PCs used in this study contained these cards, additional expansion cards were obtained from the Computer Recycling Project at JSU and included in this test to achieve sufficient number of samples. The additional cards were already separated out of PCs before being obtained, the exact models and manufacturers of the source PCs were not known. They were numbered with a suffix unk1, unk2, etc. For example, a video card from an unknown PC was numbered as VC-unk1; a sound card SC-unk1; and a network card NC-unk1; etc.

Other major components that contained PWBs were the disk drives and PSUs. Most PCs had HDDs, FDDs, and PSUs, but only PCs with a CPU of Pentium or higher had CDDs. Older PCs such as those with a CPU of Intel 286 to 486 might have both 3.5 and 5.25 in. FDDs. Unlike the motherboards and the expansion cards which were entirely PWBs, the HDDs, FDDs, CDDs, and PSUs were composed of various materials. PWBs were only a portion of the devices. Other materials included the case, the support pieces, and some mechanical parts mainly made of steel, aluminum, or plastic. The TCLP test was conducted only on the PWBs separated from the drives and the PSUs. The weight fractions of the PWBs in the HDDs, FDDs, CDDs, and PSUs were determined. The PWBs in HDDs, FDDs, and CDDs were small and easy to process into particles for TCLP extraction. The PWBs of the PSUs commonly carried some large-sized elements including transformers, radiators, and large capacitors. These large elements were removed from the PWBs and were not included in the TCLP samples.

In the TCLP test, the samples were size-reduced to pass a 9.5 mm sieve, mixed with the extraction fluid at a liquid-to-solid ratio of 20:1 on weight basis, and agitated in a rotary extractor at 30 rpm and $22 \pm 2^\circ C$ for a period of 18 ± 2 h. The size reduction of the boards and the thin IC packages was accomplished using heavy-duty hand shears. The thick IC packages including CPUs, slots, and connects were crushed using a durable iron mortar and pestle set. After the agitation, the samples were filtered through a 0.6–0.8 μm glass-fiber filter. The filtrate, defined as TCLP extract, was analyzed for heavy metal concentrations. The extraction fluid number 1 with a pH of 4.93 ± 0.05 was used based on a preliminary determination test according to the TCLP method. Among all the samples of the component groups in the TCLP test, only the boards of the motherboards and some expansion cards exceeded 100 g, which is the minimum size recommended by the TCLP method for samples of 100% solid. For the samples that exceeded 100 g, they were completely size reduced and well mixed, then 100 g were put in 2,000 g extraction fluid for extraction. For the samples less than 100 g, the amount of the extraction fluid was adjusted to meet the 20:1 liquid-to-solid ratio. Three elements Pb, Ag, and Ba, which were found to exist in large amounts in the analysis of the total contents of the eight heavy metals, were analyzed for their concentrations in the TCLP extracts.

An atomic absorption (AA) spectrophotometer (Shimadzu AA-6200) was used to analyze the concentrations of Pb, Ag, and Ba in the TCLP extracts according to EPA Method 7000A (EPA 1992b). A minimum of one matrix spike was analyzed for samples from each component group. For the analysis of Pb, a spike concentration of 5.0 mg/L was used. All the samples were diluted to a final measured Pb concentration of 2.0–8.0 mg/L. The calibration curve was obtained with a series of standard solutions with Pb concentrations from 0 to 15.0 mg/L within which a linear relationship between the absorbance and the concentration was warranted. To assure the quality of the data, some samples were analyzed independently at a different institution (Mississippi State University School of Chemical Engineering) using an inductively coupled plasma-optical emission spectrometer (ICP-OES) (PerkinElmer Optima 4300 DV).

Results and Discussion

Composition of PCs and Motherboards

The results of the composition analysis of the seven PCs are presented in Table 2. The PCs weighed from 8 to 14 kg. The two largest components were the housing and steel frame that constituted 65–85% of the total weights of the PCs. The third largest component was the motherboards which accounted for 6–9%, followed by the PSUs (6–8%), the HDDs (4–8%), the FDDs (3–5% for 3.5 in. drive and 8–11% for 5.25 in. drive), and CDDs (about 4% if any). Not all PCs had expansion cards; old PCs such as those with a CPU of Intel 486 or lower did not have SCs and NCs because stereo sound systems and high-speed Internet access were not popular at that time. Some newer PCs had these cards as separate components connected to the motherboards through expansion slots while other newer PCs had these cards built directly into the motherboard. For the three major expansion cards, VCs typically weighed from 90 to 185 g, SCs 40 to 120 g, and NCs 50 to 95 g. Expansion cards accounted for less than 2% of a PC overall weight.

The results of the composition analysis of the motherboards from the seven PCs are presented in Table 3. The board was the largest component, accounted for 24–46% of a motherboard weight depending on the PC model. The expansion slots including ISA, PCI, and AGP slots constituted a large fraction of a motherboard (13–30%). Another large component was the various connectors (7–12%). The newer the PCs were, the bigger the CPU radiators they had on the motherboards. The PCs with CPUs of Pentium II and Pentium III had CPU radiators that weighed 230–290 g (23–24% of the entire motherboard weight), while the older PCs had small or no CPU radiators. In contract, the weight of IC packages decreased with the advance of the PC models. The IC packages on MB-1 (286 CPU) weighed 67.5 g and accounted for 13% of the weight of the entire motherboard, but the IC packages on MB-7 (Pentium III CPU) weighed only 16.5 g and accounted for less than 2% of the motherboard.

Contents of Heavy Metals

The purpose of analyzing the total contents of the heavy metals in the PC components was twofold: (1) to identify the locations where the toxicant elements exist in significant amounts; and (2)

Table 2. Composition Analysis Results for PC Samples

Component	PC-1		PC-2		PC-3		PC-4		PC-5		PC-6		PC-7	
	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)
Steel housing	2,396	27.7	2,577	21.6	3,000	32.8	6,037	66.1	348	4.0	1,079	8.0	2,491	20.2
Plastic housing	2,097	24.3	441	3.7	1,649	18.0	367	4.0	1,314	14.9	2,163	16.0	526	4.3
Steel frame	1,204	13.9	5,033	42.2	2,053	22.5	1,150	12.6	4,418	50.3	7,111	52.5	5,350	43.3
Motherboard	530	6.1	626	5.2	742	8.1	741	8.1	792	9.0	1,260	9.3	993	8.0
Video card	159	1.8	92.5	0.8	—	—	185	2.0	—	—	—	—	79.1	0.6
Network card	—[a]	—	84.8	0.7	—	—	94.5	1.0	53.8	0.6	—	—	57.4	0.5
Sound card	—	—	118	1.0	—	—	—	—	—	—	—	—	92.0	0.7
Serial card	147	1.7	214	1.8	—	—	—	—	—	—	—	—	—	—
Fan	131	1.5	73.6	0.6	98.9	1.1	145	1.6	84.8	1.0	188	1.4	221	1.8
PSU	693	8.0	623	5.2	676	7.4	727	8.0	688	7.8	767	5.7	703	5.7
HDD	705	8.2	501	4.2	444	4.9	446	4.9	501	5.7	511	3.8	488	4.0
3-inch FDD	445	5.2	325	2.7	352	3.9	—	—	413	4.7	352	2.6	449	3.6
5-inch FDD	—	—	906	7.6	—	—	991	10.8	—	—	—	—	—	—
CD drive	—	—	—	—	—	—	—	—	—	—	—	—	460	3.7
IDE cable	—	—	183	1.5	71.1	0.8	208	2.3	153	1.7	92.0	0.7	96.4	0.8
Other[b]	132	1.5	140	1.2	52.0	0.6	146	1.6	26.9	0.3	15.6	0.1	340	2.8
Total	8,639	100.0	11,938	100.0	9,138	100.0	11,238	100.0	8,792	100.0	13,538	100.0	12,345	100.0

[a]Not available.

[b]Including screws, speakers (if any), and other small pieces.

to compare with the TCLP test results of the elements to determine their leachability. The measured contents of the eight heavy metals in the boards, IC packages, and CPUs of the motherboards are given in Table 4. The means and the standard derivations were calculated based on measurements of the triplicate samples. Since the standard deviations for the Pb measurements among the samples of the boards and among the samples of the IC packages and the standard deviations for the Ag measurements among the samples of the IC packages were relatively close, pooled standard deviations were calculated as shown in the note under Table 4. The pooled standard deviations were obtained by the following steps: (1) summing the squares of deviations from the means for each data subset (triplicate measurements of each sample); (2) dividing the sum of the squares by the total number of measurements minus the number of subsets; and (3) taking the square root of the quotient.

Table 3. Composition Analysis Results for Motherboards

Component	MB-1[a]		MB-2		MB-3		MB-4		MB-5		MB-6		MB-7	
	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)	Weight (g)	Fraction (%)
The board	231	43.6	194	31.0	328	44.2	267	36.1	269	33.9	396	31.4	241	24.3
IC packages	67.5	12.7	55.1	8.8	34.4	4.6	47.0	6.3	30.8	3.9	34.3	2.7	16.5	1.7
CPU	25.4	4.8	38.2	6.1	38.7	5.2	55.0	7.4	28.5	3.6	15.9	1.3	35.3	3.6
CPU radiator	—[b]	—	—	—	—	—	24.3	—	58.1	7.3	290	23.0	232	23.3
CPU housing/socket	29.0	5.5	—	—	—	—	—	—	23.4	3.0	55.4	4.4	85.0	8.6
ISA slots	9.2	1.7	148	23.6	145	19.6	164	22.1	46.6	5.9	81.8	6.5	36.2	3.6
PCI slots	—	—	—	—	—	—	—	—	41.2	5.2	69.3	5.5	53.8	5.4
DIMM slots	5.6	1.1	39.5	6.3	15	2.0	33.5	4.5	38.8	4.9	18.7	1.5	28.3	2.8
AGP slots	56.8	10.7	37.6	6.0	38.1	5.1	25.3	3.4	33.2	4.2	51.8	4.1	35.1	3.5
RAM cards	15.4	2.9	22.7	3.6	34.3	4.6	45.0	6.1	84.4	10.7	15.4	1.2	95.0	9.6
Connectors[c]	49.0	9.2	36.4	5.8	81.2	10.9	47.9	6.5	93.0	11.7	112	8.9	69.8	7.0
Timer/battery	6.8	1.3	11.1	1.8	5.4	0.7	9.0	1.2	2.9	0.4	3.8	0.3	3.8	0.4
Other[d]	27.7	5.2	22.4	3.6	17.5	2.4	15.7	2.1	37.1	4.7	92.1	7.3	51.0	5.1
Separation loss[e]	6.8	1.3	21.4	3.4	4.0	0.5	7.6	1.0	5.6	0.7	24.0	1.9	10.3	1.0
Total	530	100	626	100.0	742	100.0	741	100.0	792	100.0	1,260	100.0	993	100.0

[a]The suffix number indicates the source PC of the motherboard; MB-1 indicates that this motherboard was from PC-1, etc.

[b]Not available.

[c]Peripheral connectors, IDE cable connectors, and small sockets.

[d]Capacitors, resisters, and small, unidentified items.

[e]Loss of some solder and small items during separation of the motherboard.

Table 4. Total Contents of Eight Heavy Metals in Boards, IC Packages, and CPUs on Different Motherboards

Component	Source motherboard[a]	Content (mg/kg)[b]							
		Ag[c]	As	Ba	Cd	Cr	Hg	Pb[d]	Se
The board	MB-1	54±5	<8.2	37±4	<8.2	<8.2	<0.44	16,000	<8.2
	MB-2	<8.2	<8.2	71±7	<8.2	<8.2	<0.44	17,000	<8.2
	MB-3	<7.9	<7.9	110±15	<7.2	<7.2	<0.49	24,000	<7.9
	MB-4	<9.4	<9.4	43±4	<9.4	<9.4	<0.34	18,000	<9.4
	MB-5	<9.4	<9.4	56±6	<9.4	<9.4	<0.34	12,000	<9.4
	MB-6	13±3	<8.4	43±4	<8.4	<8.4	<0.34	16,000	<8.4
	MB-7	<10	<10	1,100±300	<10	<10.0	<0.47	26,000	<10
IC package	MB-1	2,900	<5.3	<5.0	<5.3	12±3	<0.44	6,300	<5.3
	MB-2	3,900	<5.0	<5.1	<5.0	<5.0	<0.44	6,200	<5.0
	MB-3	3,600	<5.1	<5.1	<5.1	13±3	<0.49	6,300	<5.1
	MB-4	1,600	<5.1	<5.1	<5.1	<9.4	<0.34	6,900	<5.1
	MB-5	820	<5.1	<5.1	<5.1	<5.1	<0.34	6,100	<5.1
	MB-6	1,800	<5.1	<5.3	<5.1	<8.9	<0.34	7,600	<5.1
	MB-7	1,900	<5.1	<5.0	<5.1	48±5	<0.47	7,500	<5.1
CPU[e]	Pentium III	<5.1	<5.1	<5.0	<5.1	<5.1	<0.44	630±60	<5.1
	Pentium II	420±40	<5.1	<5.1	<5.1	<5.1	<0.45	4,700±500	<5.0
	Pentium MMX	360±30	<5.2	<5.1	<5.2	<5.2	<0.49	670±70	<5.2
	Pentium	3,500±400	<5.2	<5.1	<5.2	<5.2	<0.34	3,300±400	<5.2
	Intel 486 DX	6,800±600	<5.2	<5.1	<5.2	34±4	<0.34	<5.2	<5.2
	Intel 386	3,500±400	<5.2	<5.0	<5.2	<5.2	<0.47	<5.2	<5.2

[a]The suffix number indicates the source PC of the motherboard; MB-1 indicates that this motherboard was from PC-1, etc.

[b]The values after the "±" represent the standard deviations of the measurements.

[c]For the Ag contents in the IC packages, a pooled standard deviation of 350 mg/kg was obtained.

[d]For the Pb contents in the boards and in the IC packages, pooled standard deviations of 3,000 and 500 mg/kg were obtained, respectively.

[e]CPUs are distinguished by their types instead of MBs or PCs.

The highest content of Pb was found in the boards; at 95% probability level the average and the confidence interval (CI) were calculated to be 17,400±4,900 mg/kg(average±CI) for all the boards tested. At the same probability level, the average and the confidence interval of Pb contents in the IC packages were found to be 6,700±600 mg/kg. The Pb content in CPUs varied with the type. The CPUs of Intel 486 and lower contained little Pb while the CPUs of Pentium, Pentium II, and Pentium III contained 630–4,700 mg/kg of Pb with the highest being in Pentium II. The main source of Pb was the lead-based solder which was on the boards, precoated on the pins of the IC packages and CPUs, and inside the IC packages and CPUs connecting the pins and the wires from the IC chips (Harper 2000).

High contents of Ag were found in IC packages and CPUs, while very little was found in the boards. The content of Ag in the IC packages varied significantly, from 820 to 3,900 mg/kg. Most CPUs, except Pentium III, contain a high amount of Ag with the highest of 6,800 mg/kg in the Intel 486 CPU. The Ag mainly came from the eutectic, near-eutectic tin/lead/silver solders typically used in IC packages (Harper 2000).

Barium was found in the boards with a content ranging from 40 to 1,100 mg/kg. It was not found in IC packages and CPUs. The contents of other five contaminants As, Cd, Cr, Hg, and Se in all the components tested were very low with most being below the detection limits. Cr was found in some IC packages with the highest content of 48 mg/kg. It was not detectable in all the boards and most CPUs.

TCLP Results in General

The concentrations of Pb in the TCLP extracts of all the samples were found higher than the regulatory level of 5 mg/L. However, the concentrations of Ag and Ba in all the TCLP extracts were below the detection limit of 0.1 mg/L of the AA instrument.

For all the matrix spikes performed on each component group, a recovery between 90 and 110% was obtained. The results of the samples independently checked with the ICP-OES at Mississippi State University highly agreed with the results obtained with the AA spectrophotometer. The differences were within 5%.

TCLP Results of Motherboards

TCLP test was run on the ten groups of components from the motherboards. The average Pb concentrations in the TCLP extracts for different component groups are shown in Fig. 1. The bars in the figure indicate the confidence limits at 95% probability level. The boards of the motherboards produced the highest Pb concentrations in the TCLP extracts with an average of 410 mg/L. The Pb results for the IC packages, RAM cards, and other small elements were very close; the averages were 258, 225, and 260 mg/L, respectively. All kinds of the slots and connectors produced much lower Pb concentrations, ranged from 43 to 110 mg/L. The CPUs of Intel 486 and lower did not produce detectable Pb, while the CPUs of Pentium to Pentium III produced Pb concentrations as high as those from the IC packages with an average of 243 mg/L. The values for CPUs in Fig. 1

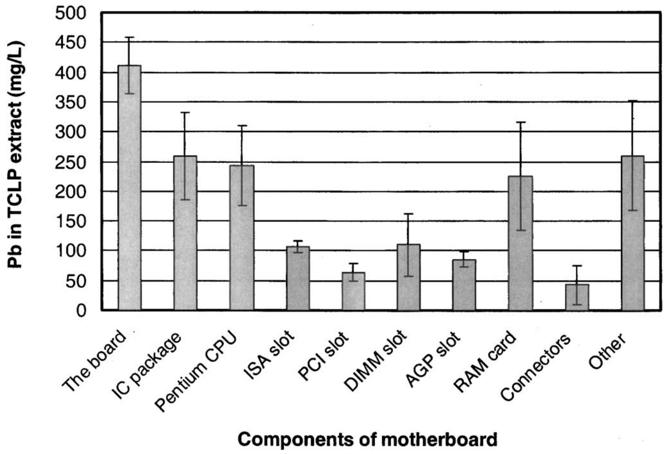

Fig. 1. Lead concentrations found in TCLP extracts of different components on seven different motherboards (results for CPUs were for CPUs of Pentium to Pentium III from four of the seven motherboards; error bars represent confidence limits at 95% probability level for samples of each component group)

(denoted as Pentium CPU) represent the concentrations in the TCLP extracts of the CPUs of Pentium to Pentium III from four of the seven motherboards studied.

Using the percentages of the weights for different components on the motherboards (Table 3) as the weight factors and assuming the Pb contents in the CPU radiator, the CPU housing, and the timer battery were negligible, the weighted average TCLP Pb concentrations of the seven motherboards were obtained as 245, 212, 237, 238, 196, 214, and 172 mg/L, respectively. These values are very close; the mean is 216 mg/L with a confidence interval of 26 mg/L at 95% probability level. This implies that the TCLP concentrations of Pb for most motherboards would be about 40 times higher than the regulatory level. The motherboards should be treated as hazardous wastes when being discarded or disposed of.

The total Pb contents in the boards and the IC packages of the motherboards were compared to the Pb concentrations in the corresponding TCLP extracts to find the leachabilities. Since the liquid-to-solid ratio of 20:1 was used in the TCLP extraction and the specific gravity of the extraction fluid was measured to be 1.00, the milligrams of Pb leached out from per kilogram of solid sample is equal to 20 times the Pb concentration in the extract. Therefore, the percentage of the leachable Pb is equal to the concentration (milligram/liter) in the TCLP extract times 20 and divided by the Pb content (milligram/kilogram) in the solid sample. Table 5 summarizes calculation results of the leachable Pb in the boards and the IC packages of the seven motherboards. The results show that approximately 50% of the Pb in the boards and 75% in the IC packages was leachable in the TCLP test.

Table 6. TCLP Pb Results for Different VCs, SCs, and NCs

Sample ID	Source PC	Overall Weight (g)	Pb in TCLP extract (mg/L)
VC-1	PC-1	159.3	588
VC-2	PC-2	92.5	243
VC-4	PC-4	185.2	318
VC-7	PC-7	79.1	220
VC-unk1	unknown	95.1	351
VC-unk2	unknown	63.6	311
Average±CI[a]	—[b]	—	338±144
SC-2	PC-2	118.4	165
SC-7	PC-7	92.0	194
SC-unk1	unknown	38.7	197
SC-unk2	unknown	35.7	138
SC-unk3	unknown	56.3	310
Average±CI	—	—	201±80
NC-2	PC-2	84.8	147
NC-4	PC-4	94.5	154
NC-5	PC-5	53.8	183
NC-7	PC-7	57.4	136
NC-ukn1	unknown	71.0	170
NC-unk2	unknown	65.0	126
Average±CI	—	—	153±23

[a]Confidence interval for the average at 95% probability level.

[b]Not applicable.

TCLP Results of Expansion Cards

The three major expansion cards including VCs, SCs, and NCs were tested by the TCLP. Since Ag and Ba did not show a detectable level in the TCLP extracts of all the motherboards, only Pb was analyzed for the expansion cards. Table 6 shows the TCLP results for these expansion cards. The overall weights of the cards were also measured as given in the table. The VCs generally leached more Pb in the TCLP test than the SCs and the NCs. The average Pb concentration in the TCLP extracts was about

Table 5. TCLP-Leachable Pb from Boards and IC Packages of Different Motherboards

	The board			IC package		
Motherboard	Total Pb (mg/kg)	TCLP Pb (mg/L)	Leachable Pb (%)	Total Pb (mg/kg)	TCLP Pb (mg/L)	Leachable Pb (%)
MB-1[a]	16,000	393	49	6,300	247	78
MB-2	17,000	442	52	6,200	184	59
MB-3	24,000	385	32	6,300	243	77
MB-4	18,000	410	46	6,900	216	62
MB-5	12,000	358	60	6,100	200	66
MB-6	16,000	503	63	7,600	359	94
MB-7	26,000	387	30	7,500	362	97
Average±CI[b]	17,400±4,890	411±48	47±13	6,700±635	258±73	76±15

[a]The suffix number indicates the source PC of the motherboard; MB-1 indicates that this motherboard was from PC-1, etc.

[b]Confidence interval for the average at 95% probability level.

Table 7. TCLP Pb Results for PWBs of HDDs, FDDs, CDDs, and PSUs

Sample ID	Source PC	Overall weight (g)	PWB weight (g)	PWB fraction (%)	TCLP Pb for PWB (mg/L)
HDD-1	PC-1	488	51.2	10.5	284
HDD-2	PC-2	495	66.7	13.5	266
HDD-3	PC-3	506	31.7	6.3	210
HDD-4	PC-4	446	62.9	14.1	234
HDD-5	PC-5	502	55.7	11.1	214
HDD-6	PC-6	465	34.3	7.4	233
HDD-7	PC-7	488	30.7	6.3	199
FDD3-1[a]	PC-1	445	45.0	10.1	11
FDD3-2	PC-2	326	20.1	6.2	132
FDD3-3	PC-3	341	16.0	4.7	333
FDD3-5	PC-5	413	22.8	5.5	245
FDD3-6	PC-6	353	21.6	6.1	200
FDD3-7	PC-7	334	20.3	6.1	180
FDD5-2[a]	PC-2	984	87.4	8.9	56
FDD5-4[b]	PC-4	991	66.5	6.7	17
FDD5-unk1	unknown	1,300	118.5	9.1	277
FDD5-unk2	unknown	1,135	46.6	4.1	289
FDD5-unk3	unknown	928	59.8	6.4	288
CDD-7	PC-7	406	48.0	11.8	341
CDD-unk1	unknown	861	130.3	15.1	169
CDD-unk2	unknown	1,049	146.2	13.9	383
CDD-unk3	unknown	957	125.5	13.1	222
PSU-1	PC-1	693	142.5	20.6	293
PSU-2	PC-2	469	71.7	15.3	303
PSU-3	PC-3	676	111.3	16.5	270
PSU-4	PC-4	763	112.2	14.7	340
PSU-5	PC-5	684	62.6	9.2	203
PSU-6	PC-6	767	69.0	9.0	431
PSU-7	PC-7	699	93.0	13.3	280

[a]FDD3 and FDD5 indicate 3.5 in. and 5.25 in. floppy disk drives, respectively.

[b]This sample was a combo of a 3.5 in. FDD and a 5.25 in. FDD.

340 mg/L for the VCs, 200 mg/L for the SCs, and 150 mg/L for the NCs. These are 30–68 times the regulatory level. Therefore, all these cards should be considered as hazardous wastes when being discarded or disposed of.

TCLP Results of Disk Drives and Power Supply Units

The TCLP results of the PWBs of the HDDs, FDDs, CDDs, and PSUs are given in Table 7. The weight fraction of the PWB in each unit and the overall weight of each unit are also included in the table. The average fractions of PWBs were approximately 14% in both CDDs and PSUs, 10% in HDDs, 7% in 5.25 in. FDDs, and 6.5% in 3.5 in. FDDs. The Pb concentrations in the TCLP extracts ranged from 200 to 280 mg/L for the PWBs of the HDDs, 170 to 340 mg/L for the PWBs of the CDDs, and 200 to 430 mg/L for the PWBs of the PSUs. For the PWBs of the FDDs, the concentrations spread widely from 11 to 330 mg/L. It was noticed that the PWBs in FDD3-1, FDD5-2, and FDD5-4, which generated low concentrations of Pb in the TCLP extracts, consisted of steel boards. The iron (Fe) in the steel boards could have competed with Pb in the dissolving reactions and led to low Pb levels in the extracts.

Conclusions

Among the eight heavy metal elements Ag, As, Ba, Cd, Cr, Hg, Pb, and Se on the EPA D list, Pb is the predominant one that causes the toxicity characteristic of PC components. Although Ag exists in large amounts in most IC packages and CPUs and Ba exists in certain amounts in some boards, they are not leachable under the TCLP test conditions and do not pose toxicity characteristic hazards. The other five elements are very insignificant in total contents and do not have the potential to cause a toxicity characteristic concern.

The board and the IC packages of a motherboard contain, on the average, 17,400 and 6,700 mg/kg of lead, respectively, of which more than 50% can be leached out in the TCLP test. The Pb concentrations in the TCLP extracts of the vast majority of the PWBs range from 150 to 500 mg/L which is 30–100 times the regulatory level of 5 mg/L for classifying them as hazardous wastes. These are also much higher than the TCLP leaching of Pb from color CRTs (average 22 mg/L) as found in the previous study (Townsend et al. 1999).

The motherboard is the largest PWB in a PC and contributes 50–80% of the total lead leachable in the TCLP test of all the PC components containing PWBs. Therefore, proper handling and disposal of the motherboards in the obsolete PCs can significantly reduce the environmental impact.

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