

LEACHING OF LEAD FROM DISCARDED NOTEBOOK COMPUTERS USING THE SCALE-UP TCLP AND OTHER STANDARD LEACHING TESTS

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Abstract : The proper management of discarded electronic devices (often called electronic-waste) is an emerging issue for solid waste professionals throughout the world because of the large growth of the waste stream, and the content of toxic metals in them, most notably heavy metals such as lead. Notebook computers are becoming one of the major components of discarded computer devices and will continue to increase in the waste stream in the future. While the computers hold great promise for recycling, a substantial amount of this waste is often disposed in municipal solid waste (MSW) landfills. The toxicity characteristic leaching procedure (TCLP) is commonly used to simulate worse case leaching conditions where a potentially hazardous waste is assumed to be disposed along with municipal solid waste in a landfill with actively decomposing materials overlying an aquifer. The objective of this study was to examine leaching potential of lead from discarded notebook computers using the scale-up TCLP, other standard leaching tests such as California waste extraction test (Cal WET), and the synthetic precipitation leaching procedure (SPLP) and actual landfill leachates as leaching solution. The scale-up TCLP is a modified TCLP (where the device was disassembled and leached in or near entirety) to meet the intent of the TCLP. The results showed that the scale-up TCLP resulted in relatively high lead found in the leachate with an average of 23.3 mg/L. The average level was less than those by the standard TCLP and WET (37.0 mg/L and 86.0 mg/L, respectively), but much greater than those by the SPLP and the extractions with the landfill leachates (0.55 mg/L and 1.47 mg/L, respectively). The pH of the leaching solution and the ability of the organic acids in the TCLP and WET to complex with the lead were identified as major factors that controlled the amount of lead leached from notebook computers. Based on the results obtained by a number of leaching tests in this study, notebook computers may present a potential leaching risk to the environment and human health upon land disposal. However, further investigation is still needed to assess the true risk posed by the land disposal of discarded notebook computers.

Key Words : Electronic waste, notebook computer, lead, leaching, TCLP, WET, SPLP

INTRODUCTION

The management of electronic waste (often called E-waste) has been raised as an issue of major concern for the solid waste community around the

world. The advanced development of information technology and the growing consumer demand for cutting-edge electronic products in many developed countries have resulted in significant amounts of obsolete electronic devices that are disposed of. The devices include personal computers and peripherals, notebook (or laptop) computers, TVs, telephones, copy and fax machines, and audio/video equipment. Computer is one of the

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Table 1. Toxic hazardous chemical in notebook computer components

Toxic Chemicals	Components	Use
Antimony	Cabling	Stabilizer, flame retardants, combined with PVC
	Solder alloy	Printed wire boards
	Housing	Flame retardants, combined with PVC
Beryllium	Printed wire board, Relays, Switches	Copper-beryllium alloy Contact springs
Cadmium	Batteries (Ni Cd)	Power supply
	Cabling	Color pigment and plastic stabilizer
	Printed wire board	Surface finish, chip resistors, semiconductor
Hexavalent chromium	PVC housing	Stabilizer combined with PVC Decorative, hardener, housing
	Cabling	Anti-corrosion treatment
Lead	Tin-lead solder	Connect computer chips to printed wire board
	Cabling	Use as stabilizer in PVC cable
	Batteries in earlier notebook	Power supply, sealed lead-acid battery
Mercury	Fluorescent lamp	Back light for LCD
	Batteries	Power supply, switches,
PBBs (Polybrominated biphenyls), PBDEs (Polybrominated diphenyl ethers), TBBP-A (tetrabromobisphenol)	Printed wire board, Plastic cover housing, Keyboard buttons, Connectors, Cable	Flame retardants

major components in this waste stream. The management of obsolete computers upon disposal has become a major concern for environmental regulators in solid waste arena because of two reasons: the magnitude of the waste stream and the potential environmental impacts associated with the toxic chemicals found in most computers.

More than 300 millions personal computers were in use around world in 1998.¹⁾ In the US alone, it was estimated that approximately 20 million personal computers (approx. 7 million tons) became obsolete in 1998.²⁾ In 2005, more than 63 million personal computers are projected to be retired in the US.³⁾ In Canada, it is expected that approximately 23,500 tons of information technology equipment such as personal computers, notebook computers and peripherals will be disposed in 2005.⁴⁾ As US sales of notebook computers have significantly increased more than five times (from 2.0 millions to 10.5 millions) for the past decade,³⁾ the amount of discarded notebook computers would increase in the waste stream. In addition, the shortened life-time of recent notebook computers due to rapid advances in technology results in rendering formerly cutting-

edge notebook computers becoming obsolete at an increasingly rapid pace. For instance, the life-time of computer changed from 4-6 years in 1997 to 2 years in 2005.⁵⁾

A notebook computer consists of a larger number of components (central processing unit (CPU), monitor, and casing) with various sizes and shapes, some of which contain toxic hazardous chemicals such as lead, mercury, cadmium, hexavalent chromium, and brominated flame retardants. The CPU is composed of hard and disk drives, printed wire boards (also referred to as printed circuit boards) with integrated circuit chips, ferrous and non-ferrous metals, and a battery pack. The monitor contains a glass panel, a mercury-containing fluorescent lamp, and a printed wire board. Table 1 presents a list of toxic hazardous chemicals commonly found in components and their use in a notebook computer. Actual amounts of hazardous chemicals found in the components depend largely on a number of factors such as type of model, manufacturer, and manufactured date.

Lead is the element with known toxic properties that is found in large amounts in printed wire boards in a notebook computer. For example,

lead-based solder (typically a 63:37 ratio of tin to lead), which is used to attach electrical components to printed wire boards, represents the most common solder alloy used in the computer. The potential hazards and effects of lead on the environment and human health are well known in the literature. It is known to cause damage to brain and kidney in humans and is also identified as being a cause of mental retardation, especially for children. Lead can accumulate in the environment and has toxic effects on plants and animals.⁶⁻⁸⁾ Therefore, it is classified as one of priority toxic metals and currently becomes the subject of electronic industry efforts to reduce or eliminate its use in various materials in consumer electronics. In a recent study, color cathode ray tubes (CRTs) from televisions and computer monitors were found to leach enough lead to be toxicity characteristic (TC) hazardous wastes.⁹⁾ Recently, discarded color CRTs are thus considered TC hazardous wastes because of lead by the US Environmental Protection Agency (EPA).¹⁰⁾

Obsolete notebook computers are being rarely recycled and reused when retired. This is partly because notebook computers are typically assembled in a dense and complex form, resulting in demanufacturing them more difficult and costly. In addition, due to high costs and lack of consumer incentives, only a very small percentage of obsolete notebook computers are being refurbished and resold to consumers. Infrastructure of recycling the computers is not well-established around the world. Therefore, the computers are often being ended up with in storage, landfills, or incineration facilities. The disposal of the computers with the rest of the municipal solid waste (MSW) stream in a landfill may result in negative impacts on the environment (e.g., groundwater contamination by lead leaching, high concentrations of lead in landfill leachate). When the computers are combusted at incinerators, heavy metals become concentrated in the ash, limiting disposal and reuse options of ash. Since most of plastic materials in computers contain flame retardants that are mainly halogenated organic chemicals, toxic organic contaminants such as dibenzodioxins and dibenzo-

furans cannot be avoided during incineration and may exit through the stack to the surrounding area in the form of gaseous pollutants. Little is known regarding the extent that management of discarded notebook computers via traditional waste management systems such as landfills and incineration causes adverse impacts on the environment.

In this study, leaching characteristics of lead from notebook computers were examined by using several laboratory leaching tests. A number of leaching tests are currently available for examining leachability of pollutants from waste materials. The toxicity characteristic leaching procedure (TCLP) is one of the most commonly employed leaching tests when evaluating leaching risk of waste upon land-disposal (US EPA SW-846 method 1311).¹¹⁾ The TCLP is designed to simulate the leaching of contaminants from wastes disposed in a municipal solid waste landfill and also used for determining whether a solid waste is hazardous because of the toxicity characteristic (TC). Currently, discarded notebook computers are not listed hazardous wastes in the US. The known presence of heavy metals, especially lead, in discarded notebook computers raises the potential that the devices might be toxicity characteristic (TC) hazardous wastes, similar to color CRTs.

In California, Waste Extraction Test (WET) is used for simulating leaching potential of waste when land-disposed in a MSW landfill.¹²⁾ The primary difference between the WET and the TCLP is the choice of leaching fluid used to simulate the leaching potential of waste. While the TCLP uses acetate ion in the leaching fluid, citrate ion is used for the WET. An US EPA's Synthetic Precipitation Leaching Procedure (SPLP, US EPA SW-846 method 1312)¹³⁾ is also the commonly used leaching test method to assess the leachability of wastes disposed in inert landfills that do not contain large amount of biodegradable matter. Unlike the TCLP and WET, the leaching solution in this test is comprised of inorganic ions (sulfate and nitrate ions) to simulate slightly acidic rainfall. Municipal solid waste leachate (MSWL) from actual landfills as leaching

fluid has been also used to examine leaching potential from a number of solid wastes.¹⁴⁻¹⁶⁾

While the standard leaching tests above have been routinely performed on a larger number of solid waste materials, data regarding the leaching of pollutants from discarded notebook computers are not currently available. This may result partly from the difficulties in running the leaching tests for the computers. For the standard leaching test, it is required that solid waste materials should be size-reduced by crushing, cutting, or grinding to pass through the sieve (less than 0.95-mm diameter) before the test is performed. A whole device such as a notebook computer must therefore be ground, shredded, or cut to the particle size that is required. Unlike most wastes that either inherently meet the size requirement (e.g. ash, sludge) or exist in a homogeneous physical state that can be crushed or cut (e.g. cement-stabilized forms, wood), discarded notebook computers do not lend themselves to ready size reduction. In addition, selecting a 100-g representative sample of the entire device is a difficult task when performing standard leaching tests on notebook computers. Since a notebook computer is composed of different material types each with distinct physical properties (e.g. printed wire boards, plastics, metals, and wires/cables), selecting the materials to be tested is often left to the technician collecting the sample. Accordingly, human bias may be introduced into the sample collection process.

In order to overcome the difficulties in size reduction and representative sampling, a scale-up TCLP method has been used for this study. The objective in this case was to scale-up the size of the TCLP so that larger amounts of sample could be tested. By leaching an entire notebook computer, one gains the advantage of having a truly representative sample. The device is only disassembled without any further size reduction before the test is performed. Other requirements such as liquid to solid ratio and extraction fluid are maintained as does the standard TCLP.

In this study, both the scale-up TCLP and several standard leaching tests were performed

to examine leachability of lead from discarded notebook computers. The objective of the research was to gather information regarding how much lead would leach from notebook computers under scale-up TCLP conditions relative to standard TCLP. This paper was not intended to present the characterization leaching results of discarded notebook computers for limitations of the current US hazardous waste policy. Since no single study can characterize the myriad of different computer device models and manufacturers, much effort on the characterization should be made to provide a basis for attaining whether the device has a potential to be TC hazardous waste. In this study lead concentrations measured in the scale-up TCLP extracts were also compared with those from other batch leaching tests (the WET, the SPLP, and the extractions with MSW landfill leachates). Based on the results of the leaching tests conducted, this study also examined the factors that influence lead leachability from notebook computers. So far, only very limited data are currently available on the leaching of lead from discarded electronic devices.^{9,16,17)} A better understanding of lead leaching characteristics of electronic devices is helpful for assessing the degree of management options and regulation of such devices.

MATERIALS AND METHODS

Experimental methods include collection and characterization of discarded notebook computers, performance of leaching tests, and analysis of extracted leachates. Two separate experiments, Phase 1 and Phase 2, were performed. The Phase 1 experiment investigated the leaching of lead from a total of 18 discarded notebook computers under the scale-up TCLP conditions. The Phase 2 involved the evaluation of the leaching characteristics of lead from a total of six discarded notebook computers using the standard leaching tests and the extractions with actual landfill leachates.

Sample Collection and Preparation

In this study, a total of 24-discarded notebook

Table 2. Type and mass composition of discarded notebook computer

Sample	Manufacturer	Model	Year	PWB (g)	Metal (g)		Plastic (g)	Battery (g)	Others (g)	Total (g)	Type of TCLP
					Fe	Non-Fe					
A	COMPAQ	LTE 5000 (Series 2880B)	1998	487	359	465	875	622	49.4	2856	Scale-up [†]
B	COMPAQ	LTE 5280 (Series 2880G)	1998	399	136	362	1338	594	6.95	2836	Scale-up
C	COMPAQ	LTE lite 4/25 (Series 2810F)	1996	388	217	454	1309	519	60.2	2947	Scale-up
D	IBM	ThinkPad 9545	1995	494	133	360	1414	539	28.6	2968	Scale-up
E	NEC	VERSA m/100 (PC-580-6552)	1994	486	227	589	1353	504	43.7	3203	Scale-up
F	Toshiba	T1200 (PA7044U)	1994	959	575	37.1	1598	540	62.3	3772	Scale-up
G	Zenith	ZWL-184-97	1993	1140	729	332	1940	620	59.1	4820	Scale-up
H	Zenith	ZWL-625NL	1996	345	189	360	821	617	45.8	2377	Scale-up
I	Zenith	ZWL-625NL	1996	320	191	385	796	620	46.6	2358	Scale-up
J	AST	Premium Exec 386 SX/20	1994	414	361	245	1360	599	30.0	3009	Standard
K	COMPAQ	Contura Series, 4/25C (2820)	1996	585	92.0	335	1324	573	12.9	2922	Standard
L	DELL	325N	1994	440	197	276	1052	44.5	21.7	2031	Standard
M	IBM	ThinkPad 350c	1994	350	129	211	1502	569	16.6	2777	Standard
N	IBM	ThinkPad 9545	1995	362	133	329	1237	430	34.0	2524	Standard
O	NEC	VERSA m/100 (PC-580-6552)	1994	476	220	559	1388	504	16.8	3163	Standard

[†] Note. Two identical computer models were used during the scale-up TCLP.

computers (designated as #A through #O) were collected from individual donations, local electronics repair shops, and a local household hazardous waste collection facility. Table 2 presents the major components of the notebook computers and their mass composition. Significant heterogeneity and high complexity of components and materials in a computer (in terms of type, size, and shape) made it difficult to separate detailed categories. Thus, it was divided into five major material categories: printed wire board (PWB), plastic, metal (ferrous and non-ferrous), battery, and others (e.g., wire, glass, lamp, rubber). The brand, model type, and total weight of each computer were recorded. The computers were disassembled by the categories. Following disassembly, the total weight of each category was recorded to determine the computer composition. Larger mass fractions resulted from plastic materials, metals, battery, and PWBs (in order). On average, the plastic materials made up approximately 40% of the total weight of the computers (Figure 1). No preference was given in the selection of computers to any specific type, manufacturer, or age; manufacturing dates of the computers ranged from 1993 to 1998. Some of the computers tested (D and N, H and I) were identical models to used

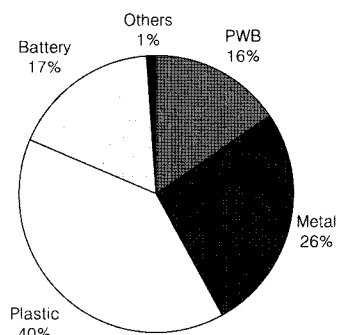


Figure 1. Average mass composition of notebook computers.

to examine the impact of computer component heterogeneity on metal leaching levels (Table 2).

Phase 1 - Scale-up Modified TCLP

A total of 18 discarded notebook computers (Samples #A through #I) were tested for the scale-up modified TCLP. The scale-up TCLP extraction process included placing a whole sample of two disassembled notebook computers as a pair into an high density polyethylene (HDPE) drum (approx. 208-liter), adding leaching solution (TCLP extraction fluid #1 pH 4.93 ± 0.05 prepared by 114 ml of glacial acetic acid and 129 ml of 10 N sodium hydroxide in 20 liters

Table 3. Protocols of leaching tests

	Scale-up TCLP	Standard Leaching Test			Extraction with MSW leachate
		TCLP	WET	SPLP	
pH of leaching solution	4.93 \pm 0.05 (acetic acid and sodium hydroxide)	4.93 \pm 0.05 (acetic acid and sodium hydroxide)	5.0 \pm 0.1 (citric acid and sodium hydroxide)	4.20 \pm 0.05 (sulfuric and nitric acids)	7.75 or 7.49
No. of Notebook Computers used	18	6	6	6	6
Solid to liquid ratio (gram of waste to liter of solution)	20:1	20:1	10:1	20:1	20:1
Leaching Time	18 hr	18 hr	48 hr	18 hr	18 hr

of de-ionized water) to the drum, and tumbling in a drum rotator (Morse 1-300 Series, Endover Drum Rotator, Morse Manufacturing, USA) at 13 rpm for 18 \pm 2 hrs. Rotation speed of the scale-up TCLP extractor was not expected to be a major factor, based on a preliminary experiment conducted on lead fishing weights in a standard TCLP extractor.¹⁸⁾ It should be noted that in each test two identical models of notebook computers were added to the drum to minimize headspace in the extractor. The mass of the sample added to the drum depended on the manufacturer of the notebook computer, ranging from 4,600 to 7,400 g. Liquid to solid (L/S) ratio was maintained at 20:1, however. For example, a 5,000-g notebook sample required 100 liters of extraction fluid. After rotation, a portion of the extract was taken to determine a final pH of the sample, and the extract was then filtered using a pressurized filtration apparatus with a 0.7- μ m pore size borosilicate glass fiber filter (Environmental Express TCLP filter). After filtration, the extract was digested using the US EPA method (SW-846 Method 3010A)¹³⁾ and analyzed for lead by the inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Thermo Jarrell Ash Corp. Model 95970: SW-846 Method 6010B).¹³⁾

Phase 2 - Standard Leaching Tests

Phase 2 involves the leaching of discarded notebook computers using the commonly used standard leaching tests. The standard leaching tests performed in this study included the TCLP, SPLP, and WET. In addition, the extractions

with actual MSW landfill leachates following the TCLP protocol were carried out to examine leaching potential of lead from the computers. Six notebook computers (Sample #J through #O) were selected and disassembled for Phase 2. Each component collected was size-reduced to less than 9.5 mm diameter using hand-held shears, as required by the standard leaching tests. The pieces of each size-reduced component was manually mixed and then stored in a 2-liter high-density polyethylene (HDPE) container. The "synthetic" mixture samples were prepared by mixing representative subsamples of each component. Since the total weight required for the standard leaching tests is 100 g, a synthetic mixture of 100 g was then created to match the mass composition measured for each computer with an exception for battery, as shown in Table 2. Battery in the computers was not included in Phase 2 due to the difficulties in cutting some of the materials affixed to the battery.

Table 3 summarizes the three standard leaching test protocols used as well as the extraction test protocol that utilized landfill leachates. While TCLP was performed in triplicate, SPLP and WET were leached one sample per run. The leaching tests using landfill leachates were run in duplicate. The following describes the leaching test protocols in more detail.

Standard Leaching Test Protocols- TCLP, SPLP, and WET

For the standard TCLP test a 100-g mixture sample reduced in size was loaded into an

extraction vessel (HDPE). Two thousand grams of extraction fluid (TCLP extraction fluid #1: pH 4.93 ± 0.05) were prepared using 11.4 mL of glacial acetic acid in 2 L reagent water with 128.6 mL of 1 N sodium hydroxide. The extraction fluid was added to a 2-liter extraction vessel to achieve 20:1 of L/S ratio. The sample was rotated at 30 ± 2 rpm for 18 ± 2 hrs in a 12-vessel rotary extractor (Analytical Testing Corporation). After rotation, the pH of extract was measured and the extract was filtered by following the same procedure as the scale-up TCLP.

The WET test is similar to the TCLP in that it uses a buffered organic acid solution as the extraction fluid. This test uses a pH-buffered citrate acid solution using sodium hydroxide, L/S ratio of 10:1, and a testing period of 48 hours. The WET extraction solution was prepared with a combination of 0.2 M citric acid solution and 4.0 N sodium hydroxide to pH 5.0 ± 0.1 . One liter of this solution was added to a 100-g size-reduced mixture sample in the vessel, as discussed in the TCLP, and rotated for a period of 48 hours. After rotation, the remaining procedure was the same as the TCLP.

The SPLP test was performed in the same manner as the TCLP and WET. The extraction fluid was made of two inorganic acids (nitric and sulfuric acid) to simulate slightly acidic rainwater. The prepared fluid was pH 4.20 ± 0.05 , which reflects the impact of air pollution due to heavy industrialization and coal utilization. In a similar fashion as for the TCLP, a 100-g mixture sample was placed in the extraction vessel and mixed with the extraction fluid. The mixture was rotated for 18 ± 2 hr at 30 ± 2 rpm. The leachate was then filtered and analyzed for lead analysis.

Leaching tests using MSW landfill leachates

The six notebook computers were also leached using the leachates collected from actual municipal solid waste (MSW) landfills (Site A and Site B) in Florida. Site A is a closed lined-MSW landfill which began receiving waste in 1988 and was

closed in 1996. Site B was open in 1996 and has been actively operating as a lined MSW landfill since 1997. The objective of the extraction using the landfill leachates was to examine lead leachability from discarded notebook computers under actual MSW landfill leachate conditions relative to other standard leaching tests. Leachates from the MSW landfills were collected from leachate collection sumps using Teflon bailers. Approximately 20 liters of leachate were also collected in a high density polyethylene (HDPE) container for leaching tests. The amount of headspace was minimized to reduce any potential oxidation of the collected leachate by filling the container as much as possible. The tests were carried out within 24 hours of collection to minimize possible changes in leachate characteristics.

Analytical Methods of Leaching Samples and Characteristics of Landfill Leachate

The samples collected from the scale-up TCLP and standard leaching tests were analyzed for lead. A blank sample of each test extraction fluid was also collected to determine lead. Samples were acid-digested following the US EPA Method 3010A. This method refluxes 100 mL of liquid leaching sample with repeated additions of nitric acid (HNO_3) and finally with hydrochloric acid (HCl). When the digestion was completed, the digestates were filtered through a Whatman 41 filter paper and the volume was raised to 100 mL by adding de-ionized water. Matrix spike samples were also digested with at least one set of spike and spike duplicate samples in every 15 samples. The digested samples were then analyzed for lead using the ICP-AES (US EPA Method 6010B).

After collecting the landfill leachates in the field, the samples were analyzed for various chemical parameters, including metals, soluble ions, alkalinity, total dissolved solids, and organic acids. The pH and oxidation reduction potential (Accumet portable AP10), dissolved oxygen (DO) (YSI Inc. Model 55/12 FT) and specific conductance (HANNA Instruments, Model H19033) were measured in the field. US EPA methods

Table 4. Chemical characteristics of landfill leachates

		Unit: mg/L				
Parameters		Site A	Site B		Site A	Site B
	pH	7.75	7.49	<u>Metal</u>		
	Conductivity (mS/cm)	18.7	10.7	Ag	<0.01	<0.01
	TDS (mg/L)	7140	4845	Al	0.045	8.3
	Alkalinity (mg/L as CaCO ₃)	6648	3735	As	0.02	0.108
	COD (mg/L)	2925	1925	Be	0.16	0.253
<u>Anions and cation</u>	Sulfide	0.213	0.09	Cd	<0.01	<0.01
	Chloride	1780	1009	Cr	0.04	0.17
	Sulfate	17.6	14	Cu	0.06	0.02
	Ammonia	1722	1009	Fe	0.25	5.74
	Calcium	51.8	108	Ni	0.15	0.17
	Potassium	582	312	Mn	0.15	1.06
	Sodium	1545	1370	Pb	<0.04	<0.04
				Zn	0.08	0.06
<u>Organic Acid</u>	Acetic acid	20.0	104.1			
	Propionic acid	8.5	48.0			
	Isobutyric acid	5.2	9.8			
	Butyric acid	<0.5	16.6			
	Isovaleric acid	<0.5	<0.5			
	Valeric acid	<0.5	<0.5			

and other standard methods were employed for the chemical analyses. For ion analysis, the samples were filtered through a 0.45- μ m membrane filter and analyzed by an ion chromatograph (Dionex DX-500). Metals in the leachate were determined by the ICP-AES after metals liquid digestion, as discussed above. Table 4 presents some of the parameters analyzed and the chemical characteristics of the leachates. The neutral pH values were observed from both landfill leachates, similar to other landfill leachates.¹⁹⁻²¹⁾ Major soluble ions found in the leachates at relatively higher levels include chloride, ammonia, calcium, potassium, sodium). Such ions are commonly produced as a result of the dissolution of soluble ions contained in landfilled wastes.¹⁹⁾ A number of metals were found in the leachates at relatively lower levels. It is known that strong chemical and biological reactions occurring in the actual landfills distinctively reduced heavy metal concentrations in the leachate.^{22,23)}

All glassware was soaked in 1:5 nitric acid and hydrochloric acid with water, and then rinsed with de-ionized water prior to use for laboratory analysis. All chemicals used were analytical grade.

Nano-pure water was used for preparation of all leaching solutions. During the leaching and analytical processes, quality assurance and quality control (QA/QC) samples such as laboratory blanks, sample spikes, sample duplicates, and calibration check samples were performed as appropriate.

RESULTS AND DISCUSSION

Results of Scale-up TCLP

A total of 18 notebook computers in pairs were leached by the scale-up TCLP. Lead results from the scale-up TCLP tests are presented in Table 5. Lead concentrations ranged from 14.6 to 34.5 mg/L, with an average of 23.3 mg/L. Lead may have resulted mainly from the leadsolder in printed wire boards in the computers. The scale-up TCLP lead concentrations among the samples varied slightly. This can be attributed to different composition of each sample during the test. For the same model and year of the samples (H and I) for determining redundancy, lead concentrations in the extracts were relatively close to each other (25.0 mg/L vs. 27.9 mg/L). All samples tested in the scale-up TCLP exceeded the toxicity characteristic

Table 5. Lead leaching results of discarded notebook computers using scale-up TCLP

Sample	Manufacturer	Model	Initial pH	Final pH	Pb (mg/L)
A	COMPAQ	LTE 5000 (Series 2880B)	4.93	5.15	17.2
B	COMPAQ	LTE 5280 (Series 2880G)	4.88	4.95	25.7
C	COMPAQ	LTE lite 4/25E (Series 2810F)	4.96	5.02	21.2
D	IBM	ThinkPad 9545	4.93	5.13	25.6
E	NEC	VERSA m/100 (PC-580-6552)	4.94	5.02	34.5
F	Toshiba	T1200 (PA7044U)	4.93	5.10	14.6
G	Zenith	ZWL-184-97	4.93	5.00	18.3
H	Zenith	ZWL-625NL	4.90	5.07	25.0
I	Zenith	ZWL-625NL	4.92	5.04	27.9
Average			4.92	5.05	23.3

hazardous waste limit for lead (5.0 mg/L).

Previous leaching studies have shown that the leaching behavior of lead is typically characterized by the greatest amount of leaching at low pH values, a minimum leachability observed at neutral pH values, and an increased degree of leachability at pH values above 11.²⁴⁻²⁹⁾ The pH of the leaching solution was measured after the scale-up TCLP was performed. The final pH values of the samples were found to be acidic (ranging from 4.95 to 5.15), with only slight increases noted from the original leaching solution (4.93 ± 0.05). This indicates that the acid neutralization capacity of the extracted leachates from the samples was minimal relative to the acidity of the TCLP fluid buffered with sodium hydroxide. When the lead concentrations were compared to final pH values to examine a possible relationship, no significant correlation was observed. This resulted partly from the very narrow ranges encountered among the final pH values. Other factors such as the presence of organic ions (acetate), oxidation-reduction potential, ionic strength, and adsorption to hydrous ferric oxide may have impacted the differences of lead leached among the samples. For example, acetate ion, a component of the TCLP leaching solution, chelates strongly with lead, resulting in enhanced dissolution and complexation of lead.^{23,30)}

Results of Standard Leaching Tests-TCLP, WET, SPLP, and MSW Leachate

Standard leaching tests and the extractions

with two municipal solid waste landfill (MSWL) leachates were performed on a 100-g sample of the "synthetic" component mixture to evaluate lead leachability from a notebook computer. A total of six notebook computers were used and tested for lead leachability. Lead results of the TCLP for the samples are shown in Table 6. Lead concentrations ranged from 11.4 to 86.2 mg/L, with an average of 37.0 mg/L. The lead concentrations varied, depending upon the sample. The final pH of all of the samples did not vary greatly and did not change greatly from the initial pH of 4.93. Relatively high concentrations of lead in TCLP resulted mainly from both acidic pH conditions and complexation of acetate ion with lead, as previously discussed in the scale-up TCLP result section.

In case of the WET, the lead concentrations varied greatly, ranging from 8.10 to 163 mg/L. The final pH values of all the samples slightly increased from the initial pH of 5.0. The use of citric acid in the WET coupled with lower pH values resulted in higher concentrations of lead from most of the samples. Citrate, a component of the WET leaching solution, is a tridentate ligand that chelates with metal ions such as lead.³¹⁾ The lead concentrations of two samples (K and M) of the WET were relatively low when compared to other samples. It is uncertain whether the mechanism for relatively lower concentrations of lead in the samples was precipitation or interference with other chemicals in the size-reduced mixture samples. Additional experimen-

Table 6. Lead leaching results of discarded notebook computers using standard leaching tests

Sample	Manufacturer	Model	TCLP ¹		WET ¹		SPLP ¹		MSWL Site A ¹		MSWL Site B ¹	
			Final pH	Pb (mg/L)	Final pH	Pb (mg/L)	Final pH	Pb (mg/L)	Final pH	Pb (mg/L)	Final pH	Pb (mg/L)
J	AST	Premium Exec 386 SX/20	5.02	11.4	5.23	51.4	7.21	< 0.1	7.74	0.23	7.34	1.45
K	COMPAQ	Contura Series, 4/25C (2820)	4.99	19.3	5.25	8.10	8.24	< 0.1	7.84	0.22	7.49	2.02
L	DELL	325N	5.16	41.5	5.18	135	6.25	0.72	7.62	0.56	7.43	3.05
M	IBM	ThinkPad 350c	4.98	26.9	5.16	10.3	8.27	< 0.1	7.65	0.10	7.43	3.30
N	IBM	ThinkPad 9545	4.99	86.2	5.18	163	7.00	< 0.1	7.69	0.26	7.43	2.90
O	NEC	VERSA m/100 (PC-580-6552)	4.96	36.5	5.14	149	6.60	0.37	7.66	1.08	7.37	2.46
Average			5.02	37.0	5.19	86.0	7.26	0.55	7.70	0.41	7.42	2.53

¹ Initial pH: TCLP=4.93 ± 0.05, WET=5.0 ± 0.1, SPLP=4.20 ± 0.05, MSWL Site A=7.75, MSWL Site B=7.49; Test runs in triplicate for TCLP, duplicate for MSWL, and single measurement for WET and SPLP.

tation using more WET samples with a more complete analysis is needed to determine the cause of the lower lead concentrations.

Lead in all the SPLP samples was either detected slightly above the detection limit or not found. The synthetic acid rain in the SPLP was not buffered; this resulted in an increase in pH (from initial pH of 4.20 to final pH values (6.25 to 8.24)) (Table 6). The unbuffered, neutral (or above neutral) pH of the SPLP along with the absence of chelating or complexing agents in the SPLP (unlike TCLP and WET) can be attributed to the lower lead concentrations in the SPLP extract.

The results of the extractions with two MSWL leachates (Site A and Site B) are also shown in Table 6. For both sites, MSW landfill leachates extracted less lead than those obtained with the TCLP and WET. A possible reason for less lead leached into the landfill leachate extracts is that neutral pH conditions as well as lower concentrations of organic acids found in the landfill leachates may have limited dissolution and complexation during the leaching test. The lead concentrations in the Site A extracts ranged from less than 0.1 to 0.71 mg/L, while the range of lead concentrations in the Site B extract was from 1.45 to 3.30 mg/L, with an average of 2.53 mg/L. The MSW leachate from Site B extracted lead significantly greater than that of the MSW

Site A ($\alpha=0.05$, p value <0.01). Several factors such as pH, organic strength, ionic strength, and species that might result in precipitation or adsorption (sulfides, hydroxides) can impact how a given leachate will extract lead. In this study, the pH values of both leachates fell within the neutral ranges of 7-8; the change in pH during the leaching test was minor, with only slight decreases noted from the original leachates. No correlation between pH and lead concentration was found as a result of the very narrow pH range encountered between the leachate samples. Difference in organic acids found in the landfill leachate may have resulted in different amounts of lead leached.^{32,33} Higher organic acid concentrations found in Site B may be attributed to extract more lead than Site A leachate by enhancing metal mobility due to complexation.

Comparisons of Scale-up TCLP Results to Standard Leaching Tests

Figure 2 presents a comparison of the average concentration of lead measured using the scale-up TCLP with the average concentrations measured using the TCLP, WET, SPLP, and the extraction with MSW leachate. The scale-up TCLP results represent an average of all nine samples (A through I: a total of 18 notebook samples-nine batches) tested, while the results of other leaching tests were averaged with six samples (J

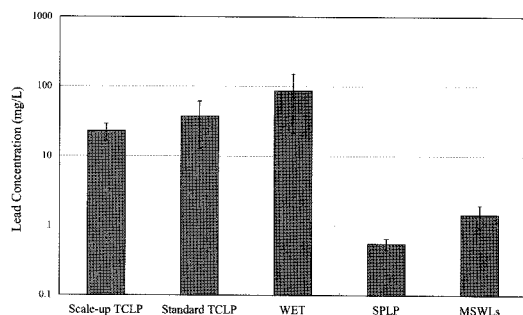


Figure 2. Comparisons of scale-up TCLP results to standard leaching tests.

through O: six notebook samples). The scale-up TCLP extracted less lead from the non-size-reduced notebook samples than did the standard TCLP. A possible contributing factor to the difference of lead results between the scale-up TCLP and the standard TCLP may be particle size. While the scale-up TCLP used the manual disassembly of notebook computer components without any further size reduction, the standard TCLP sample was size-reduced down to less than 9.5 mm that was required by the TCLP protocol. This reduction in size increased the specific surface area of the particles, which increased the leaching potential of lead. It is well-known that smaller particle size of waste materials leaches more pollutants than does the large particle size of waste material.^{27,34)}

When the average concentration of lead in the scale-up TCLP extracts was compared to that of the WET, the lead result of WET was higher than that that obtained with the scale-up TCLP. Citrate ion in the WET leaching solution is a tridentate ligand that chelates with metal ions such as lead, while the TCLP uses acetate ion in the leaching solution that is a monodentate ligand.^{35,36)} Therefore, the higher affinity of citrate ions in WET for lead complexation coupled with particle size effect may have resulted in higher levels of lead in the extracts than those in the scale-up TCLP and standard TCLP extracts. Increased leaching time (48 hr) when compared to the other leaching tests (18 hr) may have affected higher leaching levels of lead in the WET extracts unless the chemical equilibrium

was achieved. When comparing the scale-up TCLP results with those from the SPLP and the extraction with MSW leachates, a similar rationale can be used to explain the difference, as previously discussed. The higher pH values along with the absence of complexing agents resulted in the lower lead concentrations in the SPLP extracts and the extractions with MSW leachates.

Environmental Implications and Limitations

It should be recognized that the leaching tests performed here were not designed to simulate the leaching processes of lead from notebook computers under actual disposal conditions. Rather, the leaching tests, especially the TCLP and WET, are designed to simulate worse-case leaching conditions in a municipal waste landfill because the amount of acetic and citric acids in the TCLP and WET solution corresponds to the maximum amount expected to be produced under a given co-disposal scenario. The results of the scale-up TCLP, standard TCLP and WET showed that notebook computers leached lead at relatively high levels, much greater than the US Toxicity Characteristic limit for lead (5.0 mg/L). Thus, there is a potential for discarded notebook computers to be toxicity characteristic hazardous wastes. The disposal of discarded notebook computers with the rest of the MSW stream may result in measurable impacts on human health and the environment via leaching of lead. However, it is important to point out that a number of unknowns associated with the true impacts posed by disposal of notebook computers in MSW landfills still exist and should be further investigated. The unknowns may include changes in lead concentrations with respect to different landfill age (or stabilization phase of landfill: acetogenic phase vs. methanogenic phase), oxidation and reducing condition of a landfill, waste type, weather, landfill operation, and temperature. For example, young landfills often classified as being in the acetogenic phase (or acid phase) generate leachates containing relatively large amounts of volatile fatty acids, while biologically stabilized landfills often classified as being in the methanogenic phase contain leachates with

less fatty acids. For the reasons discussed previously, lead would tend to leach less in leachates from biologically stabilized old landfills. Although lead as the most abundant heavy metal in a typical notebook computer is the primary chemical of interest in this paper, discussion of the results of other toxic metals such as antimony, arsenic, beryllium, cadmium, copper, hexavalent chromium, and mercury would be valuable to evaluate potential leaching risks upon disposal.

CONCLUSIONS

Notebook computers are one of the common components of discarded electronic devices in the solid waste stream. The magnitude of the computers that are disposed of will continue to increase in the future and appropriate management of these devices needs to be addressed. Lead is largely found in printed wire boards in the computers, and may leach into the environment upon land-disposal. In this study, the scale-up TCLP test was used to examine lead leachability from discarded notebook computers. Several standard leaching tests and the extractions with actual MSW landfill leachates were also performed on the device. The objective of the research was to gather information regarding how much lead would leach from notebook computers under both the scaleup TCLP conditions and standard leaching test conditions. The results of the scale-up TCLP were compared to those of the standard leaching tests.

When a total of 18 notebook computers were leached using the scale-up TCLP, lead concentrations were found to be higher in the extracts with an average of 23.3 mg/L. Lead leached from several notebook computers at average concentrations of 37.0 mg/L and 86.0 mg/L from the TCLP and WET, respectively. These exceeded the US regulatory toxicity characteristic (TC) hazardous waste limit of 5.0 mg/L for lead, indicating that discarded notebook computers containing lead solder do possess a reasonable potential of being TC hazardous wastes for lead, as similar to color CRTs in the US. Other leaching tests, such as the SPLP and the extraction with MSW landfill

leachates, may provide valuable information regarding the leaching of lead from the computers because the results showed that the pH of the leaching fluid played a significant role of lead leaching. Among the factors influencing leaching of lead from the device, the factors believed to be most responsible for lead leaching from discarded notebook computers are the lower pH conditions in the TCLP and WET, and the propensity of lead to complex with the acetate and citrate ions in the fluids.

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