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Leaching Assessments of Hazardous Materials in Cellular Telephones

JOHN D. LINCOLN,[†]
OLADELE A. OGUNSEITAN,[*,‡]
ANDREW A. SHAPIRO,[§] AND
JEAN-DANIEL M. SAPHORES[||]

Department of Chemical Engineering and Materials Science, Public Health Program, College of Health Sciences, and Program in Industrial Ecology, Department of Environmental Health, Science, and Policy, Department of Electrical Engineering and Computer Science, Department of Civil and Environmental Engineering, Economics Department, and Department of Planning, Policy, and Design, University of California, Irvine, California 92697

Protocols for assessing the risks of discarded electronic products (e-waste) vary across jurisdictions, complicating the tasks of manufacturers and regulators. We compared the Federal Toxicity Characteristic Leaching Procedure (TCLP), California's Waste Extraction Test (WET), and the Total Threshold Limit Concentration (TTLC) on 34 phones to evaluate the consistency of hazardous waste classification. Our sample exceeded TCLP criteria only for lead (average = 87.4 mg L^{-1}; range = 38.2−147.0 mg L^{-1}; regulatory limit = 5.0 mg L^{-1}), but failed TTLC for five metals: copper (average 203 g kg^{-1}; range = 186−224 g kg^{-1}; limit = 2.50 g kg^{-1}), nickel (9.25 g kg^{-1}; range = 6.34−11.20 g kg^{-1}; limit = 2.00 g kg^{-1}), lead (10.14 g kg^{-1}; range = 8.22−11.60 g kg^{-1}; limit = 1.00 g kg^{-1}), antimony (1.02 g kg^{-1}; range = 0.86−1.29 g kg^{-1}; limit = 0.50 g kg^{-1}), and zinc (11.01 g kg^{-1}; range = 8.82−12.80 g kg^{-1}; limit = 5.00 g kg^{-1}). Thresholds were not exceeded for WET. We detected several organic compounds, but at concentrations below standards. Brominated flame retardants were absent. These results improve existing environmental databases for e-waste and highlight the need to review regulatory testing for hazardous waste.

Introduction

Rapid improvements in consumer electronic devices (CEDs) and their ever wider distribution have sharply increased the quantity of electronic equipment entering the solid waste stream (*1*). Electronic waste (e-waste) contains a variety of hazardous materials, including toxic metals such as antimony, copper, nickel, lead, and others, and organic compounds such as phthalates and brominated flame retardants (BFRs), that could potentially leach into the environment after disposal and threaten human health (*2*−*6*). Unfortunately, CEDs are not recycled at the same rate (less than 10%) as other hazardous consumer products (24−90%), partly because they represent a new and poorly understood category of waste (*7*). Furthermore, the small size of CEDs increases the likelihood of their disposal in landfills. The U.S. Environmental Protection Agency reported that 4600 million kg of electronic products was discarded in landfills in the U.S. in 2000. Furthermore, an estimated 130 million cellular phones were retired in the United States in 2005, with a cumulative estimate of more than 700 million phones already discarded or stockpiled prior to disposal (*8*). As a result of this growing volume of e-waste, it is estimated that approximately 454 million kg of Pb will enter the environment in the next 10 years, although this estimate was derived when cathode ray tubes (CRTs) were likely the largest contributors, but they are slowly being phased out in favor of flat screen panels, which provoke somewhat different concerns regarding toxic material constituents (*8*).

To assess the need to regulate the disposal of e-waste items based on their hazardous material content, a variety of testing procedures have been proposed and implemented by different regulatory agencies at the state, national, and international levels. In the United States, these methods include the U.S. EPA Toxicity Characteristics Leaching Procedure (TCLP) (*9*) and Synthetic Precipitation Leaching Procedure (SPLP) (*10*), the California Department of Toxic Substance Control (DTSC) Waste Extraction Test (WET) (*11*), and the California DTSC's Total Threshold Limit Concentrations (TTLC, or "Totals test") (*11*). In some cases, these test procedures were designed, with important caveats, to simulate landfill conditions, but they exhibit significant methodological differences that suggest the likelihood of drastically different results. For example, the leaching solution is deionized water in Europe and Japan, whereas in the United States both deionized water and acidic solutions are used, depending on Federal or state-level requirements (*12*).

In California, waste materials that fail the Federal TCLP, California WET (compared to the Soluble Threshold Limit Concentration, STLC), or California TTLC are considered hazardous. If a leachate solution contains toxic materials at concentrations that exceed regulatory limits, the material is determined to have failed the test. TCLP and WET are leaching test procedures that include mechanical preparation of the sample, solution extraction of hazardous materials, and chemical analysis of the extracted solution. The TTLC test requires acid digestion and analysis and is therefore not meant to simulate landfilling scenarios, but instead to provide data on the elemental constituents in products. This information may be useful for evaluating options for remanufacturing strategies to reduce the use of toxic chemicals.

Several studies have used various leaching procedures to characterize e-waste (*13*−*16*), and they demonstrate that Pb is the metal that most frequently exceeds regulatory thresholds for hazardous waste at all jurisdictional levels. Therefore, regulatory agencies have focused on replacing Pb in electronic products (*2*). It is becoming clear that, even after Pb is replaced in electronic products, e-waste may remain classified as "hazardous" because of the presence of other toxic materials that may leach out, depending on the test protocol. However, there has been no clear consensus on the identity or concentrations of the other toxic materials. In this study, we focused on TCLP (U.S. EPA), WET (State of California), and TTLC Totals Test (State of California) because these tests generally represent worst-case scenarios for leaching as procedures for Europe, Japan, and many states utilize less aggressive neutral leachate solution than the low-pH TCLP and WET procedures. Therefore, despite their assumptions,

* Corresponding author phone: (949) 824-6350; fax: (949) 824-2056; e-mail: Oladele.Ogunseitan@uci.edu.
[†] Department of Chemical Engineering and Materials Science.
[‡] Public Health Program, College of Health Sciences, and Program in Industrial Ecology, Department of Environmental Health, Science, and Policy.
[§] Department of Electrical Engineering and Computer Science.
[||] Department of Civil and Environmental Engineering, Economics Department, and Department of Planning, Policy, and Design.

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the results of TCLP, WET, and Totals tests should provide a more comprehensive foundation for product redesign initiatives that represent the ultimate solution to the growing e-waste problem, at least in the context of hazardous waste minimization strategies. In addition, the tests facilitate comparisons of different types of waste, providing a relative assessment of desirability of materials use. After a description of sample collection and preparation, we discuss the properties of these leaching methods, and the implications they have for this study. Next, we present the data in the context of methodological differences and the results of previous e-waste studies. Finally, we discuss the sources for hazardous materials identified for cellular phones in this study, and the relationship between the formal test methods used for regulatory purposes and actual landfill conditions.

Experimental Section

Sample Collection and Preparation. One hundred and forty eight cellular phones were collected through "The Wireless Source" (Bloomfield Hills, MI), a domestic cellular phone recycling company. Phones were grouped by physical dimensions and manufacturer. To discard outliers, phones with physical dimensions more than one standard deviation away from the mean were not included in our analyses, resulting in the selection of 34 cell phones. The selected phones are representative of the current manufacturers and models of phones at end-of-life ready for recycling or disposal. The top seven cellular phone producers at this time are Motorola, LG, Nokia, Samsung, Sanyo, Kyocera, and Sony Ericsson respectively (*8*), and for this study, five of the top seven manufacturers were represented in the group of phones used. A complete list of phones and their major characteristics is available in Table A of the Supporting information (SI).

After removing batteries, phones were shredded using a hammer mill and particle sieve (Kelly Duplex Model LM-6, Duplex Mill and Manufacturing Company, Springfield, OH) to a particle diameter of 9.5 mm, as required by TCLP. The particles were agitated for 10 min in a 10 L, plastic container to homogenize the sample. The batch was partitioned evenly by mass, and 50% of the mass (approximately 1.5 kg) was further reduced to 2.0 and 1.0 mm for WET, Totals, and organic compound analysis. During processing, hammer mill temperature was monitored and did not exceed 40 °C. The samples were sealed in airtight, polyethylene bags until the next analytical step.

TCLP, WET, and TTLC "Totals Test" Procedures. We focused on three tests because of their stringency and their relevance to product redesign initiatives. The TCLP method (Method 1311; 40 CFR §261.24) was developed by the U.S. EPA as an improvement on previous methods (Extraction Procedure Toxicity Test, "EP Tox") to determine if a waste material is subject to regulation under Subtitle C of the Resource Conservation and Recovery Act (45 FR 33066; May 19, 1980). The TCLP ensures that any volatile constituent present in the sample is collected and measured. The TCLP is designed to simulate landfill leaching under a worst-case scenario. Results of the TCLP are reported in mg L^{-1}. The WET test was developed by the California Department of Toxic Substances Control (DTSC; Title 22) to evaluate the amount of a specific constituent that can be leached from a sample using a solution which is also designed to simulate landfill leaching. Results of the WET, which are reported in mg L^{-1}, are compared to the Soluble Threshold Limit Concentration (STLC). Finally, the "Totals test" is a chemical digestion procedure developed by DTSC to determine the total amount of a specific constituent in a given material. A sample is digested chemically to obtain its soluble and insoluble fractions. The total of these fractions is then compared to the Total Threshold Limit Concentration (TTLC). Results of the Totals test are typically reported in mg kg^{-1}. The particulate matter from shredded phones was extracted and analyzed using the standardized TCLP, WET, and Totals test procedures. Table B in the SI summarizes these procedures.

TCLP and WET procedures involved placing 100 g of particle reduced cellular phones into a 2.2 L extraction vessel, adding leaching solution (2 L for TCLP, 1 L for WET), placing the vessel on a rotary extractor for the specified time period (18 h for TCLP, 48 h for WET), and filtering the solution with a vacuum filtration apparatus using a 0.7 μm glass fiber filter. Following filtration, samples were prepared for analysis of metallic (ICP−MS), organic (GC−MS), semi-volatile organic (EPA 625) (*17*), and volatile organic (EPA 624) (*18*) compounds. For quality control purposes, sample blanks and spikes were performed for each metal analyzed with these tests, ensuring accurate measurements. All extractions were run in triplicate and the data are reported as an average value and a range.

The TTLC procedure calls for the use of EPA Method 3050B (*19*) for analysis, but also EPA Method 3060A (*20*) in the case of Cr (VI). For those metals analyzed by EPA 3050, 1 g of ground, 2.0 mm diameter cellular phone particles was added to a 250 mL digestion vessel. As specified, the sample was refluxed with repeated additions of HNO_3, followed by a 30% H_2O_2 solution in water. Prior to analysis by ICP−MS, the samples were filtered through Whatman No. 41 filter paper and centrifuged at 2500 rpm for 10 min. For Cr (VI) analysis, EPA method 3060 was followed and EPA method 7199 (*21*) was used for analysis. Sample blanks and spikes were also performed here to ensure accurate measurements. Totals digestions were performed in triplicate and the data are reported as an average value and a range.

Organic Compounds. A variety of extractions and analyses were utilized for analyzing organic compounds. For volatile and semivolatile compounds, TCLP extract and EPA 624 and 625 extracts were analyzed. The different extraction procedures yield different results, primarily due to the acidic nature of the TCLP extract when compared with the EPA 624 and EPA 625 extraction procedures. We followed EPA 624 for analyzing volatile compounds, and EPA 625 for analyzing semivolatile compounds for both extraction procedures. Additional organic compounds analyzed included brominated diphenyls and brominated diphenyl ethers, tributyl tin, Mirex and Arochlor, polychlorinated biphenyls (PCBs), and fluoride salts. Brominated compounds were examined by extracting hexanes and analyzing the resulting solution by GC−MS. Because some of these compounds are not included in the regulatory procedures (TCLP) described above, we conducted a variety of extraction and analytical procedures. For brominated compounds, hexanes were used for extraction and subsequent analysis was performed with GC−MS. For fluoride salts, extraction was performed with deionized water and analyzed by an ion selective electrode (ISE). Tributyl tin was determined by extraction into 0.2% tropolone in hexane followed by concentration and derivatization with hexylmagnesium bromide (Grignard Reagent) to form tetra-alklytin derivatives which were then analyzed by direct injection into a gas chromatograph, separated by temperature and column affinity, and detected by a flame photometric detector. Organic lead compounds were determined through an ICP−MS method using pentane for extraction, followed by nitric acid digestion, an improved alternative to California's standard xylene-based extraction HLM Method 939-M (West Coast Analytical Laboratories, Santa Fe Springs, CA). The analysis of Mirex and PCBs was performed using EPA Method 608 (*22*). For fluoride salts, samples were extracted with deionized water and analyzed with an ion selective electrode. For quality assurance, all analyses of organic compounds were performed following verified agreement with spiked concentrations of the standard

TABLE 1. Leachates from Cellular Phones According to the Toxicity Characteristics Leaching Procedure (TCLP)

chemical constituent	average[a] concentration (mg L^{-1})	measured range (mg L^{-1})	detection limit[b] (mg L^{-1})	Federal TCLP limit for hazardous waste classification (mg L^{-1})
arsenic	0.062	0.056−0.067	0.003	5.0
barium	2.33	1.46−2.88	0.02	100.0
cadmium	0.004	0.0006−0.006	0.0001	1.0
chromium	0.07	0.04−0.13	0.03	5.0
iron[c]	200.0	114.0−311.0	0.8	N/A
lead	87.4	38.2−147.0	0.0005	5.0
mercury	0.006	0−0.010	0.005	0.2
selenium	0.093	0.073−0.12	0.03	1.0
silver	0.006	0−0.010	0.005	5.0

[a] Three independent analyses. [b] Inductively coupled plasma mass spectrometry. [c] Not required by TCLP.

TABLE 2. Leachates from Cellular Phones According to the Waste Extraction Test (WET)

chemical constituent	average[a] concentration (mg L^{-1})	measured range (mg L^{-1})	detection limit[b] (mg L^{-1})	California state WET (STLC)[c] limit for hazardous waste classification (mg L^{-1})
antimony	2.82	1.09−6.13	0.004	15.0
arsenic	0.040	0.006−1.09	0.04	5.0
barium	5.63	2.4−11.9	0.1	100.0
beryllium	0.002	0−0.0071	0.0001	0.8
cadmium	0.021	0.009−0.045	0.001	1.0
chromium	0.167	0.029−0.44	0.3	6;560 (Cr VI;III)
cobalt	1.21	0.449−2.67	0.004	80.0
copper	0.027	0−0.043	0.1	25.0
lead	1.09	0.144−2.91	0.002	5.0
mercury	0.005	0−0.008	0.1	0.2
molybdenum	0.005	0−0.008	0.1	350.0
nickel	0.53	0.19−1.20	0.005	20.0
selenium	0.121	0.031−0.30	0.1	1.0
thallium	ND[d]	ND	0.002	7.0
vanadium	ND	ND	0.07	24.0
zinc	52.4	20.4−116.0	0.02	250.0

[a] Three independent analyses. [b] Inductively coupled plasma mass spectrometry. [c] STLC = Soluble Threshold Limit Concentration (CA CCR 66262.24). [d] ND = Not detected.

compounds. Organic analyses were all conducted in triplicate, and the data are reported as an average value and a range.

Results and Discussion

Metals. The results for TCLP, WET, and Totals leaching tests are presented in Tables 1, 2, and 3, respectively. The data show that the Pb content of cell phones exceeds the regulatory limit according to TCLP, whereas the WET results show that metals extracted were below the limits for hazardous waste classification. Importantly, five metallic constituents, Cu, Ni, Pb, Sb, and Zn, exceeded the regulatory standards for hazardous waste according to the Totals test. These data provide crucial information on the variability of hazardous waste classification for cellular phones at both state and Federal jurisdictional levels. The data for metallic substances also demonstrate both their leaching properties (under two separate conditions, WET and TCLP) and their Totals concentrations (compared to TTLC).

Previous e-waste studies (e.g., *13*−*16*) have shown that Pb exceeds the regulatory standards according to TCLP, although at a much lower concentration than the average 87.42 mg L^{-1} reported in the present study. This discrepancy is likely due to two factors. First, previous studies were conducted on different types of e-waste, which would have altered concentrations, leaching availability, and leaching solution pH. Second, some investigators (e.g., *15*) have reported that the presence of Zn and Fe in the TCLP leachate creates an electrochemical condition under which lead is less soluble. Iron and zinc act to reduce Pb to a zero valency state, resulting in lower Pb solubility in the leachate solution. In addition to the higher Pb concentrations demonstrated in our study, the presence of Fe and Zn at concentrations indicated in Tables 1 and 2 may reduce Pb concentration results, thus further increasing the gap between our findings and previous assessments. Yet, another study reported that 74% of cellular phones exceed TCLP regulatory thresholds when evaluated for Pb only (*23*), thereby corroborating our results.

Although the WET did not reveal a regulatory failure for Pb (testing at 22% of the regulatory threshold), the TCLP result showed that Pb exceeded regulatory threshold limit by more than 17 times. Other studies (e.g., *15*) indicate that Pb has a higher affinity for acetate ion, a component of the TCLP leaching solution, than for the citrate ion found in the WET test, which could explain this result. WET is widely regarded as a more aggressive procedure for inorganic constituents, so it is particularly informative to note that our results show this is not the case for Pb. The U.S. EPA has not established regulatory threshold limit concentrations for Cu, Ni, Sb, or Zn under TCLP leachate procedure, so those metals were not analyzed, but when compared to the WET results, TCLP results showed lower concentrations for four out of the seven metals determined in both procedures.

For the Totals test results, Cu was identified as the metal that most exceeded regulatory limits; exceeding the California state limit by over 81 times the threshold concentration. Next is Pb with a leachate concentration of more than 10 times the California State threshold limit. Nickel, Sb, and Zn were

TABLE 3. Leachates from Cellular Phones According to the "Total Threshold Limit Concentration" (TTLC) Procedure

chemical constituent	average[a] concn. (mg kg^{-1})	measured range (mg kg^{-1})	detection limit[b] (mg kg^{-1})	California state TTLC limit for hazardous waste classification (mg kg^{-1})
antimony	1023	860−1290	0.03	500
arsenic	36.1	20.1−60.0	0.7	500
barium	5383	1410−9260	0.03	10000
beryllium	12.1	2.9−17.6	0.01	75
cadmium	2.93	2.67−3.40	0.01	100
cobalt	241.3	72−460	0.01	8000
chromium (total)	958	253−2330	3.0	500;2500 (Cr VI;III)
chromium VI	ND[c]	ND	4.0	500
copper	203000	186000−224000	0.2	2500
lead	10140	8220−11600	0.02	1000
mercury	0.79	0.37−1.70	0.08	20
molybdenum	23.5	3.73−37.0	0.02	3500
nickel	9247	6340−11200	0.2	2000
selenium	5.9	4.81−6.90	0.08	100
silver	65.9	9.28−177	0.01	500
thallium	0.11	0.05−0.19	0.01	700
vanadium	ND	ND	3.0	2400
zinc	11007	8820−12800	0.06	5000

[a] Three independent analyses. [b] Inductively coupled plasma mass spectrometry, except for Cr (VI) determined according to EPA Method 7199. [c] ND = Not detected.

detected at concentrations between 2 and 5 times more than their respective CA State thresholds. Significantly, this is the first demonstration that the Zn constituent of electronic products exceeds the regulatory limit designating hazardous waste. The data also show the presence of other toxic metal concentrations at sufficiently high levels to generate concern, including Cr (III and VI) and Ag, which were detected at levels 38% and 13% of their regulatory threshold values, respectively.

A comparison of our cell phone data with other e-waste analyses (*13*−*16*, *23*, *24*) indicates similar concentration of Pb, but also high concentrations of Cu, Ni, Sb, and Zn. These data demonstrate that electronics manufacturers who seek to design products exempt from current hazardous waste classifications will need to address not just Pb (as the current wave of responses to European and Japanese regulations has shown), but also Ni, Sb, and Zn, and most importantly Cu content. However, extensive testing should precede the selection of alternative materials. For example, if a $Sn_{95.5}Ag_{3.5}Cu_{0.7}$ solder were adopted according to the popular Pb-free design initiative as a substitute for $Sn_{63}Pb_{37}$ solder, the resulting levels of Ag in leachates may well exceed the regulatory threshold.

Organic Compounds. The results for organic compound analyses are presented in Table 4. No organic compounds exceeded either state or Federal toxicity thresholds. Yet, it is important to note the presence of several potentially toxic compounds in the leachates, including organic lead, phthalates, benzyl alcohol, and phenol. In addition to those reported in Table 4, approximately 60 additional organic compounds were tentatively identified by GC−MS at concentrations below 200 mg/kg. Although no brominated flame retardants (BFRs) were detected in our study, it is still very likely that they are used in cellular phones (*8*). Moreover, previous testing found that BFR levels are highest in VCRs, followed by telephones, printers, CPUs, microwaves, and cellular phones (*15*). One possible reason BFRs were not detected is their fairly low content and a relatively smaller fraction of polymers in cellular phones than in VCRs or CRTs, for example. Further work is necessary to understand the leaching properties and mobility of BFRs in cellular phones.

Component Sources and Regulatory Implications. Many of the substances detected in this study are on the U.S. EPA's "Resource Conservation and Recovery Act (RCRA) Waste Minimization List of Persistent, Bioaccumulative, and Toxic Chemicals" (PBTs). By lingering in the environment without degrading, PBTs create risks for both the environment and human health. PBTs identified in this study include As, Sb, Be, Cd, Cu, Hg, Pb, Ni, Se, and Zn among metals, and phthalates and phenol among organic compounds. However, the only PBT chemical that exceeded the regulatory limit at the Federal level was Pb. Though the amount of these hazardous materials in each cellular phone is generally small, the number of these devices entering the waste stream is increasing rapidly. PBT concentration and proper end-of-life management of cellular phones is therefore necessary to avoid serious adverse impacts on public health and environmental quality.

With respect to Pb, current U.S. regulations do not prohibit its use in electronic products. One of the main applications of Pb in cellular phones is in the $Sn_{63}Pb_{37}$ solder that is used to make conductive bonds between various components and the printed wiring board (PWB). Most mobile phone manufacturers have already phased out the use of $Sn_{63}Pb_{37}$ solder in cellular phones in response to regulatory restrictions originating from the European Union (*2*). However, Pb concentrations in the current accumulation of cellular phone waste generate concern in light of its PBT status. Future studies should investigate to what degree the presence of other metals in newer cell phones has risen as a result of manufacturers adopting Pb-free solders.

California's regulation of hazardous e-waste deserves particular attention. Metals exceeding California's established threshold according to the results presented here were Pb, Cu, Ni, Sb, and Zn. These metals are listed as "Hazardous Constituents" under the federal RCRA. Furthermore, they are all considered "Priority Pollutants" under the U.S. EPA's Clean Water Act. Copper is used extensively in cellular phones, primarily within PWBs to provide electrical connections to various layers in the board. The PWB laminate material, which consists mainly of glass fibers and epoxy resin, is not conductive. Copper is integrated through the "electroless" Cu process to provide the conductive layers necessary for performance. Although Cu is not included in the European RoHS-governed chemicals, it creates significant environmental problems during mining operations and during the end-of-life disposal of products containing leachable metals. The mining of Cu has been associated with

TABLE 4. Selected Organic Compounds Leached from Cellular Phones[a]

chemical constituent	extraction method	detection method	particle size (mm)	average[b] concentration (mg kg^{-1})	measured range (mg kg^{-1})	detection limit (mg kg^{-1})	WET (STLC) standard	TTLC standard	TCLP standard
nonvolatile compounds									
organic lead	SOP 7030[c]	ICP−MS	2.0	2.48	0.27−4.94	0.01	NSE	13.0	NSE
fluoride salts	aqueous	ISE	2.0	1.30	0.70−2.51	0.5	180.0	18000	NSE
monobromo-diphenyl	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
decabromo-diphenyl	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
tribromobiphenyl ethers	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
Tetrabromobiphenyl ethers	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
pentabromobiphenyl ethers	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
hexabromobiphenyl ethers	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
heptabromobiphenyl ethers	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
decabromodiphenyl ethers	hexanes	GC−MS	2.0	ND	ND	0.05	NSE	NSE	NSE
tributyl tin	SOP 3200[c]	GC−FPD	2.0	ND	ND	0.06	NSE	NSE	NSE
Mirex	EPA 608	EPA 608	1.0	ND	ND	0.20	2.1	21.0	NSE
PCB-1016	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
PCB-1221	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
PCB-1232	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
PCB-1242	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
PCB-1248	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
PCB-1254	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
PCB-1260	EPA 608	EPA 608	1.0	ND	ND	2.0	5.0	50.0	NSE
volatile compounds									
acetone	TCLP	EPA 624	9.8	50	40−60	30	NSE	NSE	NSE
benzene	EPA 624	EPA 624	1.0	0.3	0−1	1	NSE	NSE	0.5
chloroform	EPA 624	EPA 624	1.0	1.3	0−4	1	NSE	NSE	6.0
Freon-TF	EPA 624	EPA 624	1.0	1.0	0−3	1	NSE	NSE	NSE
methyl ethyl ketone	TCLP	EPA 624	9.8	103	50−150	10	NSE	NSE	NSE
methyl ethyl ketone	EPA 624	EPA 624	1.0	8.3	5−10	2	NSE	NSE	200.0
methylene chloride	EPA 624	EPA 624	1.0	10	10−10	5	NSE	NSE	NSE
methyl methacrylate	EPA 624	EPA 624	1.0	25.3	20−35	2	NSE	NSE	NSE
styrene	EPA 624	EPA 624	1.0	4.3	3−6	1	NSE	NSE	NSE
toluene	EPA 624	EPA 624	1.0	3.7	3−4	1	NSE	NSE	NSE
semivolatile compounds									
benzo(g,h,i)perylene	EPA 625	EPA 625	1.0	0.3	0−1	1	NSE	NSE	NSE
benzyl alcohol	TCLP	EPA 625	9.8	437	230−790	10	NSE	NSE	NSE
benzyl alcohol	EPA 625	EPA 625	1.0	383	290−450	5	NSE	NSE	NSE
bis(2-ethylhexyl)phthalate	TCLP	EPA 625	9.8	220	10−620	5	NSE	NSE	NSE
bis(2-ethylhexyl)phthalate	EPA 625	EPA 625	1.0	64	39−90	5	NSE	NSE	NSE
dibenzo(a,h)anthracene	EPA 625	EPA 625	1.0	0.3	0−1	5	NSE	NSE	NSE
di-n-butyl phthalate	TCLP	EPA 625	9.8	17	0−40	5	NSE	NSE	NSE
di-n-butyl phthalate	EPA 625	EPA 625	1.0	1	0−3	5	NSE	NSE	NSE
diethyl phthalate	TCLP	EPA 625	9.8	30	20−40	5	NSE	NSE	NSE
diethyl phthalate	EPA 625	EPA 625	1.0	0.3	0−1	5	NSE	NSE	NSE
indeno(1,2,3-cd)pyrene	EPA 625	EPA 625	1.0	0.3	0−1	1	NSE	NSE	NSE
phenol	TCLP	EPA 625	9.8	27	20−40	5	NSE	NSE	NSE
phenol	EPA 625	EPA 625	1.0	20	20−20	5	NSE	NSE	NSE

[a] TCLP = Toxicity characteristics leaching procedure (US EPA Method 1311); ICP−MS = inductively coupled plasma mass spectrometry; GC−MS = gas chromatography mass spectrometry; GC-FPD = gas chromatography flame photometric detector; ISE = ion selective electrode; NA = not applicable; ND = not detected; NSE = no standards established. [b] Three independent analyses. [c] See experimental section.

considerable environmental pollution. For example, the Ely Copper Mine in Vermont is included on the Long Term/ National Priority List of Superfund sites (US EPA ID VTD98836657). Although an essential dietary element for some plants and animals, high concentrations of Cu in water can be toxic to fish and other aquatic species (*25*). There is currently no incentive to eliminate Cu in electronic products. Without stronger acknowledgment that environmental disposal of materials capable of releasing Cu may cause serious pollution issues, the problem will persist, and may eventually warrant legislative action mandating extensive recycling or source reduction strategies. Nickel is used as an alloying metal in steel in cellular phones, but also in Ni−Cd batteries (though batteries were not included in this study). Additionally, Ni plating may be used on both metallic and polymer components. The presence of Sb in cellular phones is due mostly to Sb_2O_3, which is used as a synergist with BFRs for flame-retarding PWB laminates. The increasing trend to reduce the use of BFRs (*3*−*5*) should marginalize the need for Sb_2O_3, as they are less effective independent flame retardants. The presence of Zn in cellular phones can be attributed to galvanized metallic components and the presence of phosphor in visual displays.

This study also identified organic Pb compounds, phthalates, phenol, and various organic solvents in leachate from cell phones. Among these, phthalates, namely bis (2-ethylhexyl) phthalate and dibutyl phthalate, as well as phenol are listed as "Hazardous Constituents" under the RCRA as well as "Priority Pollutants" under the Clean Water Act. Organic Pb compounds are typically used in glasses and ceramics, but also to a limited degree in catalysis and stabilization of polymers. Additionally, organic Pb compounds may be formed when solder paste interacts with various physical organic surfaces. These compounds have a long history of environmental and human health toxicity, as they are recognized carcinogens and neurological, developmental, and reproductive toxicants (*26*−*27*). Phthalates are used as plasticizers in PVC and other polymers, which

improves processing and flame retardance. Phthalates are recognized carcinogens and developmental and reproductive toxicants (*27*). Phenol, a monomer used in the manufacture of PWB laminates, is present in residual amounts due to incomplete reaction during laminate manufacturing. Phenol has been detected in at least 595 of the 1,678 National Priority List (NPL) sites identified by the U.S. EPA, and it is widely recognized as a human health hazard (*28*). Organic solvents were identified in small concentrations, reflecting their limited use during electronics production. Although they were detected, it is worth emphasizing that the organic compounds identified in this study were in very low concentrations when compared to regulatory thresholds (where available), in clear contrast with our findings for toxic metals.

Veracity and Fidelity of Leaching Tests as Regulatory Tools for Environmental Protection. Contemporary landfills are designed to minimize environmental pollution, but ambient conditions at each site and age of landfills vary considerably, which may influence the actual level of human and environmental risk posed by the disposal of various potentially hazardous materials. Therefore, standardized tests designed to simulate landfill conditions are invariably approximate; while they sometimes underestimate risk, they also in many cases overestimate risk (*29*−*31*). Although TCLP and WET procedures are required for regulatory oversight, their use may not accurately reflect actual landfill conditions, and data gathered using these standardized procedures should be interpreted with caution. Several site variables can limit the realism of TCLP and WET, including liquid-to-solid ratios, extraction times, particle size, pH, the chemical composition of mixed wastes, and redox potential. All these factors will require site-specific assessment to generate predictive models (*24*). For example, despite the consistent finding that Pb is present in leachates according to TCLP, actual groundwater contamination by Pb at landfill sites containing e-waste has not been demonstrated, possibly because soils contain many constituents that limit the metal's mobility into the aqueous phase (*14*, *29*). Furthermore, TCLP has not always represented worst-case leaching scenarios under actual field conditions, as shown for oxoanion-forming elements and arsenic (*30*, *31*). These caveats must always surround the context in which data from standardized leaching tests are interpreted for regulatory purposes and for product design.

In summary, we have presented here data showing that, on average, defunct cellular phones qualify as hazardous waste according to Federal regulation due to their Pb content. However, in California, Pb-free phones will still be classified as hazardous waste due to their Cu, Ni, Sb, and Zn content. This difference in the outcome of hazard classification according to variable regulatory standards across jurisdictional and geographical boundaries has profound implications for regulating the hazard profile of e-waste through product redesign initiatives. It also has profound implications for the ultimate location of end-of-life disposal of potentially hazardous electronic products. Our analyses also indicate the presence of several organic compounds of concern, though their quantities are relatively low. Despite their current notoriety as pervasive environmental pollutants, we did not detect brominated flame retardants in leachates from cellular phones (see *32*). We fully recognize that the leaching tests described here are meant to simulate some key landfill conditions, and to the extent that each landfill site is unique with respect to ambient conditions, these standardized tests are only approximate. But, the test outcomes are powerful determinants of regulatory policies and provide strong incentives for manufacturers and consumers. Our results therefore reinforce the urgency of defining a unified framework for investigating the leaching characteristics of the potentially hazardous content of electronic products, because standardized tests employed by various regulatory jurisdictions yield such different results. The discrepancy between the outcome of WET and TCLP for notorious pollutants such as Pb is particularly worth emphasizing. Future work should include an analysis of changes in leaching behavior and total metal content of the latest models of cellular phones; this would provide information regarding both legislative compliance and product manufacturing trends. A better understanding of testing procedures and consistent leaching results, as well as improved data from actual landfill conditions for specific materials in consumer electronic devices would also advance environmentally sustainable design efforts.

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Supporting Information Available

Details of the cellular phones used and salient characteristics of leaching tests. This material is available free of charge via the Internet at http://pubs.acs.org.

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