Characterization and Analysis of Airborne Metal Exposures among Workers Recycling Cellular Phones

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Abstract

Electronic scrap contains potentially hazardous metals that may become airborne during the recycling process. Occupational exposures to airborne metals created by cellular phone recycling operations are not well characterized in the scientific literature, leaving risk assessors and policy creators little evidence upon which to base electronic scrap management decisions. A quantitative airborne metal exposure survey was conducted on workers shredding, roasting, milling, and assaying recycled cellular phones. Aluminum, arsenic, beryllium, cadmium, chromium, copper, iron, lead, manganese, nickel, selenium, and zinc were all well below the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PEL) for shredding, roasting and alloying operations. Based on their percent exceedance values, airborne silver exposure results for all four operations are expected to be above the OSHA PEL (0.01 mg/m^3) greater than five percent of the time, although less than 1.0 percent for the more toxicologically relevant exposure limit of 0.1 mg/m^3. Milling results were above the OSHA PEL for copper and lead more than five percent of the time. Operator tasks required to respond to atypical milling and screening equipment malfunctions significantly influenced their exposures. Shredding, roasting and alloying operations with work practice and ventilation controls, as is described in this study, represent a minimal inhalation hazard regarding silver and no inhalation hazard to the operators for all other metals studied.

Keywords- ***electronic scrap; airborne metal exposure; shredding; milling; roasting; cellular phone; recycling, ventilation***

I. Introduction

Electronic scrap is one of the fastest growing scrap streams today and the subject of emerging European Union directives and state regulation regarding end-of-life management of electrical and electronic products. The volume of scrap electronics increases substantially year to year due to an increase in users and a decrease in product life cycle. Recycling is preferred as valuable metals are reclaimed and precious landfill space conserved. The contents of electronic equipment are generally not hazardous to the user; however, the individual components may contain a number of potentially hazardous metals. Occupational health professionals are interested in these materials due to the potential for worker exposure during the reclamation processes. This study characterizes operator airborne metal exposures, work practices and engineering controls used during shredding, roasting, milling and melting of 4,950 kilograms (kg) used, battery less, identical cellular phones. Information was collected to help answer the following questions about the cellular phone recycling process:

1. What operator tasks contribute to exposure?
2. What engineering controls and work practices are used to control dust?
3. What was the concentration of metals in the cellular phone?
4. What are the airborne metal exposure levels of workers processing cellular phones and how do they compare to US standards?
5. What are the study's possible implications for the cellular phone recycling industry?

II. Process, Facility and Equipment Description

Typically, four steps are used to reduce the size and increase the homogeneity of electronic scrap. The product flows from a shredder, to a roasting operation, then to a milling/screening operation and finally to a copper alloying step.

A number of engineering control and work practice changes were implemented in the facility as a result of observations made during a previous study of printed circuit board shredding exposures. Examples of changes made were: ventilating the ball mill and alloying furnaces more efficiently, use of a wet floor sweeper to clean floors, altering material handling practices to reduce dust, employing wet methods for dross management and ingot cleaning.

The cellular phones were first processed by a Untha shear shredder. The shredder operator receives one cubic yard boxes containing scrap cellular phones. The box is loaded onto a tilt-lift station and the cellular phones are manually pulled from the container onto a shaker table transferring the product to the shredder conveyor. The Untha shear shredder reduces scrap cross section to less than one square inch. All input material is shredded and conveyed to a product sampler. A 12.5 percent sample of the shredded material is collected in a 55-gallon drum and sent to roasting. The remaining 87.5 percent of the material is collected and stored in bulk sacks.

The second step in the process is roasting, which separates combustible from non-combustible components. The operation consists of two roasting ovens, roasting trays and racks and a dumping hood. Shredded cellular phones are transferred from a 55-gallon drum onto mesh trays. The trays are then loaded into the roasting furnace in a rack holding nine trays. The cellular phones are roasted around 950 degrees F until the combustible fraction of the cellular phones has fully reacted. After cooling, the trays are removed from the oven and emptied into a drum using a ventilated dumping hood. Two workers perform the following tasks during the shift: material handling, loading trays, loading oven, unloading oven, dumping trays, and housekeeping.

The third step in the process to create a more homogenous product is milling. Milling produces +20 mesh and –20 mesh fractions of roasted product so that precious metal concentrations can be accurately determined. Equipment used in the milling operation include: ball mill, screener and a product sampler. One operator transfers roasted cellular phones into a ball mill. The material flows from the ball mill to the screener via a screw conveyer and then is gravity fed to a sampling device. Full drums are removed from the sampling device and sent to the alloying operation.

The final step involves the creation of assayable metal by alloying the +20 mesh product with copper. The copper and +20 mesh product are melted in a gas-fired furnace, cast into ingots and sampled. Pouring molten metal from the melt creates the sample. The precious metals contained in the sample are assayed in a laboratory and the ingots are sent for further refining along with the remaining –20 mesh product and shredded cellular phones. Six operators charge 4-6 furnaces with milled product and copper. The charge is melted and flux is added to remove unwanted impurities in the melt. A typical heat may have 3-5 charge/fluxing cycles before the slag is poured from the furnace. Once the slag is removed, the metal is cast into 25-pound ingot. The furnace operators are also responsible for removing the cooled ingots from the molds, drumming the slag and housekeeping.

III. METHODS

A. Air Samples

Depending on the operation, nine to sixteen 8-hour personal air samples were collected over a 5-week sampling period in order to assess the total mass of 16 metals present in the breathing zones of workers processing cellular phones at United Recycling Industries®, Franklin Park, IL. Methods specified in the Occupational Safety and Health Administration (OSHA) Technical Manual and the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods [1] were used for sample collection and analysis. Sample analysis was performed at an American Industrial Hygiene Association (AIHA) accredited laboratory for aluminum, arsenic, beryllium, calcium, cadmium, chromium, copper, iron, lead, magnesium, manganese, nickel, selenium, silver, sodium, and zinc.

Exposure data was analyzed in accordance with typical statistical principles [2]. For airborne metal exposure data, we calculated descriptive statistics, central tendency, and characteristics of the upper tail of the distribution. For the latter, we calculated the 95% upper confidence limit (UCL) for the 95th percentile of the distribution (the upper tolerance limit (UTL) [3] and for the fraction of the distribution that exceeded the Permissible Exposure Limit (PEL) and listed occupational exposure limits (OEL) [4]. Exceedance fractions provide information on the proportion of the distribution that exceeds a given exposure value. The uncertainty around point estimates is described by the 95 % UCL. A set of exposure measurements is generally considered to be well controlled if the exceedance fraction is less than or equal to 5 % and the geometric standard deviation (GSD) below 2.5 [5]. Values below the detection limit were divided by two for all statistical analyses.

Exposure data for this study were compared to current OSHA PEL values for each respective metal [6]. Results are also compared to other OEL's such as the European Union and the State of California for select metals.

B. Qualitative Exposure Assessment

A qualitative exposure assessment was used to judge which tasks performed within a given job are most likely resulting in the highest exposure. This information is used to prioritize future task sampling efforts and determine Short Term Exposure Limit (STEL) exposures.

C. Engineering Control Analysis

The type and design specifications of engineering control equipment used and hood locations were recorded based on visual assessment. Ventilation flow rates were measured using a Shortridge Air Data Meter.

D. Bulk Samples

Five cellular phones were processed through each step of the recycling operation. A 1-gram sample of each recycle product intermediate was analyzed according to NIOSH method 7300. The results were used to determine average metal concentrations contained in the cellular phones processed during this study. The concentrations were then used to examine the relationship between air sampling results and processed metal concentrations or production volumes.

IV. RESULTS

A. Airborne Metal Exposure Characterization of Shredding, Roasting, Milling and Alloying Operations (Table 1)

Aluminum, arsenic, beryllium, cadmium, chromium, iron, manganese, nickel, selenium, and zinc:

- All exposure measurements for these metals were below respective OSHA PEL's and expected to be below the OSHA PEL greater than 95 percent of the time. In addition, all airborne beryllium exposures were below the State of California's PEL of 0.0002 milligram per cubic meter (mg/m^3) and statistical analysis demonstrated that exposures are anticipated to be below this limit greater than 95 percent of the time.

Silver:

- The mean of the silver samples was 0.006 mg/m^3 for shredding; 0.008 mg/m^3 for roasting, 0.036 mg/m^3 for milling and 0.005 mg/m^3 for alloying. Geometric standard deviations were less than 2.5 for all four operations. Exceedance fractions of the silver PEL (0.01 mg/m^3) ranged from 14.6- 95.3. Percent exceedance fractions were less than 5 percent for the more toxicologically relevant exposure level of 0.1 mg/m^3 in shredding, roasting and alloying operations. A percent exceedance value of 22.7 at the 0.1 mg/m^3 limit was observed in milling.

Lead:

- The mean of the lead samples for the milling operation was 0.013 mg/m^3, with a GSD of 2.00 and a 95th/95UTL of 0.091 mg/m^3. The percent exceedance value for the OSHA PEL of 0.05 mg/m^3 is 13.25.

Copper:

- The mean of the copper samples for milling was 0.19 mg/m^3, a GSD of 2.77 and a 95th/95UTL of 2.43 mg/m^3. The percent exceedance value for the OSHA PEL of 1.0 mg/m^3 is 13.7.

Table 1. Summary of Airborne Metal Exposure Analysis (mg/m^3)

		Shredding (N= 16)		Roasting (N= 18)		Milling (N= 9)		Alloying (N= 16)	
Metal:	**PEL**	**Mean**	**PEL exceedance UCL (%)[a]**	**Mean**	**PEL exceedance UCL (%)[a]**	**Mean**	**PEL exceedance UCL (%)[a]**	**Mean**	**PEL exceedance UCL (%)[a]**
Aluminum	15.0	0.010	<1.0	0.011	<1.0	0.014	<1.0	0.004	<1.0
Beryllium	0.002/ 0.0002	0.00001	<1.0/<1.0	0.00001	<1.0/<1.0	0.00002	<1.0/2.46	0.00005	<1.0/3.86
Cadmium	0.005	0.0001	<1.0	0.0002	<1.0	0.0001	<1.0	0.001	<1.0
Chromium	1.0	0.0003	<1.0	0.0003	<1.0	0.001	<1.0	<LOD	
Copper	1.0	0.022	<1.0	0.038	<1.0	0.19	13.7	0.01	<1.0
Lead	0.05	0.016	<1.0	0.012	<1.0	0.013	13.25	0.004	<1.0
Manganese	5.0	0.001	<1.0	0.001	<1.0	0.001	<1.0	0.0005	<1.0
Nickel	1.0	0.003	<1.0	0.002	<1.0	0.007	<1.0	0.001	<1.0
Selenium	0.2	0.0003	<1.0	<LOD		<LOD		<LOD	
Silver	0.01	0.006	27.35	0.008	48.18	0.036	95.3	0.005	14.62
Zinc	5.0	0.003	<1.0	0.007	<1.0	0.01	<1.0	0.014	<1.0

[a] Occupational exposure limit exceedance fraction upper confidence limit (UCL) – upper 95% confidence limit for fraction of samples that exceed a given occupational exposure limit.

B. *Bulk Sample Analysis*

Metal concentrations (ppm) were derived from the chemical analysis of five identical cellular phones that were roasted, milled, and cast into an ingot. Metal concentrations were: aluminum (10,450), arsenic (<30), beryllium (52), cadmium (43), chromium (59), copper (375,000), iron (51,000), lead (2,360), manganese (983), nickel (3,500), selenium (<80), silver (80) and zinc (9,150).

C. *Engineering Control Analysis*

A 2,000 cubic feet per minute (CFM) dust collector ventilated the shredder. Partial enclosure and canopy style hoods were used on the shredder, product sampler and for elevation changes between conveyance systems.

Capture velocities for these hoods ranged from 45- 150 fpm. A 125 CFM High Efficiency Particulate Air (HEPA) filtered vacuum ventilated an enclosure style hood used for roasted product transfer. Face velocities for the hood ranged from 80- 100 feet per minute (fpm). In milling, the ball mill charging hood, the sampler and sampling drums were ventilated by a 3,000 CFM portable dust collector. Capture velocities for the partial enclosure style hood ranged from 180- 200 fpm. A 16,000 CFM dust collector ventilated five 24-inch diameter furnaces using close capture side draft slot ring hoods. Centerline capture velocities for the exhaust hoods ranged from 350- 400 fpm.

It is important to identify which components of a given process are ventilated, as personal exposures would be significantly higher absent these controls. Table 2 describes the local exhaust ventilation hoods needed to produce the results described in the study.

Table 2. Ventilation Hood Details

Process	Hood Locations		
Shredding	shredder		product sampler
Roasting	tray dumping hood		
Milling	size reduction mill		product sampler
Alloying	melting furnace	Dross/ ingot pouring	ingot de-scaling

D. Qualitative Exposure Assessment

Based on visual observation, work practices during shredding likely resulting in airborne particulate exposure included: changing the sampler or product container, removing full dust collector drums, inspecting the product sampling device, and housekeeping. Tasks performed during roasting that likely result in airborne particulate exposure were: loading roasting trays with shredded cellular phones, unloading roasting trays from furnace, transferring roasted product into drums, and housekeeping. Work practices during milling that likely resulted in airborne particulate exposure were: loading the ball mill with roasted cellular phones, sample collection and weighing, disconnecting process containers, unclogging product samplers and conveyance systems, and housekeeping. Tasks performed by the operators during melting and casting that likely resulted in airborne particulate exposure were: furnace charging, the melting cycle, mixing fluxes into the melt, skimming dross, casting ingots, managing cooled dross, removing ingots from the molds, cleaning ingots, and housekeeping.

Work practices used to reduce airborne dust levels included: cleaning of process equipment, floor cleaning with a sweeper/scrubber, employing wet methods when removing cooled ingots and dross from containers, and using a water blaster to remove dross from ingots.

V. Discussion

As in previous studies of recycling of printed circuit boards, air sampling data for cellular phone processing showed that with the described engineering controls and work practices in place, occupational exposure to airborne metals analyzed fit the definition of “well controlled” for shredding, roasting, and alloying for nearly all metals characterized. Silver was the exception with exposures expected to be above the current OSHA PEL greater than 5 percent of the time, above conventional guidelines. The geometric standard deviations for all of the metals studied are less than 2.5, indicating good process stability.

Elevated silver exposures for each operation present an interesting dilemma for domestic electronic scrap processors. The current OSHA PEL of 0.01 mg/m^3 does not differentiate between the metal and the metallic salt as is done in other countries. This current PEL is overly protective based on Drake’s [7] meta analysis of silver toxicity and exposure data. This is unfortunate as the PEL for the metal is typically 10 times higher. The percent exceedance values around 0.1 mg/m^3 were < 1.0 for shredding, roasting and alloying.

Good work practices such as, diligent facility cleanliness and avoidance of airborne dust creation (dry cleaning or uncontrolled material handling) are important methods that E-scrap workers can employ to reduce their exposures. Appropriately designed and placed engineering controls (described in Table 2.) are equally necessary to reduce worker exposures to below regulatory limits.

Bulk sample results were within the ranges reported in the literature [8].

The milling operation equipped with ventilated milling and screening equipment hoods would be expected to better control airborne metal levels under normal operating conditions. However, equipment malfunctions need further study.

VI. Conclusion

In this study, shredding, roasting and alloying represented a minimal inhalation hazard for silver and no inhalation hazard to the operators for all other metals studied. Airborne silver exposure results for all four operations are expected to be above the OSHA PEL (0.01 mg/m^3) greater than five percent of the time, although less than

1.0 percent for the more toxicologically relevant exposure limit of 0.1 mg/m^3. Milling results were above the OSHA PEL for copper, silver and lead. Operator tasks required responding to atypical milling and screening equipment malfunctions significantly influenced operator exposures. US electronic scrap recyclers may be at a regulatory disadvantage as work practices and additional ventilation may be required to comply with the OSHA PEL for silver, when most countries in the European Union regulate metallic silver differently than the salt form.

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