

Evaluation of a modified TCLP methodology for RCRA toxicity characterization of computer CPUs

Kevin Vann, Stephen Musson, Timothy Townsend*

Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611-6450, USA

Received 23 February 2005; received in revised form 2 August 2005; accepted 5 August 2005

Available online 12 September 2005

Abstract

A leaching method similar to the toxicity characteristic leaching procedure (TCLP) was designed and evaluated for testing of bulky wastes, such as discarded electronic devices. The objective was to meet the intent of the TCLP (same leaching solution, liquid-to-solid ratio and same leaching time) but to allow more representative and rapid testing. The procedure was evaluated by examining lead leaching from computer CPUs as a test case; disassembled CPUs were leached in their entirety (or close to entirety) in a large vessel using a drum rotator. The difference in rotation speed between the large-scale test and the TCLP was found to have no statistical impact on lead leaching. The lack of size reduction resulted in less reducing conditions than the standard TCLP (because of increased iron and zinc leaching), and this resulted in greater lead leaching. For electronic wastes with large amounts of steel, the large-scale procedure provides a more conservative estimate of TCLP lead leaching. The large-scale procedure greatly reduces sample processing effort but does increase the cost of analysis. Evaluation of this approach by the regulatory community is important as the CPUs tested here tended to leach lead at greater than the toxicity characteristic (TC) limit (5 mg/L) using the large-scale test, but less than the TC limit using the standard TCLP.

© 2005 Elsevier B.V. All rights reserved.

Keywords: TCLP; Lead; Computer; Toxicity; Leaching

1. Introduction

The growing need for cheap, reliable and efficient computing power has resulted in an increasing number of computer CPUs entering the municipal solid waste (MSW) stream. The National Safety Council estimated the number of personal computers becoming obsolete in the US between 1997 and 2007 at more than 20 million [1]. In the US, computer CPUs have the potential to be classified as Resource Conservation and Recovery Act (RCRA) toxicity characteristic (TC) hazardous wastes as they are known to contain elements, such as arsenic, barium, cadmium, chromium, lead, mercury and silver. Reports document that approximately 6.3% of a typical computer is composed of lead, a majority of which is attributed to the cathode ray tube (CRT) [2]. Lead also occurs in printed wire boards (PWBs); tin/lead solder (63% tin and

37% lead) is the most common solder alloy used in electronics today [3].

Although individual components encountered in electronic devices have been found to leach lead at concentrations greater than the RCRA TC limit (CRTs [4], PWBs [5,6]), the TC status of a device is impacted by the entire composition [7]. In order for generators to comply with existing US waste regulations, there is a need to determine the TC status of electronic devices such as computer CPUs. The TC status of a solid waste is determined by performing the toxicity characteristic leaching procedure (TCLP), a method developed by the US Environmental Protection Agency (USEPA) [8]. The TCLP was designed to simulate the plausible worst-case leaching scenario that might occur when a solid waste is co-disposed in a MSW landfill. Limitations to the TCLP have been identified [6,9–11], but the procedure remains the testing requirement that waste generators must follow.

Prescribed as part of the TCLP methodology are the sample mass (100 g), waste particle size (<0.95 cm),

* Corresponding author. Tel.: +1 352 392 0846; fax: +1 352 392 3076.
E-mail address: ttown@ufl.edu (T. Townsend).

liquid-to-solid ratio (20:1), speed of the rotary extractor (30 ± 2 rpm), time on the extractor (18 ± 2 h) and extraction fluid composition (glacial acetic acid and 1N sodium hydroxide; pH 4.93 ± 0.05). Within the bounds of the testing protocol, the analyst must determine how best to size reduce the waste and how best to collect a sample representative of the waste as a whole; this can prove difficult for bulky devices such as computer CPUs. Laboratory grinders commonly used for sample preparation are ill equipped to process large items and materials containing components having different mechanical properties (e.g., plastic versus steel). Electronic equipment recycling facilities often use large-scale industrial equipment (e.g., shear shredders) to size reduce electronic scrap; such equipment, however, is not readily available for routine testing and in most cases will not provide adequate size reduction for the TCLP. Manual size reduction using devices such as shears is an option, but it is difficult, time consuming and may introduce human bias into the sample preparation process. Selecting a representative sample can be difficult due to the various materials of differing properties that comprise discarded electronics.

The research presented in this paper was conducted in support of an effort to determine the likely TC status of a number of different types of discarded electronic equipment [12]. A leaching method was developed and tested to address the difficulty in applying the TCLP to bulky and heterogeneous waste materials. It was designed to represent a large-scale version of the TCLP in which an entire electronic device is placed into a large extraction vessel and leached; the TCLP requirements for liquid-to-solid ratio, extraction time and extraction fluid are maintained. The scaling of the TCLP for larger sample sizes [13] and smaller sample sizes [14,15] has been reported previously. The major difference between the testing protocol examined here and the TCLP is that the samples are not size reduced; devices are disassembled into primary components before leaching, but they are not further processed. It was hypothesized that (1) disassembled devices would be more representative of the condition that such devices would exist as when disposed in a landfill and (2) leaching concentrations for disassembled devices would be conservative (i.e., size reduced devices would leach more than disassembled devices). In this experiment, computer CPUs were examined as a test case, with lead investigated as the element of greatest concern.

2. Materials and methods

2.1. Sample collection and processing

Computer CPUs were collected from a demanufacturing facility and a local household hazardous waste collection center. A total of 43 personal computer CPUs were collected. Each CPU was completely disassembled and separated into five material categories to determine the CPU composition and total weight: PWBs, ferrous metals, nonferrous metals,

plastics and wires/cables. The manufacturer and model of each CPU is shown in Table 1. Forty of the collected CPUs were tested to compare the results between the standard TCLP and the modified large-scale TCLP. Three methods were performed on each of the eight CPU models collected: (1) a large-scale TCLP on disassembled CPUs, (2) a standard TCLP on samples of mechanically shredded CPUs and (3) a standard TCLP on manually size-reduced (i.e., hand cut) CPUs.

2.2. Standard leaching procedure: TCLP

Two techniques for conducting the standard TCLP, each meeting the requirements of the method, were performed on 23 of the CPUs. Eleven CPUs were shredded by passing the entire CPU through an industrial shear shredder located at an electronic equipment demanufacturing facility in Largo, FL and equipped with 5 cm blades (SSI Series 40H Model 2000-H). Since the materials did not meet the TCLP size requirement after passing through this shredder, each CPU was passed through a second shear shredder located at SSI Shredding Systems Inc. headquarters in Oregon, reducing the material nominally to 1.9 cm (SSI Series 22Q Model Q55ED(40)). The shredded CPUs were placed in plastic storage containers and transported to the laboratory. Six 100 g samples were collected from each CPU and placed on a 0.95 cm sieve. Any material that was retained on the sieve was further processed by manually size reducing (i.e., hand cutting) the pieces until they were capable of passing the 0.95 cm sieve.

Twelve CPUs were disassembled and portions of the five major material categories were selected at random. The materials were then manually size reduced (hand cut) using shears to a size capable of passing the 0.95 cm sieve; 100 g samples were created corresponding to the component distribution determined during sample collection and disassembly.

Each 100 g CPU sample was placed into a 2 L extraction vessel. Two liters of TCLP extraction fluid #1, which consists of 11.4 mL of glacial acetic acid and 128.6 mL of 1N sodium hydroxide solution diluted to 2 L with reagent water, was added to the extraction vessel. The initial pH of the TCLP extraction fluid was 4.93 ± 0.05 . Initial measurements of the pH, oxidation–reduction potential (ORP), and dissolved oxygen (DO) were recorded. All pH and ORP measurements were made using an Orion Model 710A+ benchtop meter equipped with an Orion Model 91-55 combination pH electrode and an Orion Model 91-79 ORP platinum triode. The pH probe and meter were calibrated with standard buffer solutions (4.0, 7.0 and 10.0) with a three-point calibration. The ORP probe and meter were calibrated using a reference standard (475 mV) in the relative millivolt (RMV) mode and all measurements were in RMV. Dissolved oxygen measurements were collected using an YSI Inc. Model 55 handheld dissolved oxygen meter. The samples were placed on a rotary extractor and rotated at 30 ± 2 rpm for 18 h. The leachates were then filtered through a $0.7 \mu\text{m}$ glass fiber filter using pressure filtration and preserved with nitric acid for metals analysis [16]. In addition to collecting the filtered leachate,

Table 1
Summary of computer CPU test methods

Manufacturer/model	Sample number	Standard TCLP mechanically shredded	Standard TCLP hand cut	Large-scale TCLP disassembled
Number of CPUs tested				
Sun Microsystems SPARK Station 2	1–8	3	2	3
Compaq ProLinea 4/66	9–12	2	1	1
IBM PS2 55SX	13–16	1	1	2
NCR 6020	17–20	1	2	1
Oli M4 Module M464	21–28	2	2	4
Network General Sniffer Server	29–32	1	1	2
AT&T Globalyst 550	33–36	1	2	1
Compaq Prlinea 4/33	37–40	0	1	3
Total		11	12	17

samples of unfiltered leachates were also collected and preserved to determine possible differences by filtration.

2.3. Modified leaching procedure: Large-scale TCLP

The modified TCLP was performed by leaching an entire computer CPU using a large-scale version of the TCLP method. A 55 gal extraction vessel (high density polyethylene (HDPE) drum) was placed on a Morse 1-300 Series, Endover Drum Rotator (Morse Manufacturing, East Syracuse NY) and a sufficient volume of TCLP extraction fluid #1 was added to the drum to maintain a 20:1 liquid-to-solid ratio. For example, a 10 kg CPU required 200 L of extraction fluid. The maximum sample mass possible for the large-scale TCLP was 10 kg due to volume limitations of the extraction vessel. For samples larger than 10 kg, representative fractions by weight of each material type were chosen at random to obtain a 10 kg sample.

The extraction fluid was mixed by rotating the solution on the drum rotator. Initial measurements of the pH, oxidation–reduction potential and dissolved oxygen were recorded. The disassembled CPU was placed into the extraction fluid and rotated end-over-end at a speed of 13 rpm for 18 h. After rotation, samples were obtained from the bottom of the extraction drum and the final pH, DO and ORP of the leachates were measured. Filtered and unfiltered TCLP leachates were collected and preserved using the identical procedures used in the standard TCLP.

2.4. Digestion and analysis of leachates

Although lead was the primary metal of concern, other studies have shown that the presence of iron and zinc can affect the resulting lead leachate concentration [17]. Therefore, analysis of lead, iron and zinc were performed by digesting the samples using the hotplate acid digestion procedure (USEPA Method 3010A) [16]. The digested samples were then analyzed using USEPA Method 6010B (Inductively Coupled Plasma-Atomic Emissions Spectrometry) on a Thermo Terrell Ash Trace Analyzer ICP [16].

2.5. Impact of extractor speed

The TCLP requires the rotation of the samples at 30 ± 2 rpm. However, the rotator used in the large-scale TCLP was only capable of 13 rpm. To determine the impact of the slower extractor speed on lead leachability, three samples of a “synthetic” CPU mixture were tested at 0, 13 and 28 rpm using the standard TCLP (USEPA Method 1311) [16]. Samples of 100 g were prepared by manually size reducing (i.e., hand cutting with shears) a “synthetic” CPU mixture to pass through a 0.95 cm sieve [16]. Five additional CPUs were collected at random to create the synthetic CPU mixture. Approximately 500 g of PWB, 240 g of plastic, 2200 g of ferrous metal, 170 g of nonferrous metal and 100 g of wires were randomly selected from each of the five CPUs. Each material type was combined and mixed. The “synthetic” CPU samples were prepared by mixing the differing material types to match the component composition determined previously. Thus, each 100 g sample was comprised of 15.8 g of PWB, 7.5 g of plastic, 68.2 g of ferrous metal, 5.4 g of nonferrous metal and 3.1 g of wires/cables. Three samples and a blank were tested for each of the rotation speeds (0, 13 and 28 rpms). The samples were prepared, rotated, filtered and preserved as previously described.

2.6. Time studies

A series of tests were conducted to investigate lead leachability from CPUs as a function of time for the large-scale TCLP method. The standard TCLP was developed under the assumption that the leaching solution chemistry would be at equilibrium after approximately 18 h. Since the CPUs were not size reduced, the time tests were conducted to assess when equilibrium conditions at the larger particle size of the waste (relative to standard TCLP) would be obtained. Three CPUs, two of which were identical models, were leached in the large-scale vessel for approximately 90 h. Throughout the testing period, 2 L of leachate were collected approximately every 9 h for analysis. Fresh extraction fluid was not added to replace the sample, thus the liquid-to-solid ratio of the sample gradually decreased below 20:1 over the period of the experiment. However, the ratio was greater than 19:1 after 90 h.

Samples were collected of filtered and unfiltered leachate and preserved using the prescribed procedure as before.

3. Results

3.1. Impact of extractor speed

Although the TCLP requires samples to be rotated at 30 ± 2 rpm, the large-scale TCLP extractor was only capable of 13 rpm, requiring determination of the change in speed on test results. Results of the extractor speed study are presented in Fig. 1. A Student's *t*-test ($\alpha = 0.5$) performed on the results indicated that lead and iron concentrations in the standard TCLP leachate were not significantly different between the samples rotated at 28 rpm and the samples rotated at 13 rpm. Therefore, the speed of the large-scale extractor was concluded not to be a factor.

Results also showed that the lead concentration measured in the TCLP leachate was significantly higher in the sample that was not rotated (0 rpm). Conversely, the iron concentration in the 0 rpm sample was significantly lower (Student's *t*-test, $\alpha = 0.05$). The impact of iron and zinc leaching from the steel content of the computer CPUs was recently examined [7] and this impact will be discussed throughout this paper. In the rotation speed experiment, lead ions, normally oxidized in the TCLP solution to the divalent Pb^{2+} , were reduced to metallic lead by iron and zinc in the leachate, thus decreasing the amount of lead released [17]. In the 0 rpm sample, it is thought the lack of mixing allowed an oxidation layer to form on the iron, decreasing the amount of iron available and increasing the quantity of lead entering the solution.

3.2. Time studies

The lead and iron results of the large-scale TCLP time studies are presented for three different CPUs in Fig. 2. This figure also provides a comparison of the filtered and unfiltered leachate results. In all three runs, the leachate samples were visually observed to change from an initial gray color

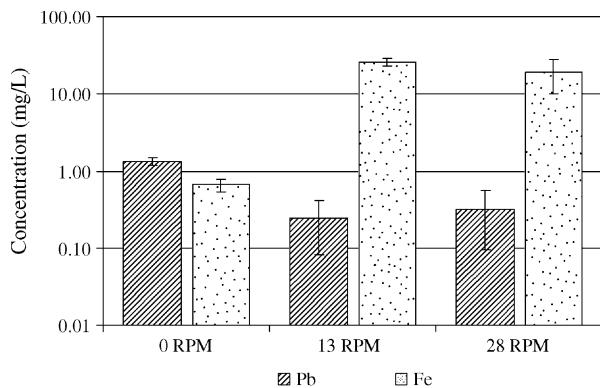


Fig. 1. Impact of rotation speed results.

to an orange (rust) color as time progressed, an indication of iron oxidation. The lead concentrations measured in the filtered leachates ranged from 1 to 10 mg/L, while the iron concentrations ranged from 13 to 341 mg/L. The zinc concentrations in the filtered leachates varied between 116 and 167 mg/L and did not change greatly with time. The highest lead concentrations (6–10 mg/L) measured in the filtered leachates occurred between 18 and 27 h of rotation. After 27 h the lead concentration decreased below the 5 mg/L TC limit, but did begin to increase again over time. Iron concentrations in the filtered leachates increased with time and peaked between 45 and 60 h at concentrations ranging from 292 to 341 mg/L. After approximately 60 h, the iron concentrations in all three samples decreased somewhat during the remainder of the experiment.

The pH of the TCLP leachate measured in Samples 1, 2 and 3 peaked between 45 and 60 h of rotation with values of 5.47, 5.42 and 5.44, respectively. After 60 h the pH tended to decrease with time to values ranging from 5.22 to 5.30 at approximately 90 h. The ORP of the leaching solution fluctuated throughout the study and peaked between 9 and 27 h, ranging from 55 to 153 RMV. Measurements indicated that the TCLP leaching fluid in the large-scale vessel remained an oxidizing environment during the duration of the experiment.

In the same fashion as has been reported by Kendall [17] for the impact of added iron waste to lead-bearing foundry sand, it is believed that the initial lead leachability was dominated by the oxidation–reduction process. Lead leaching was affected by the preferential oxidation of metallic iron and zinc in the solution. As time progressed beyond approximately 30 h, lead leachability was impacted by adsorption to hydrous ferric oxide (HFO); iron continued to oxidize and form HFO, which adsorbed the Pb^{2+} in solution. This allowed additional lead to leach into solution as evidenced by the relatively constant lead concentrations measured in the filtered leachate samples. The lead adsorbed to the HFO was removed during the filtration process, and as time increased, the difference in the lead and iron concentrations between the filtered and unfiltered samples increased. Zinc concentrations measured in the filtered and unfiltered samples did not greatly differ, which indicated that zinc was not adsorbed; this follows previous work that shows that zinc is not significantly adsorbed to HFO at pH values below 7 [17].

3.3. Comparison of standard TCLP and large-scale TCLP

Results of the TCLP method comparison are presented in Table 2. The lead concentrations measured in all of the leachates ranged from 0.2 to 21.4 mg/L with 14 of the 40 CPUs tested exceeding the 5 mg/L TC limit. Of the 14 CPUs that exceeded the TC lead limit, 13 were tested using the large-scale TCLP method and one was tested using the standard TCLP method (shredded). Shredding the CPUs did not greatly impact the lead concentration in the leachate when

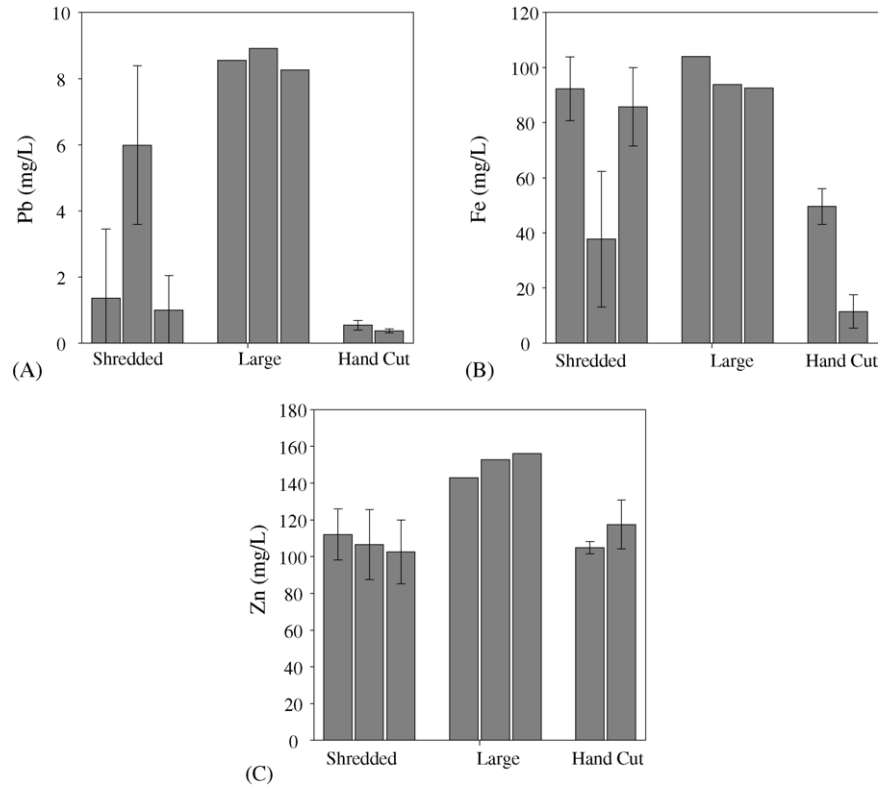


Fig. 3. Metal concentrations from method comparison for Sun Microsystems CPU (A) lead concentration, (B) iron concentration and (C) zinc concentration.

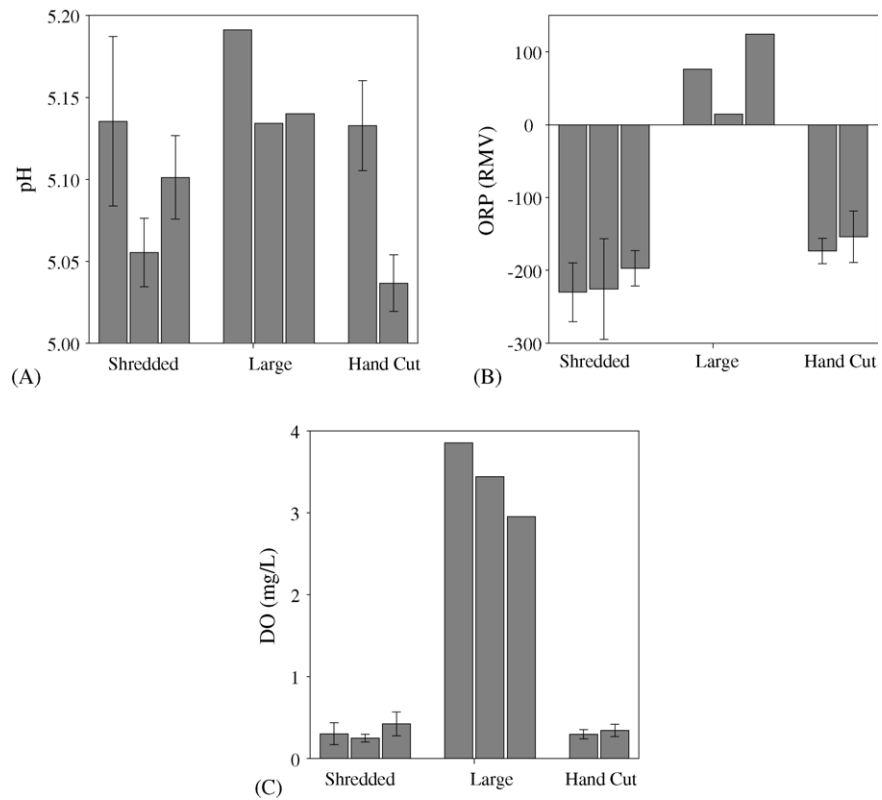


Fig. 4. Laboratory measurements from method comparison for CPU #1–8: (A) Final pH, (B) final ORP and (C) final DO.

Table 2
TCLP leachate concentrations for differing methods

CPU	Processing method	TCLP method	Lead (mg/L)	Iron (mg/L)	Zinc (mg/L)
1	Shredded	Standard	1.4	92	112
2	Shredded	Standard	6.0	38	107
3	Shredded	Standard	1.00	86	103
4	Disassembled	Large-scale	9.0	104	143
5	Disassembled	Large-scale	9.0	94	153
6	Disassembled	Large-scale	8.0	93	156
7	Manual	Standard	0.5	50	105
8	Manual	Standard	0.4	11	118
9	Shredded	Standard	1.1	106	84
10	Shredded	Standard	0.9	85	122
11	Disassembled	Large-scale	5.5	255	128
12	Manual	Standard	0.3	18	147
13	Shredded	Standard	3.2	84	128
14	Disassembled	Large-scale	21.4	117	81
15	Disassembled	Large-scale	16.4	132	92
16	Manual	Standard	2.3	20	147
17	Shredded	Standard	1.0	119	99
18	Disassembled	Large-scale	9.5	127	103
19	Manual	Standard	0.4	24	130
20	Manual	Standard	0.5	31	122
21	Shredded	Standard	3.6	96	43
22	Shredded	Standard	1.5	136	52
23	Disassembled	Large-scale	5.3	65	21
24	Disassembled	Large-scale	3.1	24	33
25	Disassembled	Large-scale	15.5	131	27
26	Disassembled	Large-scale	4.0	62	34
27	Manual	Standard	0.3	5	172
28	Manual	Standard	3.1	59	115
29	Shredded	Standard	1.3	111	111
30	Disassembled	Large-scale	0.6	44	99
31	Disassembled	Large-scale	0.5	50	101
32	Manual	Standard	0.3	35	106
33	Shredded	Standard	0.5	147	111
34	Disassembled	Large-scale	9.1	189	114
35	Manual	Standard	0.2	6	168
36	Manual	Standard	0.1	19	129
37	Disassembled	Large-scale	8.4	201	215
38	Disassembled	Large-scale	7.1	253	160
39	Disassembled	Large-scale	6.6	267	134
40	Manual	Standard	0.5	44	220

in the large-scale TCLP test was more oxidizing than the leachate of the standard TCLP.

The difference between the standard TCLP and the large-scale TCLP can be explained by understanding the oxidation/reduction capabilities of metallic iron, zinc and lead. The electrode potentials, with respect to the oxidization of the metal to divalent ions of zinc (-0.76 V) and iron (-0.44 V) are higher than lead (-0.126 V), which means that both metallic zinc and metallic iron can reduce Pb^{2+} ions that are leached into solution [18]. As iron is oxidized, it consumes dissolved oxygen and hydrogen ions (H^+), causing the TCLP solution to become more reducing and increasing the solution pH [18]. The fact that pH did not change greatly in these experiments is likely a result of the buffered nature of the TCLP solution.

In the standard TCLP, the CPU components were decreased in size. Size reduction of the components greatly

increased the surface area of the steel exposed to the leaching solution. In addition, since the steel in a computer tends to be coated with a thin galvanizing layer of zinc, the size reduction process resulted in more raw steel (iron) being exposed to the leaching solution. The size reduction step likely had only a minimal impact on creating more surface area for lead leaching, as the initial size of tin-lead solder on the PWBs was small. The additional iron and zinc exposed to the leaching solution caused the TCLP leaching environment to become more reducing, consuming the DO and H^+ and lowering the ORP, which reduced lead leachability. This was observed by the negative ORP measurements and the greater DO consumption in the samples that were tested using the standard TCLP.

The leachates of the large-scale TCLP were more oxidizing than the standard TCLP as evidenced by the positive ORP measurements and relatively higher DO concentrations. In the large-scale procedure, solution preparation introduced more dissolved oxygen into solution by mixing the TCLP solution in the vessel. Additionally, the components were not sized reduced, limiting the amount of iron and zinc exposed to the solution. To verify the effects of the size reduction upon the solution ORP and DO, samples of the shredded CPUs were leached in the large-scale apparatus and the ORP and DO recorded. The final leachates of the shredded CPU's tested in the large scale device were lower in both ORP and DO (-102 RMV; 1.30 mg/L) when compared to disassembled CPUs leached in the large scale device (-2.6 RMV; 3.03 mg/L), supporting the concept that the greater the iron surface area, the greater the impact on oxidation–reduction chemistry of the solution.

Analysis of the unfiltered samples indicated that the lead, iron and zinc concentrations did not greatly differ from the concentrations measured in the filtered samples during both TCLP methods evaluated in this study. This indicated that although the large-scale TCLP produced a more oxidizing environment, lead leachability was not impacted by adsorption by hydrous ferric oxide. This was expected since the time study results indicated that adsorption by hydrous ferric oxide did not occur until after 30 h of rotation.

4. Discussion

The standard TCLP method has requirements that often make it difficult to perform on electronic devices, such as size reduction and mass of the sample being tested. The largest issue with performing the TCLP on electronic devices is obtaining a representative size-reduced sample of the device. In addition, size reducing an electronic device such as a CPU is difficult due to the large bulky nature of the components. CPUs, for example, are composed of a high percentage of steel and other metals that are difficult to cut or grind. The use of industrial shredders for processing electronic devices is not practical because they often lead to sample loss and cross contamination, in addition to not meeting the size requirements.

Manual size reduction (i.e., hand cutting) using small-scale laboratory equipment is the only reasonable option; this is difficult and very time consuming. It is often left to the technician that is performing the test to select the components and to process them for testing, which can introduce human bias into the results.

A modified procedure was developed to allow testing of an entire device by scaling up the TCLP. The intent was to design a procedure that met the basic intent of the TCLP but would permit more representative testing. Several advantages to using the proposed large-scale TCLP for testing of devices such as CPUs are evident. The modified procedure allows an entire electronic device to be tested (or nearly an entire device). This reduces possible analyst bias introduced when collecting the sample and processing it for testing, and results in a sample more representative of the device as a whole. As demonstrated here and in a related study [7], even components that do not contain the toxic element of interest can have a notable effect on TCLP results for that element. The method is clearly advantageous with respect to the time and effort of processing a given sample.

It is important to recognize that the large-scale method is not the TCLP; it is a different test designed to meet the intent of the TCLP. The leaching solution, liquid-to-solid ratio and leaching time are maintained the same as the standard procedure. The rotation speed differs, but this was found to be inconsequential. A greater sample mass is used, but this is matched by a greater leaching solution volume; the use of larger sample masses has precedent [13]. The largest departure from the defined TCLP methodology is the lack of size reduction. The results indicate that size reduction of computer CPUs does have an impact, but one different than that first hypothesized. In most cases smaller particle sizes (with increased surface area) result in greater leachate concentrations; in this case, the size reduced CPU samples created more reducing conditions in the leachate (due to increased iron and zinc leaching) which resulted in lower dissolved lead concentrations. Additional factors for consideration are the increased dissolved oxygen levels within the large-scale rotator and its head space, proven to be a factor in prior research by the authors [7].

The use of the large-scale method should result in greater lead concentrations than the standard TCLP for wastes of similar characteristic. The opposite phenomenon might be observed for other waste types and other elements (i.e., greater leachability using the standard TCLP); testing of additional waste types should be conducted. The utility of the method is thus somewhat dependent on how it will be interpreted by regulatory agencies. One could certainly argue that since test conditions are not the same, test results for the modified procedure cannot be substituted for those obtained using the standard procedure. On the other hand, one could also argue that if the intent of the TCLP is to identify those wastes with a potential to leach elements of concern to human health and the environment, the large-scale testing protocol provides a more conservative estimate for these wastes. The TCLP

does not specify oxidizing or reducing conditions; this can be controlled within the framework of the test to some extent by changing the head space volume or composition, which can thus have an impact on leaching results [11,19]. The reducing conditions in the small scale test of computer CPUs are an artifact of the particular waste composition. Since the TCLP does not provide a minimum particle size, a generator could in theory continue to reduce TCLP lead concentrations of a waste by even more aggressive size reduction.

The authors conclude that the large-scale testing procedure provides value in that it allows testing of devices that would otherwise prove too difficult to examine without great effort and expense. Recent work (to be reported elsewhere) is using the large-testing protocol as part of a study examining the TC of a variety of electronic devices. The acceptance of the results of the large-scale test by the regulatory community remains to be seen. Aside from the potential regulatory significance of this work, the results add to the current understanding of the TCLP and its limitations for some waste streams and elements.

5. Conclusions

A modified leaching procedure was designed to meet the intent of the TCLP but to allow more representative sampling of bulky, heterogeneous wastes such as electronic devices. The procedure was evaluated by examining lead leaching from computer CPUs as a test case. The primary differences between the large-scale test and the standard TCLP were the sample size, the rotation speed and sample processing. The larger sample size was considered a benefit because it permitted a more representative sample to be tested; the liquid-to-solid ratio was maintained the same as the TCLP. The rotation speed difference was determined to have no statistical impact on lead leaching. The lack of size reduction resulted in less reducing conditions than the standard TCLP (because of increased iron and zinc leaching), and this resulted in greater lead leaching. For electronic wastes with large amounts of steel, the large-scale procedure provides a more conservative estimate of TCLP lead leaching. The large-scale procedure greatly reduces sample processing effort but does increase the cost of analysis.

Acknowledgements

This research was sponsored by Regions 4 and 5 of the US Environmental Protection Agency (USEPA). Special thanks are extended to Pamela Swingle of the USEPA Region 4 and Ray Moreau of the Southern Waste Information eXchange (SWIX). Special thanks are also extended to Kurt Seaburg of Alachua County Household Hazardous Waste Center, Secure Environmental Electronic Recycling (SEER), and James Wood of RecycledPCParts.com, Inc. for providing CPUs. Thanks to Concurrent Technologies Corporation

for shredding the CPUs that were tested during the research. The following students assisted with this project: Sarvesh Mutha, Brajesh Dubey, Lakmini Wadanambi and Pradeep Jain.

References

- [1] National Safety Council (NSC), Electronic Product Recovery and Recycling Baseline Report: Recycling of Selected Electronic Products in the United States, National Safety Council's Environmental Health Center, Washington, DC, 1999.
- [2] Microelectronics and Computer Technology Corporation (MCC), Electronics Industry Environmental Road Map, Document No. MCC-ECESM-001-96, Austin, Texas, 1996, pp. 249.
- [3] Nordic Council of Ministers (NCM), Waste from Electrical and Electronic Products: A Survey of the Contents of Materials and Hazardous Substances in Electric and Electronic Products, TemaNord Copenhagen, Denmark, 1995.
- [4] S. Musson, Y. Jang, T. Townsend, I. Chung, Characterization of lead leachability from cathode ray tubes using the toxicity characteristic leaching procedure, *Environ. Sci. Technol.* 34 (2000) 4376–4381.
- [5] G. Yang, Environmental threats of discarded picture tubes and printed circuit boards, *J. Hazard. Mater.* 34 (1993) 235–243.
- [6] Y. Jang, T. Townsend, Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates, *Environ. Sci. Technol.* 37 (2003) 4778–4784.
- [7] K. Vann, S. Musson, T. Townsend, Factors affecting TCLP lead leachability from computer CPUs, *Waste Manage.*, in press.
- [8] United States Environmental Protection Agency (USEPA), Identification and Listing of Hazardous Waste, The Code of Federal Regulations, Title 40, Chapter 1, Part 261, Office of the Federal Register, National Archives and Records Administration, Washington, DC, 1999.
- [9] K. Hopper, M. Iskander, G. Sivia, F. Hussein, J. Hus, M. Deguzman, Z. Odion, Z. Ilejay, F. Sy, M. Petreas, B. Simmons, Toxicity characteristic leaching procedure fails to extract oxoanion-forming elements that are extracted by municipal solid waste leachates, *Environ. Sci. Technol.* 32 (23) (1998) 3825–3830.
- [10] C. Halim, J. Scott, H. Nattwardaya, R. Amal, D. Beydoun, G. Low, Comparison between acetic acid and landfill leachates for the leaching of Pb(II), Cd(II), As(V), and Cr(VI) from cementitious wastes, *Environ. Sci. Technol.* 38 (14) (2004) 3977–3983.
- [11] A. Ghosh, M. Mukiibi, W. Ela, TCLP underestimates leaching of arsenic from solid residuals under landfill conditions, *Environ. Sci. Technol.* 38 (17) (2004) 4677–4682.
- [12] T. Townsend, K. Vann, S. Musson, S. Mutha, B. Pearson, Y. Jang, A. Jordan, RCRA Toxicity Characterization of Computer CPUs and Other Discarded Electronic Devices, final report submitted to U.S., EPA Regions 4 and 5, University of Florida, Gainesville, FL, 2004.
- [13] National Electrical Manufacturers Association, Procedures for Fluorescent Lamp Sample Preparation and the Toxicity Characteristic Leaching Procedure, Information Handling Services/Global Engineering Documents, Denver, CO, 2003.
- [14] M. Jang, S. Hong, J. Park, Characterization and recovery of mercury from spent fluorescent lamps, *Waste Manage.* 25 (1) (2005) 5–14.
- [15] M. Stone, E. Pederson, M. Cohen, J. Ragain, R. Karaway, R. Auxer, A. Saluta, Residual mercury content and leaching of mercury and silver from used amalgam capsules, *Dent. Mater.* 18 (2002) 289–294.
- [16] United States Environmental Protection Agency (USEPA), Test Methods for Evaluating Solid Waste, SW-846, third ed., Office of Solid Waste and Emergency Response, Washington, DC, 1996.
- [17] D. Kendall, Toxicity characteristic leaching procedure and iron treatment of brass foundry waste, *Environ. Sci. Technol.* 37 (2003) 367–371.
- [18] V. Snoeyink, D. Jenkins, *Water Chemistry*, John Wiley & Sons Inc., New York, 1980, pp. 363–378.
- [19] X. Meng, G. Korfiatis, C. Jing, C. Christodoulatos, Redox transformations of arsenic and iron in water treatment sludge during aging and TCLP extraction, *Environ. Sci. Technol.* 35 (2001) 3476–3481.