Evaluation of Exposures to Metals and Flame Retardants at an Electronics Recycling Company

Jessica G. Ramsey, MS, CPE
George R. Grimes, MD, MPH
Catherine C. Beaucham, MPH, CIH, RS/REHS

HHE|HealthHazard Evaluation Program

CDC NIOSH

Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Contents

The cover photo is a close-up image of sorbent tubes, which are used by the HHE Program to measure airborne exposures. This photo is an artistic representation that may not be related to this Health Hazard Evaluation. Photo by NIOSH.

Highlights of this Evaluation

The Health Hazard Evaluation Program received a request from an electronics recycling company. The managers were concerned about exposure to metals and flame retardants.

What We Did

- We evaluated the electronics recycler in March and August 2017.

- We collected surface, handwipe, and air samples for 32 elements and 22 flame retardants.

- We collected blood samples for cadmium, lead, and 8 flame retardants.

- We collected urine samples for 7 flame retardants.

- We reviewed existing procedures, programs, and testing results.

What We Found

- Two employees in the dismantling building, who worked near a granulator, were overexposed to silver. All other personal air samples for metals were below occupational exposure limits.

- We found lead and cadmium in some employees' blood. Some blood lead levels were above reference levels of 5 micrograms per deciliter.

- We found the levels of some flame retardants on some employees' hands were higher after their shift than before.

- We found some flame retardants in the air samples.

- We found some flame retardants and metals in employees' blood and/or urine.

- We observed employees wearing N95 respirators incorrectly.

- We observed employees dry sweeping.

- We observed the conveyor segment from the optical sorter to the eddy current separator did not have an emergency stop pull cord.

> We assessed employees' exposures to metals and flame retardants at an electronics recycling company. We found some flame retardants typically associated with electronics in the air, on employees' hands, in their blood, and in their urine. Some employees had elevated levels of lead in their blood. Two personal air samples for silver were above occupational exposure limits. Among a number of recommendations, we recommend providing employees with a lead-removing product to wash their hands and prohibiting dry sweeping to clean work areas.

What the Employer Can Do

- Evaluate silver exposures for employees near the granulator to determine if employees continue to be overexposed to silver.

- Perform blood lead level testing for all processing employees in the shred building in accordance with expert panel guidelines.

- Prohibit dry sweeping. Use wet cleaning methods or high-efficiency particulate air vacuuming instead.

- Provide employees with a lead-removing product to wash their hands. Soap and water is not enough.

- Include employees working near the granulator in the hearing conservation program.

- Use both National Institute for Occupational Safety and Health and Occupational Safety and Health Administration criteria to identify hearing threshold shifts to improve early detection of potential hearing loss.

- Retrain employees on the proper wear and use of respirators, even if worn voluntarily.

- Install an emergency stop pull cord along the entire length of the conveyor that is accessible to employees.

What Employees Can Do

- Wash your hands with a lead-removing product before eating, drinking, smoking, or leaving work.

- Do not dry sweep. Use wet cleaning methods or high-efficiency particulate filter vacuuming instead.

- Wear N95 respirators correctly.

Abbreviations

α-HBCD	α-hexabromocyclododecane
β-HBCD	β-hexabromocyclododecane
γ-HBCD	γ-hexabromocyclododecane
μg	Microgram
μg/m^3	Micrograms per cubic meter
μg/dL	Micrograms per deciliter
μg/g	Micrograms per gram
μg/L	Micrograms per liter
μg/sample	Micrograms per sample
ACGIH®	American Conference of Governmental Industrial Hygienists
ACOEM	American College of Occupational and Environmental Medicine
ATSDR	Agency for Toxic Substances and Disease Registry
BCEP	bis(2-chloroethyl) phosphate
BCIPP	bis(l-chloro-2-propyl) phosphate
BDCIPP	bis(l,3-dichloro-2-propyl) phosphate
BDE-47	2,2',4,4'-tetrabromodiphenyl ether
BDE-85	2,2',3,4,4'-pentabromodiphenyl ether
BDE-99	2,2',4,4',5-pentabromodiphenyl ether
BDE-100	2,2',4,4',6-pentabromodiphenyl ether
BDE-153	2,2',4,4',5,5'-hexabromodiphenyl ether
BDE-154	2,2',4,4',5,6'-hexabromodiphenyl ether
BDE-183	2,2',3,4,4',5',6-heptabromodiphenyl ether
BDE-206	2,2',3,3',4,4',5,5',6-nonabromodiphenyl ether
BDE-209	decabromodiphenyl ether
BEH-TEBP	Bis(2-ethylhexyl) tetrabromophthalate
BLL	Blood lead level
BTBPE	1,2-Bis(2,4,6-tribromophenoxy) ethane
CDC	Centers for Disease Control and Prevention
CDPH	California Department of Public Health
CFR	Code of Federal Regulations
CSTE	Council of State and Territorial Epidemiologists
DecaBDE	Decabromodiphenyl ether technical mixture
DBDPE	Decabromodiphenyl ethane
DoCP	di-o-cresylphosphate
DpCP	di-p-cresylphosphate
DPHP	diphenyl phosphate
EH-TBB	2-ethylhexyl 2,3,4,5-tetrabromobenzoate
GM	Geometric mean
HEPA	High-efficiency particulate air
IARC	International Agency for Research on Cancer
LOD	Limit of detection
LOQ	Limit of quantification
mg/m^3	Milligrams per cubic meter

mL	Milliliter
ng/g	Nanograms per gram
ng/sample	Nanograms per sample
ng/100 cm^2	Nanograms per 100 square centimeters
ng/m^3	Nanograms per cubic meter
ND	Not detected
NHANES	National Health and Nutrition Examination Survey
NIOSH	National Institute for Occupational Safety and Health
NTP	National Toxilogy Program
OctaBDE	Octabromodiphenyl ether technical mixture
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
PBDE	Polybrominated diphenyl ether
PCB	Polychlorinated biphenyl
PEL	Permissible exposure limit
PentaBDE	Pentabromodiphenyl ether technical mixture
PP	Persistent pesticide
PPE	Personal protective equipment
REL	Recommended exposure limit
STEL	Short-term exposure limit
TBBA	2,3,4,5-tetrabromobenzoic acid
TBBPA	tetrabromobisphenol A
TCP	Tricresyl phosphate
TCEP	Tris(chloroethyl) phosphate
TCIPP	Tris(2-chloroisopropyl) phosphate
TDCIPP	Tris(1,3-dichloro-2-propyl) phosphate
TPHP	Tris(phenyl) phosphate
TLV®	Threshold limit value
TWA	Time-weighted average
WHO	World Health Organization
ZPP	Zinc protoporphyrin

Introduction

The Health Hazard Evaluation Program received a request from an electronics recycling company. The employer was concerned about possible employee exposures to flame retardant chemicals (flame retardants) and metals while recycling electronics. We first visited the facility in March 2017. We met with employer and employee representatives and toured the workplace to observe operations, work practices, and working conditions. We returned in August 2017 to collect air, handwipe, and blood samples for flame retardants and metals. We also collected urine samples to evaluate flame retardant exposure. We provided preliminary observations and recommendations to the employer and the employee representatives in March and September 2017.

Background

Electronic devices contain heavy metals and chemical substances that include flame retardants. Specifically, flame retardants are found in plastic and resin housings and components, wires, cable insulation, and circuit boards. They are also added to manufactured materials, surface finishes, and coatings to inhibit, suppress, or delay combustion and impede the spread of fire. Many electronics also contain dusts from sources, such as carpet padding or office furniture foam, which may contain flame retardants.

Polybrominated diphenyl ethers (PBDEs), tetrabromobisphenol A (TBBPA), and organophosphates are examples of flame retardants used in electronics. Recent observational epidemiological research concluded that PBDEs are associated with liver, thyroid, reproductive/developmental, and neurological effects [Dallaire et al. 2009; Grant et al. 2013]. Although PBDEs are no longer used in the manufacture of U.S. electronics, they will remain in the electronic recycling stream for decades. TBBPA, tris(phenyl) phosphate (TPHP), and other brominated flame retardants and organophosphate flame retardants will continue to be used and be present in the electronics recycling stream. Organophosphate flame retardants have been associated with adverse reproductive/developmental and neurological effects in animals [van der Veen and de Boer 2012]. We are able to measure levels of some flame retardants in blood and urine, but there is scientific uncertainty regarding the relationship between these levels in the body and specific health outcomes. More detailed information about flame retardants can be found in Appendix B.

Previous National Institute for Occupational Safety and Health (NIOSH) health hazard evaluations [NIOSH 2009a, 2014, 2018a,b, 2019a] found employee exposures to metals and flame retardants during electronic recycling, such as the following:

- Lead from batteries, printed circuit boards, power cords, and cathode ray tubes.
- Cadmium from batteries, pigments, plastic stabilizers, metal coatings, and cathode ray tube phosphors.
- Mercury from fluorescent lights, batteries, medical and telecommunication equipment, and some flat-panel displays.
- Flame retardants in computer and monitor housings, printed circuit boards, cables, conveyor belts, wire and cable insulation, and polyurethane foam.

Employee overexposures and potential take-home exposures to metals in the electronics recycling industry have also been documented [Ceballos and Dong 2016; Ceballos et al. 2016; Newman et al. 2015; NIOSH 2009a]. More detailed information about lead, cadmium, and other metals can be found in Appendix B.

Process Description

The company began operations in two warehouses in 2004. At the time of our evaluation, 38 employees worked full-time at the company. Their primary activities included shipping and receiving electronics, manual disassembly of electronics, shredding and sorting of electronics material, refurbishing and resale of functional electronics, and office work. Eight temporary workers also worked at the company, but these employees did not participate in the evaluation. Special projects employees performed work in multiple areas. Shredding was performed in a separate building from manual disassembly, resale, and special projects.

Shipping and Receiving

Approximately three employees received electronics when it entered the two buildings. These electronics were sorted and either categorized as "end-of-life" or "reusable." If the material was end-of-life, it was sent through the disassembly process (either manually or mechanically via shredding). If it was reusable, it was sent to the refurbishing and resale stations. Prior to distribution to either disassembly or refurbishing, the electronics were catalogued.

Refurbished electronics or recycled electronic parts were prepared and loaded onto trucks for shipping. Shipping and receiving employees routinely operated a forklift to unload and load electronics onto trucks.

Shredding and Sorting

Shredding was performed as a multistage process. An employee loaded components from a box placed on a tipper onto a conveyor where it proceeded to a shredder. After the first shred, a magnet was used to pick up any metal. Employees were located at top-rail stations to remove any undesired components. The material then went through a second shredder and another magnet. Another employee removed any undesired components. The material went over a vibrating screen to sort by size and then through an optical sorter to remove plastic. Finally, the material went through an eddy current separator to remove nonferrous metal. At the magnet locations, metal was collected in large pans. When employees removed the pans to empty them, they also used a broom to sweep up any material on the floor. Sweeping compound was provided.

Thirteen employees worked in the processing area of the shred building. One or two employees sorted mixed circuit boards on a sort table into 10–15 different boxes depending on the type and amount of precious metals they contained.

Refurbishing and Resale

Refurbishing and resale had five employees in the dismantling building. Employees inspected electronics for reusable parts, cleaned sticky residue from the back of computer central processing units, photographed electronic equipment, listed it on used equipment internet sales sites, and prepared it for shipping.

Manual Disassembly

The manual disassembly department had five full-time employees in the dismantling building. Employees could rotate through all of the positons during manual disassembly throughout the day.

Two employees worked in cabinet disassembly. They removed components from large cabinets that were approximately 6 feet tall and 2 feet wide. The unusable electronic components inside the cabinets were consolidated and sent to the shred building. This workstation was located next to a partial wall that separated the employees from a "granulator" that was owned and operated by another company that shared the building. The granulator was a piece of equipment that was used to reduce the size of material prior to refining. The company used it for size reduction of steel wire.

Three to five employees worked in the disassembly (A-line). Multiple disassembly workstations were located along a long-push (nonmechanical) conveyor. Employees worked on each side of the conveyor to disassemble various electronic products, such as computer towers, laptops, and printers. The employee at the first workstation removed the cases around the electronics. The part was then pushed along the conveyor to the next series of workstations where the employees separated the usable parts (for resale) from the unusable parts (for shredding). Other components were separated by the type of material and placed in cardboard boxes.

Special Projects

The special projects department had seven employees in the dismantling building. Employees rotated through a number of departments throughout the day. Their job duties involved unboxing items, scanning hard drives, removing batteries from metal housings, and sorting the housing, battery, and circuitry. These employees also helped with shipping and receiving when necessary. On the days of our evaluation, two special projects employees were assisting with cabinet disassembly.

Office Employees

Four employees worked in the office. These employees typically worked at a desk using a computer. Some employees periodically entered the processing area of the shred building, while others rarely entered the processing area.

Methods

We presented the objectives and elements of our evaluation to all full-time employees present who performed shipping and receiving, shredding and sorting, refurbishing and resale, manual disassembly, special projects, and office work. We obtained informed consent from all participants prior to beginning the evaluation. We asked all participants to fill out a questionnaire about their pertinent personal and work history, such as length of employment, job tasks, current work practices, use of personal protective equipment (PPE), and hygiene practices. At the end of each shift, we asked each participant to complete a brief questionnaire about their work practices on that day. Our objectives were to evaluate flame retardant and metal exposures, as detailed below:

Flame retardants

1. Characterize employee exposures to selected flame retardants.

2. Compare the levels of selected flame retardants in employees' blood and urine to levels in the general population.

3. Assess whether airborne and dermal exposures to selected flame retardants contributed to the levels in employees' blood and urine.

Metals

1. Characterize employee exposures to metals.

2. Assess whether employee exposures to airborne metals exceed applicable occupational exposure limits (OELs).

3. Assess whether employees' blood lead and cadmium levels exceed biological exposure indices.

4. Evaluate the potential for take-home contamination from metals.

In Appendix A, Table A1 lists the flame retardants that we sampled for, where they are typically found, and when they are typically used, if used in electronics. Table A2 lists the three types of PBDE technical mixtures that we sampled for and their major congeners (a group of related chemicals). PBDE technical mixtures include pentabromodiphenyl ether (PentaBDE), octabromodiphenyl ether (OctaBDE), and decabromodiphenyl ether (DecaBDE). For some of our analyses, we divided the flame retardants into five categories on the basis of their usage in electronics.

Surface and Handwipe Samples for Flame Retardants

In August 2017, we collected preshift and postshift handwipe samples on two sampling days. We pre-soaked two 3-inch by 3-inch gauze pads with approximately 6 milliliters (mL) of laboratory grade 99% isopropyl alcohol and placed them in a glass vial [Carignan et al. 2013]. We donned clean nitrile gloves, then opened the glass vial. We asked the employee to take one wipe from the vial and wipe both palms from wrist to finger tips for 30 seconds, and then place the wipe back into the same glass vial. We then asked the employee to take the second wipe from the vial and repeat the process for the back of both hands and again place the wipe into the same glass vial. We sealed the vial with its lid and a Parafilm® wrap. We collected the postshift

sample before each participating employee washed his or her hands prior to going home.

We collected surface wipe samples for flame retardants in the processing areas. We used a 10-centimeter by 10-centimeter square disposable template to define the sampling area, and then used the premoistened alcohol wipes to wipe the surfaces. We collected these surface wipe samples to determine which type of flame retardants were present in the work environment, where they were located, and in which areas their levels were the highest.

A contract lab analyzed all handwipes for flame retardants by ultra-performance liquid chromatography atmospheric pressure photoionization tandem mass spectrometry using methods previously described by La Guardia and Hale [2015]. All wipes were spiked with surrogate standards prior to extraction to determine the percent recovery for each type of flame retardant. The wipe sample results were surrogate corrected for percent recovery.

The flame retardants we analyzed are listed below. We used the abbreviation standard for flame retardants proposed by Bergman et al. [2012]:

- α-hexabromocyclododecane (α-HBCD)
- β-hexabromocyclododecane (β-HBCD)
- γ-hexabromocyclododecane (γ-HBCD)
- 2,2',4,4'-tetrabromodiphenyl ether (BDE-47)
- 2,2',3,4,4'-pentabromodiphenyl ether (BDE-85)
- 2,2',4,4',5-pentabromodiphenyl ether (BDE-99)
- 2,2',4,4',6-pentabromodiphenyl ether (BDE-100)
- 2,2',4,4',5,5'-hexabromodiphenyl ether (BDE-153)
- 2,2',4,4',5,6'-hexabromodiphenyl ether (BDE-154)
- 2,2',3,4,4',5',6-heptabromodiphenyl ether (BDE-183)
- 2,2',3,3',4,4',5,5',6-nonabromodiphenyl ether (BDE-206)
- decabromodiphenyl ether (BDE-209)
- 1,2-Bis(2,4,6-tribromophenoxy) ethane (BTBPE)
- Decabromodiphenyl ethane (DBDPE)
- 2-ethylhexyl 2,3,4,-tetrabromobenzoate (EH-TBB)
- tetrabromobisphenol A (TBBPA)
- Bis(2-ethylhexyl) tetrabromophthalate (BEH-TEBP)
- Tricresyl phosphate (TCP)
- Tris(chloroethyl) phosphate (TCEP)
- Tris(2-chloroisopropyl) phosphate (TCIPP)
- Tris-(1,3-dichloro-2-propyl) phosphate (TDCIPP)
- Tris(phenyl) phosphate (TPHP)

Air Samples for Flame Retardants

We collected full-shift personal air samples on two consecutive days on each participant. We collected the air samples for flame retardants on an Institute of Medicine sampler with a glass fiber filter at a flow rate of 2 liters per minute. The Institute of Medicine sampler collects the inhalable fraction of particulates. A contract lab analyzed the samples for the same flame retardants that were analyzed from the handwipes according to an internal method [La Guardia and Hale 2015].

Blood Samples for Flame Retardants and Metals

We collected approximately 30 mL of blood from each participant at the end of their shift at the end of the workweek. A trained technician drew venous blood into 2 serum separating tubes and 1 whole blood tube. We sent one tube of serum to the National Center for Environmental Health laboratory for analysis for PBDEs, polychlorinated biphenyls (PCBs), persistent pesticides (PPs), and cholesterol and triglycerides. PBDEs included BDE-47, BDE-85, BDE-99, BDE-100, BDE-153, BDE-154, BDE-183, and BDE-209. Cholesterol and triglycerides were measured to adjust brominated flame retardant, PCB, and PP levels for body fat. We sampled for PCBs and PPs to address the possibility of dietary effects on the levels of the PBDEs. The tube of whole blood was sent to a commercial laboratory to be analyzed for blood lead and cadmium levels.

Urine Samples for Flame Retardants

We collected preshift and postshift urine samples on each day that air and handwipe sampling for flame retardants was done. Each urine sample was collected in a sterile, 250 mL plastic cup. We measured the specific gravity of each sample, shook it, then aliquoted 30 mL into a container that was sent to the National Center for Environmental Health laboratory for analysis of the following flame retardant metabolites:

- diphenyl phosphate (DPHP) – a metabolite of TPHP
- bis(l,3-dichloro-2-propyl) phosphate (BDCIPP) – a metabolite of TDCIPP
- bis(l-chloro-2-propyl) phosphate (BCIPP) – a metabolite of TCIPP
- bis(2-chloroethyl) phosphate (BCEP) – a metabolite of TCEP
- di-p-cresylphosphate (DpCP) – a metabolite of TCP
- di-o-cresylphosphate (DoCP) – a metabolite of TCP
- 2,3,4,5-tetrabromobenzoic acid (TBBA) – a metabolite of EH-TBB

These analyses were conducted using the approach reported by Jayatilaka et al. [2017]. We used the reference range values in urine for the flame retardant metabolites for the U.S. population ages 20–59 as described in Ospina et al. [2018].

Surface and Handwipe Samples for Metals

We collected and analyzed surface and handwipe samples for metals according to NIOSH Manual of Analytical Methods Number 9102, including indium and lithium [NIOSH 2019b]. For surface samples, we used a 10-centimeter by 10-centimeter square disposable template to demarcate the sampling area and wiped the surface with a premoistened SKC Inc. Ghostwipe® towelette. We also collected a postshift handwipe sample for metals from each participant on one day using the same method as previously described for flame retardants, except that we used the premoistened Ghostwipe towelettes instead of alcohol soaked wipes. We collected these handwipe samples after each participating employee washed his or her hands to determine the potential for take-home exposure. These samples were not collected

on the same day as the handwipe samples for flame retardants.

Air Samples for Metals

We collected personal air samples for metals and minerals, including indium and lithium, on 37-millimeter cassettes and analyzed them according to NIOSH Method 7303 [NIOSH 2019b] with modification. The modification included using a digestible Solucert® to collect particles on the inside of the cassette walls as recommended by NIOSH [2016].

Statistical Analysis

We used SAS version 9.3 software and EpiInfo version 7 for data analysis. Flame retardant wipe and air sample data were corrected for recoveries reported by the laboratory on three replicate spikes (100 nanograms per sample [ng/sample]) on blank wipes. For sample results that were reported as "not detected (ND)," we used the laboratory reporting limit divided by the square root of 2 [Hornung and Reed 1990] as the estimate. We examined the distributions of the air, handwipe, and urine data. Some were normally distributed, some were log normally distributed, and some were neither; therefore, we reported medians, geometric means (GM), and ranges. We did not calculate medians or GMs unless 70% or more of the samples had detectable results. We also did not report medians or GMs if the sample size was five or less. Comparisons of medians or GMs were based simply on observation. Statistical testing was not done due to the small number of participants in the evaluation. The reporting limit was 1 ng/sample for all of the flame retardant air samples. The reporting limit was 10 ng/sample for all of the flame retardant wipe samples. We compared the levels of urine and serum flame retardants biomarkers with the general population using the National Health and Nutrition Examination Survey (NHANES) data [ACGIH 2019; NIOSH 2014; Ospina et al. 2018; Sjödin et al. 2008]. We reported GMs for the study participants and the general population using relevant age ranges. We reported creatinine-uncorrected and creatinine-corrected urinary concentrations, as both methods have been used for comparisons in the literature. Creatinine-corrected results can account for individual variation.

Observation and Document Review

We observed workplace conditions and work processes and practices. We also reviewed the following information provided by the company: industrial hygiene monitoring procedures, hearing conservation program, previous air sampling and noise assessment results, voluntary dust mask usage and fitting instructions, and results of blood lead and zinc protoporphyrin (ZPP) testing.

Results

Participant Characteristics

Twenty-five employees participated in this evaluation: six were female. The average age was 43.2 years (range: 22–65 years), and the median length of time in this company was 60 months (range: 12–144 months). Thirteen employees worked in the dismantling building,

and 12 employees worked in the shred building. Participants usually worked 40 hours per week (range: 38–50 hours). Job titles for participants included shredding and sorting (eight participants), disassembly (five), special projects (four), shipping and receiving (three), resale (three), and office (two). Three employees reported that they currently smoked. We asked employees about handwashing, the use of gloves, and if they took their work clothes and shoes home with them. Responses to these questions are shown in Table 1.

Table 1. Self-reported handwashing and use of work clothes, gloves, and shoes in employees by building (n = 25)

Work characteristic	Work location, number (%)	
	Dismantling building (n = 13)	Shred building (n = 12)
Wear work clothing home	12 (95)	3 (25)
Wear work shoes home	9 (69)	2 (17)
Wear work gloves at work	12 (92)	11 (92)
All the time	7 (58)	6 (50)
Most or some of the time	5 (42)	6 (50)
Reuse gloves at work	10 (91)*	12 (100)
Frequency of employees washing hands at work		
More than 5 times per day	6 (46)	4 (33)
4 or 5 times per day	6 (46)	7 (58)
3 or fewer times per day	1 (7.7)	1 (8.3)
Always wash hands before leaving work	12 (100)	11 (85)

*n = 11 because only 11 employees reported wearing gloves in the dismantling building.

Surface and Handwipe Sampling for Flame Retardants

Tables 2 and 3 summarize the results of the preshift and postshift handwipe sampling for flame retardants taken on two consecutive days for each of the departments. In general, we found higher median levels of the flame retardants categorized as "commonly used in electronics now and in the past" in the postshift samples for participants in both buildings. We saw a similar trend for the primary DecaBDE congener (BDE-209), which was commonly used in electronics until around 2013. Employees working in the shredding department had the highest postshift DBDPE level (58,000 micrograms per sample [µg/sample]) and BDE-209 level (3,900 µg/sample). Employees working in the disassembly department had the highest postshift TCP level (47,000 µg/sample).

The congeners for OctaBDE flame retardants (commonly used in electronics until 2004) were found in very few of the samples, and when found, were not detected in sufficient quantities to calculate medians in either the preshift or postshift measurements. HBCD (α,β,γ) was only found in four postshift handwipe samples in the shred building.

The congeners for PentaBDE (rarely used in electronics) and other flame retardants "less commonly used in electronics now and in the past" did not show substantial differences or trends between median levels in preshift and postshift handwipes.

Table 2. Preshift and postshift levels of flame retardants in handwipe samples in the dismantling building, by job task, in ng/sample

Flame retardant	Disassembly (n = 10) % detected median* range		Special Projects (n = 7) % detected median* range		Resale (n = 6) % detected median* range	
	Preshift	Postshift	Preshift	Postshift	Preshift	Postshift
OctaBDE (commonly used in electronics until around 2004)						
BDE-183	0%	40% ND–330	0%	0%	0%	0%
BDE-154†	0%	0%	0%	0%	0%	0%
BDE-153†	0%	20% ND–43	0%	0%	0%	17% ND–13
OctaBDE and DecaBDE (commonly used in electronics until around 2013)						
BDE-209	80% 130 ND–500	100% 390 23–1,300	100% 57 24–340	86% 200 ND–1,100	67% ND–79	100% 57 44–270
BDE-206	0%	50% ND–75	0%	14% ND–100	0%	0%
Commonly used in electronics now and in the past						
TPHP	100% 220 83–800	100% 690 300–2,100	100% 650 190–1,200	100% 700 340–980	100% 310 120–4,100	100% 730 130–1,700
TCP	90% 460 ND –23,000	100% 1,200 ND–47,000	100% 650 190–1,200	100% 850 380–1,700	100% 1,200 290–2,300	100% 1,700 780–4,200
BTBPE	50% ND–240	60% ND–330	29% ND–710	57% ND–120	0%	17% ND–22
DBDPE	70% 900 ND–7,200	80% 2,100 ND–11,000	100% 380 280–2,500	43% ND–28,000	50% ND–710	50% ND–2,200
TBBPA	80% 44 ND–200	100% 180 22–800	43% ND–230	100% 610 340–880	0%	83% 28 ND–80
Less commonly used in electronics now and in the past						
EH-TBB	70% 25 ND–410	90% 25 ND–240	86% 14 ND–120	71% 26 ND–110	17% ND–8.4	17% ND–7.2
BEH-TEBP	90% 130 ND–780	100% 140 46–760	100% 51 26–2,000	71% 320 ND–4,400	67% ND–12	100% 36 17–120
TCEP	0%	0%	0%	14% ND–99	0%	0%
TCIPP	20% ND–200	20% ND–150	57% ND–2,100	57% ND–380	50% ND–130	33% ND–93
Rarely used in electronics‡						
PentaBDE						
BDE-99	70% 22 ND–65	70% 14 ND–68	71% 11 ND–31	43% ND–14	100% 24 12–70	100% 22 16–160
BDE-47	60% ND–53	40% ND–62	71% 8.3 ND–20	29% ND–17	83% 15 ND–57	100% 16 11–89
BDE-100	30% ND–22	20% ND–24	0%	0%	33% ND–9.9	33% ND–29
BDE-85	0%	0%	0%	0%	0%	17% ND–24
TDCIPP	80% 160 ND–960	80% 170 ND–410	86% 660 ND–2,500	100% 410 250–430	83% 530 ND–1,100	100% 230 130–1,100

Limit of detection (LOD) = 10 ng/sample
*Medians were not calculated if percentage detected was below 70%.
†Also present in PentaBDE in small amounts.
‡Primarily used in polyurethane foam and commonly present in dust.

Table 3. Preshift and postshift levels of flame retardants in handwipe samples in the shred building, by job task, in ng/sample

Flame retardant	Shredding (n = 14) % detected median* range		Shipping and Receiving (n = 6) % detected median* range		Office (n = 4) % detected median* range	
	Preshift	Postshift	Preshift	Postshift	Preshift	Postshift
OctaBDE (commonly used in electronics until around 2004)						
BDE-183	7% ND–12	57% ND–140	0%	33% ND–15	0%	0%
BDE-154†	7% ND–180	0%	0%	0%	0%	0%
BDE-153†	29% ND–200	71% 9.7 ND–32	0%	0%	25% ND–14	0%
OctaBDE and DecaBDE (commonly used in electronics until around 2013)						
BDE-209	93% 120 ND–390	100% 1,200 240–3,900	100% 310 7.8–1,100	100% 92 40–390	100% 58–110	100% 33–230
BDE-206	0%	36% ND–130	33% ND–63	0%	0%	0%
Commonly used in electronics now and in the past						
TPHP	100% 280 120–740	100% 1,100 420–6,600	83% 400 ND–4,200	100% 1,200 220–4,100	100% 93–190	100% 150–350
TCP	100% 740 210–1,400	100% 1,800 740–12,000	83% 690 ND–1,200	100% 670 300–2,800	100% 190–550	100% 240–610
BTBPE	14% ND–12	100% 100 16–290	67% ND–17	50% ND–24	25% ND–21	25% ND–13
DBDPE	93% 530 ND–2,500	100% 5,900 1,800–58,000	83% 1,300 ND–3,100	83% 1,100 ND–2,800	100% 86–730	100% 180–3,900
TBBPA	93% 32 ND–140	100% 500 91–3,900	83% 74 ND–190	83% 67 ND–270	100% 6.6–30	100% 17–140
Less commonly used in electronics now and in the past						
EH-TBB	86% 20 ND–140	43% ND–50	67% ND–430	67% ND–340	75% ND–31	50% ND–32
BEH-TEBP	64% ND–60	100% 40 11–120	67% ND–100	67% ND–600	75% ND–67	100% 16–79
TCEP	7% ND–740	7% ND–970	17% ND–170	67% ND–2,400	0%	0%
TCIPP	64% ND–720	29% ND–550	33% ND–160	50% ND–150	100% 83–260	50% ND–120
Rarely used in electronics‡						
PentaBDE						
BDE-99	79% 29 ND–2,700	93% 41 ND–220	67% ND–37	50% ND–39	75% ND–84	100% 14–97
BDE-47	71% 30 ND–2,200	86% 54 ND–240	67% ND–41	33% ND–51	75% ND–67	100% 12–79
BDE-100	50% ND–430	57% ND–31	17% ND–11	17% ND–7.1	25% ND–16	50% ND–15
BDE-85	21% ND–140	14% ND–17	0%	0%	0%	0%
TDCIPP	86% 320 ND–1,600	43% ND–3,100	100% 1,200 330–3,200	83% 290 ND–3,100	0%	25% ND–160

LOD = 10 ng/sample

*Medians were not calculated if percentage detected was below 70% or the n > 5.

†Also present in PentaBDE in small amounts.

‡Primarily used in polyurethane foam and commonly present in dust.

Table 4 shows the results of the surface wipe sampling collected throughout the facility. The areas with the highest concentration of flame retardants in the shred building were the shredder station (78,794 nanograms per 100 square centimeters [ng/100 cm^2]), followed by the forklift seat (26,388 ng/100 cm^2) and sort table (20,230 ng/100 cm^2). The areas with the highest concentration of flame retardants in the dismantling building were the A-line second workstation (43,708 ng/100 cm^2), followed by the drill handle for cabinet disassembly (38,341 ng/100 cm^2) and the resale workstation (19,724 ng/100 cm^2).

We found TCP in all sample locations, with the highest level (15,000 ng/100 cm^2) at the shredder station. Similarly, we found the other flame retardants classified as "commonly used in electronics now and in the past" in nearly all of the sample locations. We found DBDPE in 8 of the 10 sample locations, with the highest level (33,000 ng/100 cm^2) at the A-line second workstation followed by the shredder station (32,000 ng/100 cm^2). Though classified as "less than commonly used in electronics now and in the past," we found BEH-TEBP in all sample locations, but at relatively lower levels than TCP.

Table 4. Surface wipe samples for flame retardants, in ng/100 cm²

Flame retardant	Forklift - new seat	Shredder - station	Sort table	Shredder - top rail	Shipping and receiving office	Cabinet disassembly - drill handle	A-line 2nd work station	A-line 1st work station	Resale	Shipping and receiving forklift
		Shred building						Dismantling building		
OctaBDE (commonly used in electronics until around 2004)										
BDE-183	ND	240	ND	ND	ND	90	ND	ND	ND	ND
BDE-154*	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
BDE-153*	12	48	6.9	9.4	ND	5.8	48	ND	13	ND
OctaBDE and DecaBDE (commonly used in electronics until around 2013)										
BDE-209	1,700	4,200	580	1,300	110	420	2,500	350	430	ND
BDE-206	70	75	12	53	ND	36	86	10	ND	ND
Commonly used in electronics now and in the past										
TPHP	3,900	7,100	1,500	1,800	900	1,900	800	1,600	1,800	ND
TCP	8,900	15,000	2,600	3,600	710	2,200	1,400	2,600	1,900	920
DBDPE	9,400	32,000	7,800	8,600	ND	18,000	33,000	2,700	14,000	ND
BTBPE	600	8,800	110	79	ND	90	410	40	87	ND
TBBPA	1,000	9,900	610	360	27	1,600	3,500	250	290	ND
Less commonly used in electronics now and in the past										
EH-TBB	17	79	4.9	18	12	480	48	6.5	32	ND
BEH-TEBP	200	470	38	78	48	12,000	520	28	550	13
TCEP	ND	ND	240	ND	ND	ND	ND	ND	ND	ND
TCIPP	92	170	3,000	42	ND	86	68	ND	40	ND
α-HBCD	ND	33	ND	ND	ND	ND	190	ND	ND	ND
β-HBCD	ND	16	ND	ND	ND	ND	50	ND	ND	ND
γ-HBCD	ND	12	ND	ND	ND	1,000	36	ND	ND	ND
Rarely used in electronics†										
PentaBDE										
BDE-99	49	90	14	26	5.5	9.0	110	3.1	32	ND
BDE-47	46	91	11	26	3.7	4.2	84	3.6	ND	ND
BDE-100	7.1	100	3.5	ND	3.7	ND	ND	ND	ND	ND
BDE-85	5.0	ND	ND	ND	ND	ND	7.8	ND	ND	ND
TDCIPP	390	370	3,700	350	150	420	850	120	550	ND

LOD = 10 ng/sample
*Also present in PentaBDE in small amounts.
†Primarily used in polyurethane foam and commonly present in dust.

Air Samples for Flame Retardants

Results of personal air sampling for flame retardants are listed in Tables 5 and 6. Two flame retardant air samples were not reported in the dismantling building due to sample pump failure and calibration issues. PBDEs are listed by technical mixture (i.e., OctaBDE) and by decreasing concentration of each congener within that mixture [Alaee et al. 2003; LaGuardia et al. 2006]. All full-shift personal air samples for flame retardants were low, ranging from ND to 310 nanograms per cubic meter (ng/m^3) in the dismantling building and ND to 870 ng/m^3 in the shred building. In general, we found higher median levels of the flame retardants categorized as "commonly used in electronics now and in the past" in both buildings. We saw a similar trend for the primary DecaBDE congener (BDE-209), which was commonly used in electronics until around 2013.

In the dismantling building, DBDPE was detected in 100% of the air samples and had the highest relative median (310 ng/m^3) and GM (250 ng/m^3). TCP and TCIPP were also found in 100% of the air samples with median concentrations ranging 14–130 ng/m^3. BDE-209 and TPHP were detected in 83%–91% of the air samples with median concentrations ranging 7.7–81 ng/m^3.

In the shred building, DBDPE was detected in 95% of the air samples and had the highest relative median (870 ng/m^3) and GM (500 ng/m^3). BDE-209 and TCIPP were found in 100% of the air samples with median concentrations ranging 43–120 ng/m^3. TCP, TPHP, and TBBPA were also detected in 95% of the air samples with median concentrations ranging 33–690 ng/m^3.

Table 5. Full-shift personal air sampling results for 13 employees in the dismantling building over 2 days (n = 23*), in ng/m^3

Flame retardant	Median†	GM† (range)	# (%) detected
OctaBDE (commonly used in electronics until around 2004)			
BDE-183	—	(ND–2.3)	5 (22)
BDE-154‡	ND	ND	0 (0)
BDE-153‡	—	(ND–43)	1 (4)
OctaBDE and DecaBDE (commonly used in electronics until around 2013)			
BDE-209	7.7	8.1 (ND–63)	21 (91)
BDE-206	—	(ND–2.0)	2 (9)
Commonly used in electronics now and in the past			
TPHP	81	39 (ND–320)	19 (83)
TCP	120	130 (38–840)	23 (100)
DBDPE	310	250 (27–930)	23 (100)
BTBPE	—	(ND–29)	12 (52)
TBBPA	2.1	2.9 (ND–92)	17 (74)
Less commonly used in electronics now and in the past			
EH-TBB	—	(ND–30)	9 (39)
BEH-TEBP	4.2	5.0 (ND–110)	18 (78)
TCEP	—	(ND–24)	9 (39)
TCIPP	14	14 (5.2–33)	23 (100)
HBCD (α,β,γ)	ND	ND	0 (0)
Rarely used in electronics§			
PentaBDE			
BDE-99	1.2	1.5 (ND–77)	18 (78)
BDE-47	—	(ND–1.7)	2 (9)
BDE-100	—	(ND–7.6)	1 (4)
BDE-85	—	(ND–5.7)	1 (4)
TDCIPP	5.3	5.1 (ND–17)	20 (87)

The minimum detectable concentrations were calculated using an average volume of 877 liters (1 ng/m^3) for all of the flame retardants.

*One employee missed work on the first day of sampling and two samples had pump issues.

†Medians and GMs were not calculated if percentage detected was below 70%.

‡Also present in PentaBDE in small amounts.

§Primarily used in polyurethane foam, and commonly present in dust.

Table 6. Full-shift personal air sampling results for 12 participants in shred building over 2 days (n = 22*), in ng/m³

Flame retardant	Median†	GM† (range)	# (%) detected
OctaBDE (commonly used in electronics until around 2004)			
BDE-183	—	(ND–13)	15 (68)
BDE-154‡	ND	ND	0 (0)
BDE-153‡	—	(ND–4.4)	10 (45)
OctaBDE and DecaBDE (commonly used in electronics until around 2013)			
BDE-209	120	75 (4.3–530)	22 (100)
BDE-206	—	(ND–13)	14 (64)
Commonly used in electronics now and in the past			
TPHP	350	230 (ND–1,600)	21 (95)
TCP	690	510 (ND–2,700)	21 (95)
DBDPE	870	500 (ND–4,100)	21 (95)
BTBPE	8.6	7.0 (ND–220)	17 (77)
TBBPA	33	22 (ND–150)	21 (95)
Less commonly used in electronics now and in the past			
EH-TBB	—	(ND–3.3)	13 (59)
BEH-TEBP	3.5	3.4 (ND–13)	19 (86)
TCEP	14	7.7 (ND–47)	17 (77)
TCIPP	43	39 (8.0–110)	22 (100)
HBCD (α,β,γ)	ND	ND	0 (0)
Rarely used in electronics§			
PentaBDE			
BDE-99	2.2	2.4 (ND–7.2)	20 (91)
BDE-47	—	(ND–4.4)	15 (68)
BDE-100	ND	ND	0 (0)
BDE-85	ND	ND	0 (0)
TDCIPP	10	7.3 (ND–36)	18 (82)

The minimum detectable concentration were calculated using an average volume of 877 liters (1 ng/m³) for all of the flame retardants.

*One employee missed work each day of sampling.

†Medians and GMs were not calculated if percentage detected was below 70%.

‡Also present in PentaBDE in small amounts.

§Primarily used in polyurethane foam, and commonly present in dust.

Results of personal air sampling for flame retardants, stratified by job tasks performed during sampling, are in Table 7. In general, we detected more flame retardants in the shredding employees' air samples than in the other job tasks. However, we found both flame retardants that are commonly used in electronics as well as flame retardants that are rarely used in electronics throughout both buildings.

Table 7. Concentrations of flame retardants in full-shift personal air samples, by job task, over 2 days, in ng/m^3

Flame retardant	Shredding n = 14 % detected median* range	Shipping/Receiving n = 6 % detected median* range	Office n = 4 % detected median* range	Disassembly n = 8 % detected median* range	Special Projects n = 7 % detected median* range	Resale n = 6 % detected median* range
OctaBDE (commonly used in electronics until around 2004)						
BDE-183	93% 1.6 ND–13	33% ND–5.9	0%	50% ND–2.1	14% ND–2.3	0%
BDE-154†	0%	0%	0%	0%	0%	0%
BDE-153†	57% ND–2.9	17% ND–1.4	25% ND–4.4	13% ND–43	0%	0%
OctaBDE and DecaBDE (commonly used in electronics until around 2013)						
BDE-209	100% 170 31–530	100% 42 4.3–130	100% 4.8–15	100% 22 3.7–63	100% 10 2.8–22	67% ND–4.2
BDE-206	79% 3.8 ND–13	50% ND–4.4	0%	25% ND–2.0	0%	0
Commonly used in electronics now and in the past						
TPHP	100% 570 160–1,000	100% 110 42–1,600	75% ND–110	100% 89 44–320	100% 87 60–140	33% ND–40
TCP	100% 1,300 440–2,700	100% 310 85–590	75% ND–200	100% 130 77–840	100% 160 93–210	100% 66 38–100
DBDPE	100% 1,100 370–4,100	83% 350 ND–2,200	100% 51–89	100% 360 230–930	100% 430 140–690	100% 82 27–160
BTBPE	100% 11 5.6–220	67% ND–9.0	0%	88% 5.6 ND–29	57% ND–7.9	0%
TBBPA	100% 56 4.4–150	67% ND–83	100% N/A 2.5–4.3	88% 5.0 ND–21	100% 2.6 1.1–92	33% ND–2.1

The minimum detectable concentration were calculated using an average volume of 877 liters (1 ng/m^3) for all of the flame retardants.

*Medians were not calculated if percentage detected was below 70%.

†Also present in PentaBDE in small amounts.

‡Primarily used in polyurethane foam and commonly present in dust.

Table 7 Continued. Concentrations of flame retardants in full-shift personal air samples, by job task, over 2 days, in ng/m³

Flame retardant	Shredding n = 14 % detected median* range	Shipping/Receiving n = 6 % detected median* range	Office n = 4 % detected median* range	Disassembly n = 8 % detected median* range	Special Projects n = 7 % detected median* range	Resale n = 6 % detected median* range
Less commonly used in electronics now and in the past						
EH-TBB	79% 1.2 ND–2.9	17% ND–2.0	50% ND–3.3	63% ND–30	43% ND–4.4	0%
BEH-TEBP	100% 5.5 1.6–13	83% 3.2 ND–5.5	50% ND–3.3	100% 5.6 2.3–27	100% 4.7 3.4–110	17% ND–1.6
TCEP	86% 14 ND–47	100% 14 5.2–32	25% ND–18	50% ND–19	29% ND–9.7	17% ND–7.6
TCIPP	100% 47 8.0–110	100% 21 6.5–32	100% 43–73	100% 20 11–33	100% 18 6.0–22	100% 8.3 5.2–14
HBCD (α,β,γ)	0%	44% ND–15	0%	0%	0%	0%
Rarely used in electronics‡						
PentaBDE						
BDE-99	100% 3.4 1.6–7.2	100% 1.4 0.74–2.6	50% ND–7.0	100% 1.4 1.1–77	43% ND–1.2	83% 1.3 ND–2.6
BDE-47	93% 1.9 ND–4.4	33% ND–1.4	0%	25% ND–1.7	0%	0%
BDE-100	0%	0%	0%	13% ND–7.6	0%	0%
BDE-85	0%	0%	0%	13% ND–5.7	0%	0%
TDCIPP	100% 15 3.6–36	83% 4.7 ND–13	25% ND–4.3	100% 9.7 3.2–17	100% 4.9 3.5–12	50% ND–12

The minimum detectable concentration were calculated using an average volume of 877 liters (1 ng/m³) for all of the flame retardants.

*Medians were not calculated if percentage detected was below 70%.

†Also present in PentaBDE in small amounts.

‡Primarily used in polyurethane foam and commonly present in dust.

Blood Samples for Flame Retardants

All 25 participants had blood drawn for PBDEs. Table 8 shows the serum PBDE concentrations in our participants for 10 different polybrominated flame retardants. The table also shows the serum PBDE concentrations found in NHANES, which is a representative sample of the general population. The highest median and GM serum PBDE concentrations in our participants were for BDE-47, BDE-153, and BDE-209. In addition, all 25 participants had BDE-47, BDE-99, BDE-100, BDE-153, and BDE-209 detected in their blood serum. The GM concentration of BDE-209 was 4.4 nanograms per gram (ng/g) lipid weight in our participants, which was below the LOD of 5.8 ng/g lipid weight reported in NHANES.

Table 8. PBDE concentrations in serum of electronics recycling employees and in the NHANES, in ng/g lipid weight

Flame retardants	Electronics recycling company participants (n = 25)			NHANES*		
	Median†	GM†	Max	Median	GM	95th percentile
OctaBDE (commonly used in electronics until around 2004)						
BDE-183	0.69	0.49	1.67	Not reported	ND (< 1.7)	ND (< 1.7)
BDE-154‡	(—)	(—)	0.64	Not reported	ND (< 0.8)	4.20
BDE-153‡	4.02	5.19	35.01	4.40	5.41	73.3
OctaBDE and DecaBDE (commonly used in electronics until around 2013)						
BDE-209	3.63	4.42	24.6	Pooled sample; no mean calculated due to high proportion of ND (< 5.8) §		
PentaBDE (rarely used in electronics)¶						
BDE-99	1.02	1.08	7.31	Not reported	ND (< 5.0)	41.6
BDE-47	5.13	4.87	34.4	18.0	19.5	163.0
BDE-100	1.25	1.18	8.5	3.30	3.77	36.6
BDE-85	(—)	(—)	0.81	Not reported	ND (< 2.4)	4.10

*Age 20 and older; samples taken 2003 and 2004.

†Median and GM not calculated if percentage detected was below 70%, represented by (—).

‡Also present in PentaBDE in small amounts.

§Data from 2007–2008 NHANES.

¶Primarily used in polyurethane foam and commonly present in dust.

We also analyzed serum PBDE levels for employees in the dismantling and shred buildings. Participants working in the shred building generally had higher levels of BDE-209. These results are displayed in Table 9.

Table 9. PBDE concentrations in serum of dismantling and shred building participants, in ng/g lipid weight

Flame retardants	Dismantling building employees (n = 13)			Shred building employees (n = 12)		
	Median*	GM*	Max	Median*	GM*	Max
OctaBDE (commonly used in electronics until around 2004)						
BDE-183	0.52	0.44	1.56	0.74	0.56	1.67
BDE-154†	(—)	(—)	0.37	(—)	(—)	0.64
BDE-153†	3.58	5.41	35.0	4.36	4.96	14.2
OctaBDE and DecaBDE (commonly used in electronics until around 2013)						
BDE-209	3.36	3.43	9.31	4.45	5.83	24.6
PentaBDE (rarely used in electronics)‡						
BDE-99	1.02	1.01	3.98	0.97	1.17	7.31
BDE-47	6.61	4.65	14.8	4.37	5.11	34.4
BDE-100	1.29	1.11	3.19	1.24	1.27	8.50
BDE-85	(—)	(—)	0.47	(—)	(—)	0.81

*Median and GM not calculated if percentage detected was below 70%, represented by (—).

†Also present in PentaBDE in small amounts.

‡Primarily used in polyurethane foam and commonly present in dust.

We sampled for PCBs and PPs to address the possibility of dietary effects on the levels of the PBDEs. In Appendix A, Tables A3 and A4 show the concentrations of serum PCBs and PPs in our participants and the concentrations found in NHANES. All medians and GMs were lower in our participants than in NHANES.

Urine Samples for Flame Retardants

The results of urine testing for metabolites of certain flame retardants stratified by departments are shown in Table 10 (uncorrected concentrations in micrograms per liter [µg/L]) and Table 11 (creatinine-corrected concentrations in micrograms per gram [µg/g] creatinine). Concentrations of DPHP slightly increased from preshift to postshift among shredding and sorting, shipping and receiving, and disassembly workers. They remained similar among resale and office workers, and declined in special project employees.

DpCP and DoCP, metabolites of TCP, were undetectable in most participants. We did not detect TBBA, the metabolite of EH-TBB, in the urine of any participants. Median concentrations of BCEP, the metabolite of TCEP, increased slightly from preshift to postshift in shipping and receiving employees, but declined across the shift in all other departments. BDCIPP, the metabolite of TDCIPP, was detected in nearly all urine samples. BDCIPP median concentrations increased slightly in the shredding/sorting and shipping/receiving department samples, while it decreased slightly across shift for disassembly, special projects, and resale employees.

We compared the results for the second day postshift urinary metabolite measurements for the electronics recycling company employees to the general population in Appendix A, Table A5 (creatinine-uncorrected concentrations in µg/L) and Table A6 (creatinine-corrected concentrations in µg/g creatinine). Urinary flame retardants concentrations of DPHP, BCEP, BCIP, and BDCIPP in these electronic recycling participants were similar to the general population.

Table 10. Uncorrected concentrations of flame retardant metabolites in urine samples, by job task, in µg/L

Metabolite (parent flame retardant)	Shred/Sort (n = 14) % detected median range		Ship/Receive (n = 6) % detected median range		Office (n = 4)* % detected range		Disassembly (n = 10) % detected median range		Special Projects (n = 7) % detected median range		Resale (n = 6) % detected median range	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Commonly used in electronics now and in the past												
DPHP (TPHP) LOD = 0.16	100% 1.82 0.19–4.3	100% 2.56 0.64–6.4	100% 1.09 0.27–1.9	100% 1.83 0.40–5.9	100% 0.44–0.76	100% 0.37–0.68	100% 0.74 0.41–7.0	100% 1.4 0.28–4.96	100% 0.65 0.39–17.6	86% 0.48 ND–1.8	100% 1.45 1.0–1.9	100% 1.54 0.21–7.4
DpCP (TCP) LOD = 0.05	36% ND–0.16	36% ND–0.16	33%* ND–0.27	50%* ND–0.17	0%	0%	0%	20%* ND–0.052	29% ND–0.057	0%	17%* ND–0.092	33%* ND–0.20
DoCP (TCP) LOD = 0.05	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Less commonly used in electronics now and in the past												
TBBA (EH-TBB) LOD = 0.05	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BCEP (TCEP) LOD = 0.08	100% 0.89 0.31–4.0	100% 0.83 0.39–4.8	100% 1.86 0.20–9.1	100% 3.01 0.55–5.1	75% ND–1.1	75% ND–0.43	100% 0.33 0.16–2.2	100% 0.32 0.13–1.9	100% 0.50 0.085–0.89	86% 0.24 ND–0.39	100% 0.48 0.32–0.76	100% 0.32 0.11–0.51
BCIPP (TCIPP) LOD = 0.10	79% 0.22 ND–2.5	86% 0.20 ND–2.0	67%* ND–0.54	83%* ND–0.45	75% ND–0.93	100% 0.10–0.66	80% 0.22 ND–0.41	80% 0.20 ND–0.48	100% 0.27 0.17–0.87	86% 0.16 ND–0.95	100% 0.42 0.25–0.88	100% 0.24 0.19–0.37
Rarely used in electronics†												
BDCIPP (TDCIPP) LOD = 0.11	100% 1.8 0.33–8.4	100% 1.9 0.4–8.1	100% 3.13 1.3–7.9	100% 3.52 1.9–5.4	100% 0.31–0.83	100% 0.16–0.75	100% 1.3 0.82–2.1	100% 1.1 0.79–1.95	100% 1.2 0.15–7.1	86% 0.73 ND–2.0	100% 3.8 1.6–46.6	100% 2.2 0.71–23.7

*Median not calculated if n ≤ 5.

†Primarily used in polyurethane foam and commonly present in dust.

Table 11. Creatinine corrected concentrations of flame retardant metabolites in urine samples, by job task, in µg/g creatinine

Metabolite (parent flame retardant)	Shred/Sort (n = 14) % detected median range		Ship/Receive (n = 6) % detected median range		Office (n = 4)* % detected range		Disassembly (n = 10) % detected median range		Special Projects (n = 7) % detected median range		Resale (n = 6) % detected median range	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Commonly used in electronics now and in the past												
DPHP (TPHP)	100% 0.85 0.17–2.7	100% 1.3 0.55–2.8	100% 0.60 0.30–1.1	100% 1.10 0.18–3.3	100% 0.44–0.61	100% 0.46–0.74	100% 0.51 0.31–4.2	100% 0.77 0.36–4.1	100% 0.30 0.18–14.7	86% 0.30 ND–1.3	100% 0.72 0.58–1.1	100% 1.05 0.56–3.9
DpCP (TCP)	36% ND–0.051	36% ND–0.10	33%* ND–0.11	50%* ND–0.11	0%	0%	0%	20%* ND–0.065	29% ND–0.048	0%	17%* ND–0.042	33%* ND–0.11
DoCP (TCP)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Less commonly used in electronics now and in the past												
TBBA (EH-TBB)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BCEP (TCEP)	100% 0.43 0.17–1.5	100% 0.49 0.23–1.6	100% 1.22 0.39–4.3	100% 1.35 0.42–2.9	75% ND–0.84	75% ND–0.53	100% 0.28 0.10–1.0	100% 0.25 0.16–1.1	100% 0.20 0.04–0.44	86% 0.24 ND–0.29	100% 0.29 0.14–0.57	100% 0.22 0.093–0.39
BCIPP (TCIPP)	79% 0.093 ND–1.2	86% 0.10 ND–0.81	67%* ND–0.22	83%* ND–0.30	75% ND–0.88	100% 0.12–0.57	80% 0.15 ND–0.25	80% 0.15 ND–0.22	100% 0.27 0.09–0.40	86% 0.16 ND–0.37	100% 0.23 0.13–0.65	100% 0.12 0.093–0.57
Rarely used in electronics†												
BDCIPP (TDCIPP)	100% 0.81 0.23–3.9	100% 0.84 0.29–3.9	100% 2.45 0.77–7.0	100% 3.52 0.58–3.3	100% 0.34–0.66	100% 0.31–0.81	100% 0.56 0.13–2.6	100% 0.46 ND–2.6	100% 1.2 0.13–2.6	86% 0.73 ND–2.6	100% 2.43 1.1–17.6	100% 2.2 0.60–12.1

*Median not calculated if n ≤ 5.

†Primarily used in polyurethane foam and commonly present in dust.

We also analyzed urinary flame retardant concentrations for employees by their work in the dismantling or shred buildings. The creatinine-uncorrected and creatinine-corrected results are displayed in Tables 12 and 13. The results by building showed slight increases over a shift for DPHP. Additionally, employees' median postshift urinary concentrations of DPHP were generally higher in shred building employees (uncorrected: 2.31 µg/L; creatinine-corrected: 1.14 µg/g creatinine) than dismantling building employees (uncorrected: 1.66 µg/L; creatinine-corrected: 0.71 µg/g creatinine).

Table 12. Uncorrected concentrations of flame retardant metabolites in urine samples, by building, in µg/L

Metabolite (parent flame retardant)	Dismantling building employees (n = 25) % detected median range		Shred building employees (n = 22) % detected median range	
	Pre	Post	Pre	Post
Commonly used in electronics now and in the past				
DPHP (TPHP) LOD = 0.16	100% 0.78 0.39–17.6	96% 0.89 ND–7.4	100% 1.66 0.19–4.3	100% 2.31 0.40–6.4
DpCP (TCP) LOD = 0.05	12% ND–0.092	16% ND–0.16	32%* ND–0.27	36%* ND–0.17
DoCP (TCP) LOD = 0.05	0%	0%	0%	0%
Less commonly used in electronics now and in the past				
TBBA (EH-TBB) LOD = 0.05	0%	0%	0%	0%
BCEP (TCEP) LOD = 0.08	100% 0.46 0.085–7.5	96% 0.27 ND–5.1	95% 0.89 ND–9.1	95% 0.73 ND–4.8
BCIPP (TCIPP) LOD = 0.10	92% 0.25 ND–0.88	88% 0.20 ND–0.95	73% 0.22 ND–2.5	83% 0.23 ND–2.0
Rarely used in electronics†				
BDCIPP (TDCIPP) LOD = 0.11	100% 1.51 0.15–47.6	96% 1.28 ND–23.7	100% 1.81 0.31–8.4	100% 1.90 0.16–8.1

*Median not calculated if percentage detected was below 70%.

†Primarily used in polyurethane foam and commonly present in dust.

Table 13. Creatinine corrected concentrations of flame retardant metabolites in urine samples, by building, in μg/g creatinine

Metabolite (parent flame retardant)	Dismantling building employees (n = 25) % detected median range		Shred building employees (n = 22) % detected median range	
	Pre	Post	Pre	Post
Commonly used in electronics now and in the past				
DPHP (TPHP)	100% 0.51 0.39–14.7	96% 0.65 ND–4.1	100% 0.71 0.17–2.7	100% 1.14 0.46–3.3
DpCP (TCP)	12% ND–0.048	16% ND–0.17	32%* ND–0.11	36%* ND–0.11
DoCP (TCP)	0%	0%	0%	0%
Less commonly used in electronics now and in the past				
TBBA (EH-TBB)	0%	0%	0%	0%
BCEP (TCEP)	100% 0.28 0.04–4.3	96% 0.24 ND–2.3	95% 0.46 ND–3.6	95% 0.49 ND–2.9
BCIPP (TCIPP)	92% 0.16 ND–0.65	88% 0.14 ND–0.57	73% ND–1.2	86% ND–0.81
Rarely used in electronics†				
BDCIPP (TDCIPP)	100% 1.08 0.13–17.6	96% 0.88 ND–12.1	100% 0.81 0.23–7.0	100% 0.83 0.29–3.9

*Median not calculated if percentage detected was below 70%.

†Primarily used in polyurethane foam and commonly present in dust.

Surface and Handwipe Sampling for Metals

We wiped surfaces outside of the processing area to determine if metals were inadvertently transferred or had migrated from the processing area. We wiped surfaces inside the processing area to determine possible sources of the contamination. Our results showed the presence of metals on some of the nonprocessing surfaces, but at relatively low levels (Tables 14 and 15). The highest levels for lead in the shred building were on the floor just inside the breakroom (6.3 μg/100 cm^2), on the women's restroom door handle (5.2 μg/100 cm^2), and on the breakroom table near the coffeepot (1.5 μg/100 cm^2). These same samples also had the highest levels of cadmium and lithium. The highest levels for lead in the dismantling building were on the floor into the breakroom (4.0 μg/100 cm^2), on a production workstation (2.3 μg/100 cm^2), and on the breakroom refrigerator handle (2.1 μg/100 cm^2). The breakroom refrigerator handle in the dismantling building also had the highest levels of cadmium, lithium, and silver.

Table 14. Surface wipe samples in the shred building for selected metals in µg/100 cm^2

Sample location	Cadmium	Lead	Lithium	Silver
Breakroom - lunch Table 1	[0.014]	0.93	ND	[0.073]
Breakroom - lunch Table 2	[0.012]	0.99	ND	[0.049]
Breakroom - microwave buttons	ND	0.88	ND	ND
Breakroom - floor beyond the sticky pad	0.078	6.3	ND	0.37
Breakroom - table near coffeepot	0.047	1.5	[0.12]	ND
Office desk	ND	0.84	ND	1.2
Conference room table	[0.022]	2.2	ND	0.19
Production - men's restroom door	ND	[0.51]	ND	ND
Production - women's restroom door handle*	0.080	5.2	0.18	0.46
LOD	0.01	0.2	0.05	0.04
Limit of quantification (LOQ)	0.043	0.63	0.15	0.15

*Estimated surface area.

Note: Values in brackets are between the LOD and LOQ; more uncertainty is associated with these results.

Table 15. Surface wipe samples in the dismantling building for selected metals in µg/100 cm^2

Sample location	Cadmium	Lead	Lithium	Silver
Breakroom - coffee dispenser	ND	[0.24]	ND	0.81
Breakroom - women's restroom door handle	[0.010]	[0.33]	ND	1.8
Breakroom - men's restroom door handle	0.074	1.0	ND	4.9
Breakroom - table	[0.025]	[0.35]	ND	1.2
Breakroom - microwave buttons	[0.022]	[0.47]	[0.078]	1.4
Breakroom - refrigerator handle	0.48	2.1	[0.14]	30
Office	[0.036]	0.78	[0.089]	2.0
Floor into the breakroom, by door	0.16	4.0	ND	13
Production - workstation	0.074	2.3	[0.068]	4.5
Door handle from production to breakroom	0.14	ND	ND	ND
LOD	0.01	0.2	0.05	0.04
LOQ	0.043	0.63	0.15	0.15

*Estimated surface area.

Note: Values in brackets are between the LOD and LOQ; more uncertainty is associated with these results.

We detected metals on the hands of all processing employee participants after they washed their hands before leaving work at the end of the shift. In the shred building, among the selected metals, we found lead had the highest GM and median concentrations in the handwipes (Table 16). Employees working in the shredding department (n = 8) had the highest median lead level (17 µg/sample). Employees working in the shipping and receiving department (n = 2) had the second highest median lead level (2.4 µg/sample). Those employees working in the office (n = 2) had the third highest median lead level (2.3 µg/sample).

In the dismantling building, among the selected metals, we found silver and lead had the highest GM and median concentrations in the handwipes (Table 17). Employees working in special projects (n = 4) had the highest median lead level (7.1 µg/sample), followed by employees working in the disassembly department (n = 5), with a median level of 4.2 µg/sample. Employees working in special projects had the highest median silver level (9.9 µg/sample), followed by employees working in the disassembly department (3.7 µg/sample). Employees working in resale (n = 3) had the third highest median silver level of 0.79 µg/sample.

Table 16. Handwipe sample results for all shred building employees (n = 12) for selected metals, in µg/sample

Element	GM* (range)	Median concentration
Cadmium	0.15 (0.02–1.0)	0.13
Lead	8.3 (0.89–42)	9.0
Lithium	0.29 (ND–9.1)	0.27
Silver	0.90 (0.18–3.8)	0.95

*These calculations were based only on detected results.

Table 17. Handwipe sample results for all dismantling building employees (n = 13) for selected metals, in µg/sample

Element	GM* (range)	Median concentration
Cadmium	0.14 (ND–1.0)	0.14
Lead	3.1 (ND–28)	3.2
Lithium	0.22 (ND–0.52)	0.25
Silver	3.5 (0.35–23)	3.7

*These calculations were based only on detected results.

Air Samples for Metals

We collected personal air samples for 32 elements for 25 employees over 2 days. Tables summarizing employees' exposures can be found in Appendix A, Tables A7 and A8. Two special projects department employees in the dismantling building were exposed to silver over the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) and NIOSH recommended exposure limit (REL) of 10 micrograms per cubic meter ($\mu g/m^3$). The median silver concentration in the dismantling building was 2.1 $\mu g/m^3$ (range: 0.13–13 $\mu g/m^3$), with the highest exposures on special projects department employees. The remainder of employees' exposures were less than half of the lowest OEL.

Shred building employees had detectable exposures to cadmium and lead, but all air samples for lead and cadmium were below OELs. The median cadmium concentration in the shred building was 0.074 $\mu g/m^3$ (range: ND–0.26 $\mu g/m^3$), with the highest exposures on shredding department employees. Lead was detected in all 22 air samples in the shred building, with a median concentration of 6.0 $\mu g/m^3$ (range: 0.27–17 $\mu g/m^3$)—the highest exposures were on the shredding employees. The dismantling building employees also had detectable exposures to cadmium and lead. The median cadmium concentration in the dismantling building was 0.054 $\mu g/m^3$ (range: ND–2.2 $\mu g/m^3$), with the highest exposures on disassembly department employees. Lead was detected in 19 of 25 air samples in the dismantling building, with a median concentration of 0.96 $\mu g/m^3$ (range: ND–4.4 $\mu g/m^3$)—the highest exposures were on the disassembly department employees.

Blood Samples for Metals

Twenty-five employees had blood drawn to test for metals. Blood lead levels (BLLs) ranged from below the laboratory LOD of 0.5 to 10.0 micrograms per deciliter ($\mu g/dL$). The Centers for Disease Control and Prevention's (CDC) NIOSH Adult Blood Lead Epidemiology and Surveillance system uses a surveillance case definition for an elevated BLL in adults of 5 $\mu g/dL$ or higher [NIOSH 2015]. Three participants, who all worked in the shred building, exceeded this level. The average BLL for employees in the processing area of the shred building (4.7 $\mu g/dL$) was higher than employees working in the processing area of the dismantling building (1.5 $\mu g/dL$). The average BLL (4.7 $\mu g/dL$) of employees in the processing area of the shred building approached, but does not exceed, the CDC reference level for an elevated BLL. The GM for all participants in the processing area of the shred building was 3.7 $\mu g/dL$, which is over three times that of the general population of 1.1 $\mu g/dL$ [NIOSH 2015].

We also reviewed previous BLL testing performed by the company in 2015. BLLs were performed on 17 full-time employees at the time of testing, who all worked in the processing area of the shred building. Nine (53%) of 17 employees had BLLs equal to or greater than 5 $\mu g/dL$, with an average BLL of 5.3 $\mu g/dL$ (range: 2–12 $\mu g/dL$). ZPP levels, an indicator of chronic lead intoxication, were also collected. The average ZPP level for tested workers was 49 micromol ZPP per mol of heme (range: 35–85 micromol ZPP per mol of heme). The laboratory listed normal results as anything below 70 micromol ZPP per mol of heme. Only one test exceeded this level.

Blood cadmium levels were low, with all but three below the laboratory LOD of 0.5 µg/L (range: ND–1.4 µg/L). All participants with measureable levels of cadmium in their blood were current smokers. Two worked in the processing area of the shred building, and one worked in the processing area of the dismantling building.

Discussion

Flame Retardants

Exposure assessment (including biomonitoring) for phosphate flame retardants is in its early phase [Dodson et al. 2014; Kosarac et al. 2016]. In the absence of OELs for many of the substances noted in this evaluation, the assessments summarized in this report provide data to help minimize occupational exposures and may provide data useful to future similar assessments in this workplace or other workplaces.

Handwipes and Dermal Exposure

Exposure to flame retardants in indoor nonwork environments is thought to primarily occur from hand-to-mouth ingestion of dust and secondarily by absorption through the skin [Abdallah et al. 2015; Mäkinen et al. 2009]. These exposure pathways can also occur in workplaces. Thorough, frequent handwashing with soap and water should remove or reduce the amount of contaminants on the skin and reduce risk of possible ingestion through hand-to-mouth contact and continued dermal exposure. However, contaminants on the skin due to lack of handwashing or that remain on the skin due to incomplete removal by handwashing could be transferred to nonwork surfaces in vehicles and at home. Table 18 shows the levels of selected flame retardants on the hands of the electronics recycling employees compared to results published in studies of the general population, which were collected using similar handwipe methods.

The use of OctaBDE flame retardants in electronics was phased out after 2004. The congeners for OctaBDE (BDE-153, BDE-154, and BDE-183) were detected in less than 50% of the postshift handwipes, which suggests that at the time of our evaluation, the company was processing few electronics made before 2004. We detected BDE-209, TPHP, TCP, DBDPE, and TBBPA in higher median levels postshift than preshift. These flame retardants are commonly used in electronics now and in the past. Because of their presence and employees hand contact with electronics throughout the work shift, higher postshift levels on the hands were expected. We also found that the GM values for BDE-209 and TPHP were substantially higher than the general population.

TDCIPP and some of the PentaBDE flame retardant congeners (BDE-47 and BDE-99) did not show a consistent pattern. TDCIPP and PentaBDE are typically found in polyurethane foam, not in electronics [Alaee et al. 2003] and were phased out starting in 2005. However, several studies have shown that while PentaBDE and TDCIPP are not typically used in electronics, they are often present in high concentration in office dusts [Sjödin et al. 2008; Watkins et al. 2013], which could collect inside electronics. In general, the preshift and postshift GM values for these flame retardants were similar to the levels reported in the general population, suggesting minimal dermal exposure to these flame retardants at work.

Table 18. Geometric mean and range of flame retardants on handwipes in electronics recycling participants and the general population, in ng/sample

Flame retardant	Shred building n = 22 % detected GM* range		Dismantling building n = 25 % detected GM* range		General population† n = 53 % detected GM range	General population‡ n = 33 % detected GM range	General population§ n = 40 % detected GM range
	Preshift	Postshift	Preshift	Postshift			
OctaBDE (commonly used in electronics until around 2004)							
BDE-183	5% ND–12	45% ND–140	0%	16% ND–330	Not sampled	76% 0.7 ND–8.5	Not sampled
BDE-154	5% ND–180	0%	0%	0%	87% 1.0 ND–59.8	97% 4.9 ND–59	Not sampled
BDE-153	23% ND–200	45% ND–32	0%	12% ND–40	91% 1.3 ND–67.9	97% 15.8 ND–290	Not sampled
OctaBDE and DecaBDE (commonly used in electronics until around 2013)							
BDE-209	95% 130 ND–1,100	100% 440 33–3,900	84% 50 ND–500	96% 140 ND–1,300	96% 19.5 ND–804	67% 43.1 ND–270	Not sampled
Commonly used in electronics now and in the past							
TPHP	100% 310 93–4,200	100% 830 150–6,600	96% 280 ND–4,100	100% 690 130–2,100	87% 62.1 ND–1,230	Not sampled	100% 22.4 ?–416.7
Less commonly used in electronics now and in the past							
TCIPP	68% 57 ND–720	36% ND–550	36% ND–2,100	36% ND–380	Not sampled	Not sampled	100% 45.4 ?–255
Rarely used in electronics							
PentaBDE							
BDE-99	82% 42 ND–2,700	86% 36 ND–220	72% 17 ND–70	68% 16 ND–160	100% 26 4.4–707	100% 72.2 0.9–747	Not sampled
BDE-47	77% 41 ND–2,200	82% 34 ND–240	64% 14 ND–57	48% ND–89	100% 18.4 2.5–454	97% 72.7 ND–565	Not sampled
BDE-100	41% ND–430	50% 8.8 ND–31	20% ND–22	16% ND–29	81% 2.8 ND–128	100% 13.3 0.08–142	Not sampled
TDCIPP	73% 178 ND–3,200	45% ND–3,100	84% 230 ND–2,500	92% 200 ND–1,100	91% 84.1 ND–537	Not sampled	95% 108.3 ND–535

*GMs were not calculated if percentage detected was below 50%.

†Hoffman et al. 2015

‡Stapleton and Dodder 2008

§Hammel et al. 2016

? = Study did not provide a lower-end of the range.

The higher GM and median values of the flame retardants used frequently in electronics illustrate the potential for dermal exposure and highlight the importance of PPE and handwashing to reduce exposures. A study of flame retardant exposure in young children suggested those who washed their hands at least five times a day had lower levels of flame retardants on their hands than those who washed less often [Stapleton et al. 2014]. Office workers who washed their hands fewer than four times daily had significantly higher levels of PentaBDE on their handwipes than those who washed four or more times daily [Watkins et al. 2011]. Absorption of TCIPP and TCEP was significantly reduced by handwashing in an experimental study using human ex vivo skin, but penetration continued, presumably from the reservoir in the skin [Abdallah et al. 2016]. Handwashing did not significantly reduce absorption of TDCIPP [Abdallah et al. 2016].

Several factors can affect overall interpretation of the handwipe sampling results. The handwipe sampling procedure removes an unknown proportion of the flame retardants that are present on the hand and can vary depending on the technique of the person doing the wiping. In our pilot handwipe study, the amount removed by the first gauze wipe set varied from 0% to 98% of the total [Beaucham et al. 2019]. If a handwipe removed more of a particular flame retardant preshift than was added to the hands during the shift, it could appear there was a decline in flame retardant levels, even though exposure to that flame retardant may have occurred during the work shift.

The efficiency of handwipes in collecting all the contamination that is present is unknown. Also, we do not know the efficiency of handwashing in removing different flame retardants. If handwashing was very efficient in removing flame retardants from the employees' hands, then the postshift flame retardant levels might be far less than if handwashing had not been done. Participants with less time between their last handwashing and their postshift handwipe sample might have lower amounts of flame retardants on their hands due to removal from washing. We instructed participants to wash their hands as they normally would during the work shift, but instructed them to refrain from washing them immediately before having their postshift handwipe sampling done. We did not record the time interval from the last handwashing to the postshift wipe sampling. The wide variability of the results could be from interpersonal sampling variation, such as participants wiping their hands differently, thereby removing the flame retardants from a previously unwiped portion of the hand or differences in applied pressure and speed of wiping. We do not know if differences in skin moisture and use of skin care products could affect the results.

The surface wipe samples we collected helped us to identify which part or parts of the work area are contributing to the flame retardants in the air samples and handwipe samples. In this evaluation, the shredder station and the A-line 2nd disassembly workstation had the highest concentrations of flame retardants, and the widest variety of flame retardants. Similarly, the shredding and disassembly employees had the highest median concentrations in their air samples and the highest levels of flame retardants commonly found in electronics. Interestingly, HBCD (α,β,γ) was found on the shredding workstation. Correspondingly, HBCD (α,β,γ) was found in 4 of the 14 postshift handwipes of shredding employees but in none of their preshift handwipes. This suggests that although employees are likely being exposed to HBCD (α,β,γ) while disassembling electronics, it is likely washed off of the hands using soap and water.

Personal Air Sampling for Flame Retardants

Several published studies have examined airborne exposure to flame retardants in homes and nonindustrial settings. Allen et al. [2007] collected inhalable personal air samples for PBDEs from 20 individuals in Boston for 7 days while they were at home. The main congeners they detected were BDE-47, BDE-99, and BDE-209. BDE-47 was detected in 100% of the air samples with a GM concentration of 0.227 ng/m^3. BDE-209 was detected in 45% of the samples with a GM concentration of 0.174 ng/m^3. The authors estimated that about 22% of the participants' total BDE-209 exposures was likely through inhalation.

LaGuardia and Hale [2015] evaluated flame retardant exposures on four individuals in their homes in Seattle, Washington. Samples were collected for an 8-hour period. Inhalable personal air sampling found that the predominant flame retardants were TDCIPP (94% of the total) and TCIPP (65% of the total). BDE-209 was detected in two of the four samples, at concentrations of 0.1 ng/m^3 and 3.8 ng/m^3. Schreder et al. [2016] collected personal air samples for chlorinated organophosphate flame retardants over a 24-hour period on 10 individuals in Washington State. The median concentrations were 262 ng/m^3 (TCIPP), 82 ng/m^3 (TDCIPP), and 78 ng/m^3 (TCEP).

Swedish researchers examined the presence and levels of several organophosphate flame retardants using area air sampling for particulate and vapor at night in three schools, a day care center, and an office. TPHP was detected in all locations, but below levels of quantification in two, and at concentrations less than 1 ng/m^3 in the others [Carlsson et al. 1997]. The highest concentrations these researchers measured were for TCEP, with mean concentrations in each building ranging from 11 to 250 ng/m^3. These researchers also detected TCIPP in much lower concentrations (maximum mean concentration 41 ng/m^3).

We anticipated that occupational exposures to flame retardants in the air would differ from air sampling results in nonindustrial environments. Our evaluation demonstrated airborne exposures to several flame retardants, primarily DBDPE, TCP, TPHP, BDE-209, and TCIPP.

A study of sorters and disassemblers (not shredders) at two electronics recycling facilities in Finland documented median airborne DBDPE concentrations of 61 ng/m^3 and median sum PBDE concentrations of 295 ng/m^3 [Rosenberg et al. 2011]. The researchers recommended ventilation controls, and then resampled after their installation. Median airborne DBDPE concentrations decreased to 14 ng/m^3, and median PBDE concentrations dropped to 65 ng/m^3, indicating that controls reduced exposures. Our DBDPE results indicated median airborne DBDPE concentrations of 310 ng/m^3 in the dismantling building, similar to those in the Rosenberg study. The median DBDPE concentrations in the shred building, 870 ng/m^3, were higher than the Rosenberg study.

Mäkinen et al. [2009] found that airborne TCP was typical in electronics dismantling facilities. The GM personal air TCP concentration in a dismantling and sorting room of an electronics dismantling company was 90 ng/m^3 (range: 60–180 ng/m^3) and 110 ng/m^3 (range: < 3–810 ng/m^3) in an electronics crushing process at a separate facility. Our recycling participants in the dismantling building had a GM exposure of 130 ng/m^3 (range: 38–840 ng/m^3). Participants in the shred building had a GM exposure of 510 ng/m^3 (range: ND–2,700 ng/m^3). Our air sampling results were higher than those found by Mäkinen et al. [2009] and is most likely because items were shredded rather than crushed.

TPHP has been used as a flame retardant in electronic products as well as a plasticizer [van der Veen and de Boer 2012]. We found TPHP in the third highest concentration in our air samples, with a GM concentration of 39 ng/m^3 (range: ND–320 ng/m^3) in the dismantling building and 230 ng/m^3 (range: ND–1,600 ng/m^3) in the shred building. A study of two other electronics recycling facilities in Finland where sorting, dismantling, and crushing were performed showed TPHP was present in the highest airborne concentrations of the eight organophosphate flame retardants measured (GM personal air concentrations of TPHP of 760 ng/m^3 and 850 ng/m^3) [Mäkinen et al. 2009]. Our TPHP GM air concentrations were less than either of our comparison studies; however, the maximum exposure in the shred building (1,600 ng/m^3) was higher.

Personal air sample GM concentrations of BDE-209 measured in Swedish electronics recycling disassemblers over a 2-year period were 25 ng/m^3 [Pettersson-Julander et al. 2004]. In comparison, our BDE-209 GM values were 8.1 ng/m^3 (range: ND–63 ng/m^3) in the dismantling building and 75 ng/m^3 (range: 4.3–530 ng/m^3) in the shred building.

TCIPP and PentaBDE are not typically used in electronics and are also predominantly found in polyurethane foam [Alaee et al. 2003; Stapleton et al. 2011; van der Veen and de Boer 2012]. We detected some TCIPP and congeners of PentaBDE, and we suspect the source to be primarily from dust collected inside of the electronic equipment as shown below (Figure 1). The shredding employees in the shred building had the highest TCIPP results (maximum 110 ng/m^3). The disassembly employees in the dismantling building had the highest PentaBDE results (maximum 77 ng/m^3).

Figure 1. Example of a cooling fan on a piece of electronic equipment that has pulled in a lot of dust from the environment. Photo by NIOSH.

Mäkinen et al. [2009] detected TBBPA in few air samples and at very low concentrations. Sjödin et al. [2001] found TBBPA present in air with a mean concentration of 0.20 ng/m^3, and Rosenberg et al. [2011] found TBBPA with a median concentration of 145 ng/m^3. We detected TBBPA in the air in 95% of the shred building samples, with a median concentration of 33 ng/m^3 (range: ND–150 ng/m^3). We detected TBBPA in the air in 74% of the dismantling building samples, with a median concentration of 2.1 ng/m^3 (range: ND–92 ng/m^3). TBBPA is one of the most commonly used brominated flame retardants in printed circuit boards. Circuit boards were sorted and disassembled in the shred building, so the higher results in that building were anticipated.

BTBPE is found in Firemaster 680, which is used in many computer housings. Pettersson-Julander et al. [2004] found a GM concentration of airborne BTBPE of 15 ng/m^3. We measured similar but slightly lower concentrations with a GM of 7.0 ng/m^3 in the shred building and a GM of 2.1 ng/m^3 in the dismantling building.

These data indicate that airborne exposure in this electronics recycling company differ from those in homes and nonindustrial settings, but are within the range of exposures found in other electronic recycling facilities. Additionally, the air, surface wipe, and handwipe results were all consistent, showing DBDPE (a flame retardant commonly used in electronics now and in the past) as the highest results in each type of sampling.

Biological Burden of Flame Retardants: Blood

We examined serum PBDE concentrations and compared them to a representative sample of the general population. The GM serum concentration of BDE-209 was 4.42 ng/g lipid weight. NHANES data did not report values because so many of their samples were below the LOD of 5.8 ng/g lipid weight. NHANES samples were collected in 2007 and 2008, when concentrations were presumably higher because this was prior to the phase-out of DecaBDE.

Data are also now available for the years 2009 and 2010, but they are segregated by age groups, gender, and race/ethnicity [CDC 2018].

While the overall workforce had a GM serum concentration of BDE-209 less than the LOD for NHANES, the GM serum concentration for shred building employees was 5.83 ng/g lipid weight. Similarly, air concentrations of BDE-209 were higher in the shred building than the dismantling building. Swedish electronics disassembly employees had a median serum BDE-209 concentration of 4.8 ng/g lipid weight [Thuresson et al. 2006b]. Workers were retested several years later after the shredder was moved from the disassembly area to a different location. The median decrease in their serum BDE-209 concentrations was 46% [Thuresson et al. 2006a]. In the initial Swedish study, serum concentrations of BDE-47, BDE-153, BDE-154, and BDE-183 were also significantly higher than their reference populations of computer clerks and hospital cleaners [Sjödin et al. 1999]. We found median serum concentrations of BDE-153 similar to that of the general population sample. Concentrations of other PBDEs, PCBs, and other persistent pollutants were generally lower in our participants than in NHANES participants. This may be because NHANES specimens were collected several years before ours when concentrations of PBDEs, PCBs, and other persistent pollutants were likely higher. In addition, PCB-153 concentrations in our participants were lower than in NHANES specimens. PCB-153 is a stable, persistent contaminant, and exposure to it comes mainly from food [Jakobsson et al. 2002]. The identification of higher air BDE-209 concentrations, combined with serum BDE-209 concentrations above the NHANES LOD, lower levels of serum PCB-153, and lower levels of the other PCBs and other persistent pollutants support the conclusion that serum BDE-209 concentrations in our shred participants is more likely to be from occupational exposures rather than from diet.

Biological Burden of Flame Retardants: Urine

The identification of major metabolites and pharmacokinetics of phosphate flame retardants are not fully elucidated [Dodson et al. 2014; Kosarac et al. 2016]. However, half-lives of identified flame retardant metabolites appear to be relatively short (hours); therefore, results of urine measurements likely reflect recent exposures [Carignan et al. 2016; Dodson et al. 2014; Hammel et al. 2016; Meeker et al. 2013a]. NHANES has recently released urinary metabolite data for the general population for the years 2013 and 2014 [CDC 2018].

Median urinary concentrations of DPHP (a metabolite of TPHP used in plastic housings of electronics, among other things) increased across the shift in shredding/sorting, shipping/receiving, and disassembly participants during our visit. DPHP levels stayed about the same in participants working in the office and resale departments and decreased in special project participants. Table 19 contains results of urine testing from published studies on flame retardant metabolites in the general population. Postshift urine creatinine-uncorrected GM concentrations of DPHP ranged from 1.1 to 1.9 µg/L sampled in these studies. Our evaluation showed that employees performing shredding and sorting exceeded the maximum urine concentration identified in prior studies, with a GM of 2.4 µg/L (median: 2.56 µg/L). The urine concentrations of DPHP by all other job tasks and buildings (GM range: 0.43–1.86 µg/L) were below or within the range of the U.S. population.

Gymnasts use pits filled with foam blocks and other foam padded equipment to protect them from injury when falling—TPHP is a component of Firemaster 550 (and other flame retardant mixtures), which is used in polyurethane foam. A study of gymnasts before and after a 2.5 hour practice demonstrated that GM DPHP concentrations nearly doubled (from 6 to 11 µg/L), and then began to decline between 1 and 3 hours after practice [Carignan et al. 2016]. These levels in gymnasts were much higher than those we found (GM range: ND [< 0.16]–2.4 µg/L).

A study of the relationship between reproductive outcomes in 33 men found a 57% decrease in sperm concentration, 19% decrease in straight line velocity, 13% decrease in linearity, and 38% decrease in inhibin B concentrations in blood for each interquartile increase in urinary DPHP [Meeker et al. 2013a]. Specific gravity corrected urinary DPHP ranged from nondetectable (< 0.06 µg/L) to 9.84 (median: 0.27 µg/L; 95th percentile: 2.65 µg/L) in the study from which these men were a subset [Meeker et al. 2013b]. Another study found a significant 0.43 µg/dL increase in mean total T4 serum concentrations in individuals with specific gravity corrected urine DPHP concentrations greater than or equal to 2.65 µg/L compared to those with concentrations below 2.65 µg/L [Preston et al. 2017].

TPHP was present in the air in our electronics recycling company in the third highest concentrations, after TCP and DBDPE. Median airborne concentrations of TPHP were highest among shredding participants, and were notably higher in employees sampled in the shred building (350 ng/m^3) than those sampled in the dismantling building (81 ng/m^3). All groups of participants had increased median levels of TPHP on their hands postshift, but the difference between the preshift and postshift median levels were highest in shredding participants. These findings, in conjunction with urinary DPHP findings, suggest that TPHP is present in the workplace and may be contributing to higher levels of DPHP uptake in shredding/sorting employees than has been reported in population studies.

Table 19. Uncorrected concentrations of urine flame retardant metabolites in the general population, in µg/L

Flame retardant	General population % detected GM range				
	N = 9*	N = 39†	N = 16‡	N = 13§	N = 40¶
Commonly used in electronics now and in the past					
DPHP (parent compound TPHP)	100% 1.074 0.29–7.44	97% 1.9 ND (< 0.005)–37.3	62% 1.1 (mean) ND (< 0.23)–6.8	100% 1.5 0.2–5.6	100% 1.14 **–26.77
Less commonly used in electronics now and in the past					
BCIPP (parent compound TCIPP)	Not sampled	Not sampled	31% 0.17 (mean) ND (< 0.06)–0.97	92% 0.4 0.04–3.5	18% Not calculated **–0.57
BCEP (parent compound TCEP)	Not sampled	Not sampled	75% 0.76 (mean) ND (< 0.10)–2.1	100% 3.4 0.4–15.0	Not sampled
Rarely used in electronics					
BDCIPP (parent compound TDCIPP)	100% 0.148 0.05–1.66	97% 1.3 ND (< 0.013)–19.9	94% 0.46 (mean) ND (< 0.02)–3.9	100% 2.5 0.5–7.3	100% 2.32 **–21.21

*Cooper et al. 2011

†Hoffman et al. 2014

‡Dodson et al. 2014

§Petropoulou et al. 2016

¶Hammel et al. 2016

**LOD not given.

We identified urinary BDCIPP (a metabolite specific to TDCIPP) concentrations declined across the shift in most participants, despite TDCIPP in the air and on the hands of participants. The overall GM uncorrected postshift concentration was 1.45 µg/L, which is similar to the range reported in other U.S. studies (range: 1.3–2.5 µg/L; Table 19). Shipping and receiving participants had the highest uncorrected postshift urine BDCIPP concentration of 3.18 µg/L. Similarly, the highest concentration of TDCIPP found on handwipes (3,200 ng/sample) was in shipping and receiving. TDCIPP was also detected in the air, ranging from ND–13 ng/m^3. Uncorrected urine concentrations of BDCIPP decreased from preshift to postshift for shredding and disassembly employees, despite having the highest median concentrations of TDCIPP in the air. TDCIPP in dust has been detected at higher levels in vehicles and offices than in homes [Carignan et al. 2013]. Electronics, such as computers, utilize fans that may collect indoor dust. Shipping and receiving employees were the first employees to receive electronics upon entry to the facility. These employees may have encountered higher levels of dust from electronics accepted by the facility, thus resulting in higher levels of TDCIPP on the hands and BDCIPP in the urine.

Urinary BCIPP and BCEP concentrations in our participants were similar to what has been found in the general population. Urinary TBBA was not detected in any of our samples. One study of 52 U.S. adults reported a GM concentration of 0.0056 µg/L. Because our LOD was 0.05 µg/L, we may have been unable to detect it [Hoffman et al. 2014]. Urinary DoCP and DpCP, which are metabolites of TCP (which is also used in plastic housings of electronics) were mostly undetectable, despite TCP being present in the highest median airborne concentrations. Median handwipe levels of TCP also increased from the preshift to postshift levels for shredding, disassembly, special projects, and resale participants. The biggest differences and highest TCP concentrations of handwipes was among resale and shredding participants. The absence of urinary metabolites could be due to a variety of reasons. Urine may not be an important route of excretion for TCP in humans. Kurebayashi et al. [1985] found that TCP was excreted mainly in the feces (77%) and not the urine (12%) of rats after a single oral dose. In addition, dermal or inhalation absorption may be poor.

Biological Burden of Flame Retardants: Uncertainty Regarding Health Effects

Recognition of the potential adverse effects of exposure to flame retardants is relatively recent (unlike lead, for which effects have been recognized and studied for decades, allowing prediction of health effects based upon the BLL). Some human epidemiologic studies have shown an association between exposure to certain flame retardants and changes in male reproductive hormones, semen quality, thyroid homeostasis, and hormone levels and fertility in women; cryptorchidism (undescended testicles); low birth weight and length; delayed motor skills; decreased IQ; and cancer [Abdallah et al. 2015; Czerska et al. 2013; Dallaire et al. 2009; Dishaw et al. 2014; Grant et al. 2013; Johnson et al. 2013; Meeker and Stapleton 2010; Meeker et al. 2013a,b; van der Veen and de Boer 2012]. However, it is not clear at what levels these effects begin to occur. Studies like the one reported here help us identify populations with potential exposure and may help establish baseline levels to evaluate employees in at-risk industries during future research.

Metals

Two personal air samples taken in the cabinet disassembly area in the dismantling building exceeded the NIOSH REL and OSHA PEL for silver. We suspect that a granulator being used by another company in an adjacent part of the building contributed to these higher concentrations of silver in the air. Silver exposures in the remainder of the personal samples in the dismantling building were below the OEL. In addition, the remaining personal exposures in both buildings to airborne metals were below the lowest OELs. Overall, the highest concentrations of metals in personal samples in the shred building were from participants working in the shredding department. The mechanical action of the shredder coupled with the lack of local exhaust ventilation likely contributed to the higher concentrations of metals in the air.

The highest concentrations of metals in personal air samples in the dismantling building were from participants working in the disassembly department. With the exception of silver, in general, personal air samples for metals were lower in the dismantling building than in the shred building. Additionally, we noted dry sweeping in the shred building, particularly near the locations where metal was collected from the magnets. Although the company provided a sweeping compound, there is still a possibility of reaerosolizing metals when dry sweeping.

The surface wipe results indicated detectable levels of metals on surfaces in nonprocessing areas. We found detectable levels of several metals including cadmium, lithium, lead, and silver on breakroom surfaces. We also noted that the breakroom in the dismantling building is shared with another company, so it is unclear whether the surface levels were a result of this company or the other company.

We found metals, including lead, cadmium, and silver, on handwipe samples collected after participants washed their hands before leaving work. Again, a majority of the handwipe samples were lower in the dismantling building than in the shred building, with the exception of silver. NIOSH research shows that washing hands with soap and water alone is not completely effective in removing lead and some other toxic metals from the skin [Esswein et al. 2011; NIOSH 2009b]. Utilizing a lead-removing product to wash hands after work will be beneficial in reducing lead and other metal levels on the hands. Some commercially available lead removal products have been proven to remove more contamination from the skin. In addition, we observed that employees frequently reused gloves, which could transfer contamination from the dirty gloves to the hands. Metals present on skin or clothing when leaving work could contaminate personal vehicles and homes and present a hazard to family members.

Both historic and current BLLs indicate that employees in the processing area of the shred building are overexposed to lead, resulting in blood levels above the CDC reference level of 5 µg/dL. Previous evaluations have shown that employees shredding electronics may have higher BLLs than those who do not [CDC 2019; NIOSH 2018b]. BLLs were highest in workers performing and immediately adjacent to shred operations, indicating that shredding is a potential source of lead exposure. Employees performing office work in the shred building, resale work, and manual disassembly had lead levels similar to that of the general population.

ZPP levels were also previously measured by the company. Elevated ZPP levels have been used as an indicator of chronic lead intoxication; however, other factors, such as iron deficiency, can cause an elevated ZPP level. Additionally, monitoring the BLL over time is more specific for evaluating chronic occupational lead exposure than ZPP. Assessing ZPP levels is required by OSHA when lead levels in the air exceed the OSHA enforceable OELs or action limit. Lead air levels at this company did not approach these OELs, and thus measuring ZPP levels would not be mandated by OSHA.

Additional Observations and Document Review

Upon review of the industrial hygiene monitoring plan, we noted that air and noise sampling are conducted by outside companies, typically biannually, unless process changes occur. Employees received annual hearing tests performed on-site by an outside company. Hearing protection was only mandatory for employees working in the processing area of the shred building. We observed some employees in the shred building used personal music players and listened to music through headphones in one ear. Most headphones from personal music players are not designed to attenuate noise and the use of these headphones, instead of hearing protection, could increase employees' risk of hearing loss. Three audiograms from 2016 reported OSHA-defined standard threshold shifts. Of note, the audiometric test results were not compared to the NIOSH-defined significant hearing threshold shift criteria. The greater sensitivity of the NIOSH criteria provides an opportunity for early intervention to prevent progression of hearing loss.

During our evaluation, we noted noticeably high noise levels during use of the granulator in the dismantling building. Our review of area sound pressure level measurements taken during the company's 2015 noise sampling revealed that sound levels near the granulator ranged from 84.1 to 97.9 decibels. During the same 2015 sampling, some employees in the dismantling building were reported to have personal noise dosimetry results near the OSHA action level (85 decibels, A-weighted). Although the company's report suggested including these employees in the hearing conservation program and requiring hearing protection, these employees were later not included. Because day to day noise exposures often vary, additional full-shift noise dosimetry is suggested to capture the range of noise exposures.

The company's most recent air sampling in 2015 reported that all airborne concentrations for beryllium, cadmium, chromium, cobalt, copper, iron oxide, lead, manganese, and nickel were below applicable OSHA and American Conference of Governmental Industrial Hygienists (ACGIH) OELs. The company strongly recommended that all personnel exposed to dust wear breathing protection (i.e., dust masks). Employees could use N95 respirators on a voluntary basis when working near the shredder. During our walkthroughs, we observed employees wearing N95 respirators incorrectly.

Conclusions

Employees at this electronics recycling company were exposed to metals, including silver and lead. Two employees in the dismantling building had overexposures to silver above the OSHA PEL, and three employees in the processing area of the shred building had BLLs above the CDC reference range of 5 μg/dL. Our handwipe sampling demonstrated that there

was potential for take-home contamination of lead and other metals. Surface wipe samples for flame retardants indicated that flame retardants were present in the workplace. Air, handwipe, and biological samples indicated that employees are exposed to flame retardants during work. We believe the uptake of flame retardants in the body is potentially hazardous to human health, and continued efforts to minimize exposures should be undertaken.

Recommendations

On the basis of our findings, we recommend the actions listed below. We encourage the electronics recycling company to use a labor-management health and safety committee or working group to discuss our recommendations and develop an action plan. Those involved in the work can best set priorities and assess the feasibility of our recommendations for the specific situation at the electronics recycling company.

Our recommendations are based on an approach known as the hierarchy of controls (http://www.cdc.gov/niosh/topics/hierarchy/default.html). This approach groups actions by their likely effectiveness in reducing or removing hazards. In most cases, the preferred approach is to eliminate hazardous materials or processes and install engineering controls to reduce exposure or shield employees. Until such controls are in place, or if they are not effective or feasible, administrative measures and PPE may be needed.

Administrative Controls

The term administrative controls refers to employer-dictated work practices and policies to reduce or prevent hazardous exposures. Their effectiveness depends on employer commitment and employee acceptance. Regular monitoring and reinforcement are necessary to ensure that policies and procedures are followed consistently.

1. Refer to expert panel guidelines for the management of adult lead exposure (Table B2) for processing employees in the shred building.

2. Provide employees with the results of their individual BLLs in writing after each blood draw.

3. Ensure that employees whose only use of respirators is voluntary can safely wear the respirator. In addition, provide these employees with a copy of Appendix D of the OSHA respiratory protection standard (29 CFR 1910.134). Ensure that respirators are stored properly so they do not become contaminated.

4. Provide employees with a lead-removing product to wash their hands when they leave the processing area, and before eating, drinking, or smoking. Learn more about commercially available lead removal products by reading *Information for Workers, How You Can Keep Yourself and Your Family Safe from Lead* available at http://www.cdc.gov/niosh/topics/lead/safe.html.

5. Ensure employees in the processing area of the shred building leave work-issued clothing and shoes at work, and that work-issued clothing is laundered on-site or through a contract laundry service. Laundry personnel should be aware of the potential exposure

to lead and other contaminants on work clothes and take action to minimize exposures.

6. Prohibit dry sweeping. Use wet cleaning methods or a vacuum with a high-efficiency particulate air (HEPA) filter instead.

7. Do not permit the use of personal music players in work areas where hearing protection is suggested or required.

8. Require employees working near the granulator to wear PPE (i.e., long sleeves and respirators) until samples confirm the exposures to silver are controlled below OELs. Inform the adjacent company of employee exposures and suggest they implement ventilation controls on their equipment or work with the company to provide a physical barrier between the two areas.

9. Include employees working near the granulator in the hearing conservation program.

10. Use both NIOSH and OSHA criteria to identify hearing threshold shifts to improve early detection of potential hearing loss.

11. Clean all nonprocessing surfaces periodically to reduce the buildup of dust that contains lead, silver, and other metals. Consider using lead-removing wipes for this purpose.

12. Remove carpet in currently carpeted areas. Carpets may trap metals, flame retardants, and allergens. Eliminating carpeted surfaces can prevent buildup of these hazardous materials. If unable to remove carpet, we recommend limiting foot traffic from processing areas and using a HEPA-filtered vacuum cleaner.

Personal Protective Equipment

PPE is the least effective means for controlling hazardous exposures. Proper use of PPE requires a comprehensive program and a high level of employee involvement and commitment. The right PPE must be chosen for each hazard. Supporting programs, such as training, change-out schedules, and medical assessment, may be needed. PPE should not be the sole method for controlling hazardous exposures. Rather, PPE should be used until effective engineering and administrative controls are in place.

1. Require hearing protection for employees who work in areas adjacent to the granulator.

2. Implement a respiratory protection program for all employees that work around the granulator operations until samples confirm that silver exposure is controlled below OELs.

3. Require employees who voluntarily use N95 respirators to wear them properly. Guidelines for putting on and taking off a disposable respirator are available at http://www.cdc.gov/niosh/docs/2010-133/pdfs/2010-133.pdf.

4. Train employees on the proper insertion and use of disposable ear plugs, even if worn voluntarily. Include in the training that headphones are not hearing protection devices.

5. Provide clean gloves for daily use. If cloth, leather, or cut-resistant outer gloves are reused, ensure employees wear clean inner gloves. Instruct employees to leave dirty gloves in the work area. Encourage employees to replace dirty gloves frequently to minimize contamination of surfaces with metals.

Appendix A: Tables

Table A1. Flame retardants sampled during this evaluation and where they are typically found

Flame retardant	CAS number	Typically found in
Commonly used in electronics until around 2004		
Octabromodiphenyl ether technical mixture (OctaBDE)	32536-52-0	Acrylonitrile-butadiene-styrene resins and housings for electrical equipment; not used in United States since 2004
Commonly used in electronics until around 2013		
Decabromodiphenyl ether technical mixture (DecaBDE)	1163-19-5	High impact polystyrene for television and computer monitor housings, polycarbonate and polymer resins, rubber; not used in United States since 2013
Commonly used in electronics now and in the past		
Tris(phenyl) phosphate (TPHP)	115-86-6	High impact polystyrene and acrylonitrile-butadiene-styrene plastics for electronics housings, printed wiring boards, synthetic resins and decorative laminated sheets, photographic film, plasticizer in lacquers, varnishes, and hot melt adhesives, in roofing paper, component of Firemaster 550 (used as a PentaBDE replacement in foam)
Tricresyl phosphate (TCP)	1330-78-5	Polystyrene and plastics for housings, rubbers, cables, hoses, conveyor belts, waterproofing
Decabromodiphenyl ethane (DBDPE)	84852-53-9	Used as a replacement for DecaBDE in high impact polystyrene and acrylonitrile-butadiene-styrene plastics for electronics housings, wires and cables, and textiles
1,2-Bis(2,4,6-tribromophenoxy) ethane (BTBPE)	37853-59-1	Firemaster 680 (a replacement for OctaBDE) in high impact polystyrene and acrylonitrile-butadiene-styrene plastics for electronics housings, thermoplastics, elastomers, adhesives and coatings
Tetrabromobisphenol-A (TBBPA)	79-94-7	Printed circuit boards, epoxies, and polycarbonate resins
Less commonly used in electronics now and in the past		
2-Ethylhexyl 2,3,4,5-tetrabromobenzoate (EH-TBB)	183658-27-7	Firemaster 550 (used as a replacement for PentaBDE in foam), polyvinyl chloride and neoprene, wire and cable insulation, coated fabrics
Bis(2-ethylhexyl) tetrabromophthalate (BEH-TEBP)	26040-51-7	Firemaster 550 (used as a replacement for PentaBDE in foam), also for flexible polyvinyl chloride, wire and cable insulation, film and sheeting, coated fabrics, wall coverings, and adhesives
Tris(chloroethyl) phosphate (TCEP)	115-96-8	Polyester resins, adhesives, and coatings
Tris(2-chloroisopropyl) phosphate (TCIPP)	13674-84-5	Polyurethane rigid and flexible foam, polyvinyl chloride, and epoxy resin, thermosets and thermoplastics, textile finishes
α-, β-, γ-Hexabromocyclododecane (α-, β-, γ-HBCD)	134237-50-6 134237-51-7 134237-52-8	Polystyrene for building construction, high impact polystyrene for electronics casings, acrylic and latex dispersions (textile backings)
Rarely used in electronics		
Pentabromodiphenyl ether technical mixture (PentaBDE)	32534-81-9	Polyurethane foam and textiles, so often present in dusts; not used in United States since 2004
Tris(1,3-dichloro-2-propyl) phosphate (TDCIPP)	13674-87-8	Polyurethane foam

CAS = Chemical abstract service

Table A2. Major congeners of PentaBDE, OctaBDE, and DecaBDE [Alaee et al. 2003]

Flame retardant and major congeners	CAS Number	Percentage
PentaBDE	32534-81-9	
BDE-99*	60348-60-9	45%–49%
BDE-47*	5436-43-1	38%–42%
BDE-100	189084-64-8	7.5%–13%
BDE-153‡	68631-49-2	5.3%–4.0%
BDE-154‡	207122-15-4	2.7%–4.5%
BDE-85	182346-21-0	2.2%–3.0%
OctaBDE	32536-52-0	
BDE-183*	207122-16-5	13%–42%
BDE-209†	145538-75-5	1.3%–50%
DecaBDE	1163-19-5	
BDE-209	145538-75-5	97%–98%
BDE-206§	63387-28-0	low

*These congeners are used as markers for their parent chemicals.

†Photolytic debromination of BDE-209 can form BDE-183 [Stapleton and Dodder 2008].

‡These can also be components of OctaBDE.

§This is also a breakdown product of BDE-209.

Table A3. Comparing selected PPs found in the blood of electronics recycling employees with the NHANES for the general population, in ng/g lipid weight

Persistent pesticide	Electronics recycling company participants (n = 25)			NHANES (2003–2004)		
	Median	GM	Maximum	Median	GM	95th percentile
Polybrominated biphenyl 153	1.04	0.976	10.8	2.50	2.72	34.6
Hexachlorobenzene	6.89	6.65	10.9	15.1	15.5	29.0
*Beta-*hexachlorocyclohexane	Not calculated	Not calculated	13.0	ND	7.89	62.2
Oxychlordane	3.47	3.21	19.1	11.4	10.6	39.2
Trans-nonchlor	4.88	4.53	21.9	17.3	16.9	74.7
p,p'-dichlorodiphenyl trichloroethene	57.2	75.1	4,120	233	268	1,990
o,p'-dichlorodiphenyl trichloroethane	Not calculated	Not calculated	1.72	Not reported	ND	ND
p,p'-dichlorodiphenyl trichloroethane	Not calculated	Not calculated	14.4	Not reported	ND	20.7

Table A4. Comparing selected PCBs found in the blood of electronics recycling employees with the NHANES for the general population, in ng/g lipid weight

Polychlorinated biphenyl	Electronics recycling company participants (n = 25)			NHANES (2003–2004)		
	Median	GM	Maximum	Median	GM	95th percentile
Polychlorinated biphenyl 28	4.15	3.66	18.3	4.98	4.88	11.1
Polychlorinated biphenyl 66	0.80	0.73	3.01	1.40	1.42	4.20
Polychlorinated biphenyl 74	1.83	2.21	8.78	5.00	5.38	24.1
Polychlorinated biphenyl 99	2.26	2.18	14.1	4.08	4.52	18.6
Polychlorinated biphenyl 153	10.6	9.91	79.6	24.2	23.7	101
Polychlorinated biphenyl 156	1.29	1.22	6.64	4.10	3.31	16.8
Polychlorinated biphenyl 170	2.79	2.52	19.5	7.83	6.86	29.5
Polychlorinated biphenyl 180	7.01	6.53	49.8	21.5	19.0	88.0
Polychlorinated biphenyl 187	2.28	2.23	26.7	5.71	5.20	25.9

Table A5. Creatinine-uncorrected concentrations of flame retardant metabolites in urine of electronics recycling employees and in the NHANES, in μg/L. Samples are the second day of sampling, postshift values

Metbolite (parent flame retardant)	Electronics recycling company participants (n = 24)			NHANES*		
	Median†	GM†	Max	Median	GM	95th percentile
Commonly used in electronics now and in the past						
DPHP (TPHP) LOD = 0.16	0.89	0.91	7.4	0.73	0.76	5.5
DpCP (TCP) LOD = 0.05	ND	Not calculated	0.20	ND	Not calculated	0.10
DoCP (TCP) LOD = 0.05	ND	Not calculated	ND	ND	ND	ND
Less commonly used in electronics now and in the past						
TBBA (EH-TBB) LOD = 0.05	ND	Not calculated	ND	ND	ND	ND
BCEP (TCEP) LOD = 0.08	0.27	0.37	5.1	0.37	0.39	3.6
BCIPP (TCIPP) LOD = 0.10	0.20	0.22	0.94	0.16	0.19	1.3
Rarely used in electronics						
BDCIPP (TDCIPP) LOD = 0.11	1.3	1.4	23.7	0.85	0.82	6.4

*Age 20 to 59, n = 1,266. Samples taken 2013 and 2014.

†Median and GM not calculated if percentage detected was below 70%.

Table A6. Creatinine-corrected concentrations of flame retardant metabolites in urine of electronics recycling employees and in the NHANES, in μg/g creatinine. Samples are the second day of sampling, postshift values

Metbolite (parent flame retardant)	Electronics recycling company participants (n = 24)			NHANES*		
	Median†	GM†	Max	Median	GM	95th percentile
Commonly used in electronics now and in the past						
DPHP (TPHP)	0.65	0.66	4.1	0.70	0.79	4.7
DpCP (TCP)	ND	Not calculated	0.17	ND	Not calculated	0.18
DoCP (TCP)	ND	ND	ND	ND	ND	ND
Less commonly used in electronics now and in the past						
TBBA (EH-TBB)	ND	ND	ND	ND	ND	ND
BCEP (TCEP)	0.24	0.27	2.3	0.33	0.41	3.3
BCIPP (TCIPP)	0.14	0.16	0.57	0.18	0.20	1.3
Rarely used in electronics						
BDCIPP (TDCIPP)	0.88	0.99	12.1	0.82	0.85	4.3

*Age 20 to 59, n = 1,266. Samples taken in 2013 and 2014.

†Median and GM not calculated if percentage detected was below 70%.

Table A7. Results of personal air samples for metals (in μg/m³) collected over 2 days for 12 employees in the shred building (n = 22*)

Metal	Median	GM (range)	Lowest OEL	Agency
Aluminum	20	12 (ND–53)	10,000	NIOSH
Antimony	0.51	0.75 (ND–1.9)	500	OSHA/NIOSH/ACGIH
Arsenic	ND	ND	10	ACGIH
Barium	6.2	4.0 (0.17–76)	500	OSHA/NIOSH/ACGIH
Beryllium	ND	ND	0.05	ACGIH
Cadmium	0.074	0.068 (ND–0.26)	5	OSHA
Calcium	24	20 (ND–70)	—	N/A
Chromium	0.33	0.32 (ND–0.96)	500	NIOSH/ACGIH
Cobalt	0.31	0.18 (ND–0.57)	20	ACGIH
Copper	5.4	3.3 (0.17–25)	1,000	NIOSH/OSHA/ACGIH
Indium	ND	ND (ND–0.86)	100	NIOSH/ACGIH
Iron	61	40 (1.9–140)	5,000	NIOSH
Lanthanum	0.13	0.071 (ND–0.33)	—	N/A
Lead	6.0	3.9 (0.27–17)	50	OSHA/NIOSH/ACGIH
Lithium	0.057	0.078 (ND–0.65)	—	N/A
Magnesium	3.2	2.8 (ND–6.5)	10,000	ACGIH
Manganese	3.0	1.9 (0.068–9.3)	100	ACGIH
Molybdenum	ND	ND (ND–0.096)	10,000	ACGIH
Nickel	1.3	0.74 (ND–7.4)	15	NIOSH
Phosphorus	1.1	0.89 (ND–3.7)	100	OSHA/NIOSH/ACGIH
Potassium	2.0	1.6 (ND–4.4)	—	N/A
Selenium	ND	ND (ND–1.3)	200	OSHA/NIOSH/ACGIH
Silver	0.34	0.24 (ND–1.8)	10	OSHA/NIOSH
Strontium	0.93	0.57 (0.038–2.5)	—	N/A
Tellurium	ND	ND	100	OSHA/NIOSH/ACGIH
Thallium	ND	ND (ND–0.33)	20	ACGIH
Tin	4.0	2.2 (0.12–22)	2,000	OSHA/NIOSH/ACGIH
Titanium	1.7	1.0 (ND–14)	—	N/A
Vanadium	ND	ND (ND–0.71)	—	N/A
Yttrium	0.14	0.095 (ND–0.57)	1,000	OSHA/NIOSH/ACGIH
Zinc	12	7.9 (0.38–32)	5,000	NIOSH
Zirconium	0.18	0.12 (ND–0.99)	5,000	OSHA/NIOSH/ACGIH

N/A = Not applicable

*One employee missed work on each day of sampling.

Table A8. Results of personal air samples for metals (in µg/m^3) collected over 2 days for 13 employees in the dismantling building (n = 25*)

Metal	Median	GM (range)	Lowest OEL	Agency
Aluminum	5.5	6.0 (0.94–38)	10,000	NIOSH
Antimony	ND	ND	500	OSHA/NIOSH/ACGIH
Arsenic	ND	ND	10	ACGIH
Barium	0.32	0.29 (ND–2.7)	500	OSHA/NIOSH/ACGIH
Beryllium	ND	ND	0.05	ACGIH
Cadmium	0.054	0.065 (ND–2.2)	5	OSHA
Calcium	11	12 (ND–45)	—	N/A
Chromium	ND	ND (ND–0.16)	500	NIOSH/ACGIH
Cobalt	ND	ND (ND–0.20)	20	ACGIH
Copper	5.7	3.2 (0.20–23)	1,000	NIOSH/OSHA/ACGIH
Indium	ND	ND (ND–0.18)	100	NIOSH/ACGIH
Iron	15	11 (ND–64)	5,000	NIOSH
Lanthanum	ND	ND (ND–0.035)	—	N/A
Lead	0.96	0.72 (ND–4.4)	50	OSHA/NIOSH/ACGIH
Lithium	ND	ND (ND–0.13)	—	N/A
Magnesium	ND	1.84 (ND–5.1)	10,000	ACGIH
Manganese	0.21	0.16 (ND–2.2)	100	ACGIH
Molybdenum	ND	ND (ND–0.14)	10,000	ACGIH
Nickel	0.43	0.33 (ND–1.6)	15	NIOSH
Phosphorus	0.35	0.56 (ND–1.9)	100	OSHA/NIOSH/ACGIH
Potassium	1.9	1.4 (ND–5.3)	—	N/A
Selenium	ND	ND (ND–1.0)	200	OSHA/NIOSH/ACGIH
Silver	2.1	1.5 (0.13–13)	10	OSHA/NIOSH
Strontium	0.041	0.048 (ND–0.37)	—	N/A
Tellurium	ND	ND	100	OSHA/NIOSH/ACGIH
Thallium	ND	ND	20	ACGIH
Tin	0.86	0.63 (ND–3.6)	2,000	OSHA/NIOSH/ACGIH
Titanium	0.18	0.15 (ND–0.93)	—	N/A
Vanadium	ND	ND	—	N/A
Yttrium	0.018	0.017 (ND–0.15)	1,000	OSHA/NIOSH/ACGIH
Zinc	3.8	4.0 (0.69–18)	5,000	NIOSH
Zirconium	0.56	0.53 (ND–0.35)	5,000	OSHA/NIOSH/ACGIH

N/A = Not applicable

*One employee missed work the first day of sampling.

Appendix B: Occupational Exposure Limits and Health Effects

NIOSH investigators refer to mandatory (legally enforceable) and recommended OELs for chemical, physical, and biological agents when evaluating workplace hazards. OELs have been developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects.

However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a preexisting medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects. Most OELs address airborne exposures, but some substances can be absorbed directly through the skin and mucous membranes.

Most OELs are expressed as a time-weighted average (TWA) exposure. A TWA refers to the average exposure during a normal 8- to 10-hour workday. Some chemical substances and physical agents have recommended short-term exposure limits (STEL) or ceiling values. Unless otherwise noted, the STEL is a 15-minute TWA exposure. It should not be exceeded at any time during a workday. The ceiling limit should not be exceeded at any time.

In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations.

- OSHA, an agency of the U.S. Department of Labor, publishes permissible exposure limits

- [29 CFR 1910 for general industry; 29 CFR 1926 for construction industry; and 29 CFR 1917 for maritime industry] called PELs. These legal limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970.

- NIOSH RELs are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2007]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, PPE, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.

- Another set of OELs commonly used and cited in the United States include the threshold limit values or TLVs, which are recommended by ACGIH. The ACGIH TLVs are developed by committee members of this professional organization from a review of the published, peer-reviewed literature. TLVs are not consensus standards. They are considered voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2019].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at https://www.dguv.de/ifa/gestis/gestis-stoffdatenbank/index-2.jsp, contains international limits for more than 2,000 hazardous substances and is updated periodically.

OSHA (Public Law 91-596) requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm. This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions. NIOSH investigators also encourage use of the hierarchy of controls approach to eliminate or minimize workplace hazards. This includes, in order of preference, the use of (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation), (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) PPE (e.g., respiratory protection, gloves, eye protection, hearing protection). Control banding, a qualitative risk assessment and risk management tool, is a complementary approach to protecting employee health. Control banding focuses on how broad categories of risk should be managed. Information on control banding is available at http://www.cdc.gov/niosh/topics/ctrlbanding/. This approach can be applied in situations where OELs have not been established or can be used to supplement existing OELs.

Lead

Inorganic lead is a naturally occurring, soft metal that has been mined and used in industry since ancient times. It comes in many forms (e.g., lead acetate, lead chloride, lead chromate, lead nitrate, lead oxide, lead phosphate, and lead sulfate). Lead is considered toxic to all organ systems and serves no useful purpose in the body.

Occupational exposure to inorganic lead occurs via inhalation of lead-containing dust and fume and ingestion of lead particles from contact with lead-contaminated surfaces. Exposure may also occur through transfer of lead to the mouth from contaminated hands or cigarettes when careful attention to hygiene, particularly hand washing, is not practiced. In addition to the inhalation and ingestion routes of exposure, lead can be absorbed through the skin, particularly through damaged skin [Filon et al. 2006; Stauber et al. 1994; Sun et al. 2002].

Workplace settings with exposure to lead and lead compounds include smelting and refining, scrap metal recovery, automobile radiator repair, construction and demolition (including abrasive blasting), and firing ranges. Occupational exposures also occur among workers who apply or remove lead-based paint and among welders who burn or torch-cut metal structures.

Blood Lead Levels

In most cases, an individual's BLL is a good indication of recent exposure to lead because the half-life of lead (the time interval it takes for the quantity in the body to be reduced by half its initial value) is 1–2 months [CDC 2013a; Lauwerys and Hoet 2001; Moline and Landrigan 2005]. Most lead in the body is stored in the bones, with a half-life of years to decades. Measuring bone lead, however, is primarily done only for research. Elevated ZPP levels have also been used as an indicator of chronic lead intoxication; however, other factors, such as iron deficiency, can cause an elevated ZPP level, so monitoring the BLL over time is more specific for evaluating chronic occupational lead exposure.

BLLs in adults in the United States have declined consistently over time. The GM BLL went from 1.75 µg/dL in 1999–2000 to 0.92 µg/dL in 2015–2016 [CDC 2015; NIOSH 2015]. The NIOSH Adult Blood Lead Epidemiology and Surveillance system uses a surveillance case definition for an elevated BLL in adults of 5 µg/dL of blood or higher [NIOSH 2015]. Very high BLLs are defined as BLLs ≥ 40 µg/dL. From 2002–2011, occupational exposures accounted for 91% of adults with very high BLLs (where exposure source was known) [CDC 2013b]. This underscores the need to increase efforts to prevent lead exposures in the workplace.

Occupational Exposure Limits

In the United States, employers in general industry are required by law to follow the OSHA lead standard (29 CFR 1910.1025). This standard was established in 1978 and has not yet been updated to reflect the current scientific knowledge regarding the health effects of lead exposure.

Under this standard, the PEL for airborne exposure to lead is 50 µg/m^3 of air for an 8-hour TWA. The standard requires lowering the PEL for shifts that exceed 8 hours, medical monitoring for employees exposed to airborne lead at or above the action level of 30 µg/m^3 (8-hour TWA), medical removal of employees whose average BLL is 50 µg/dL or greater, and economic protection for medically removed workers. Medically removed workers cannot return to jobs involving lead exposure until their BLL is below 40 µg/dL.

In the United States, other guidelines for lead exposure, which are not legally enforceable, are often followed. Similar to the OSHA lead standard, these guidelines were set years ago and have not yet been updated to reflect current scientific knowledge. NIOSH has a REL for lead of 50 µg/m^3 averaged over an 8-hour work shift [NIOSH 2010]. The ACGIH has a TLV for lead of 50 µg/m^3 (8-hour TWA), with worker BLLs to be controlled to, or below, 30 µg/dL. The ACGIH designates lead as an animal carcinogen [ACGIH 2019]. In 2013, the California Department of Public Health (CDPH) recommended that Cal/OSHA lower the PEL for lead to 0.5 to 2.1 µg/m^3 (8-hour TWA) to keep BLLs below the range of 5 to 10 µg/dL [Billingsley 2013].

Neither NIOSH nor OSHA has established surface contamination limits for lead in the workplace. The U.S. Environmental Protection Agency and the U.S. Department of Housing and Urban Development limit lead on surfaces in public buildings and child-occupied housing to less than 40 micrograms of lead per square foot [EPA 1998; HUD 2012]. OSHA requires in its substance-specific standard for lead that all surfaces be maintained as free as

practicable of accumulations of lead [29 CFR 1910.1025(h)(1)]. An employer with workplace exposures to lead must implement regular and effective cleaning of surfaces in areas such as change areas, storage facilities, and lunchroom/eating areas to ensure they are as free as practicable from lead contamination [OSHA 2003].

Health Effects

The PEL, REL, and TLV may prevent overt symptoms of lead poisoning, but do not protect workers from lead's contributions to conditions such as hypertension, renal dysfunction, reproductive, and cognitive effects [Brown-Williams et al. 2009; Holland and Cawthorn 2016; National Research Council 2013; Schwartz and Hu 2007; Schwartz and Stewart 2007]. Generally, acute lead poisoning with symptoms has been documented in persons having BLLs above 70 µg/dL. These BLLs are rare today in the United States, largely as a result of workplace controls put in place to comply with current OELs. When present, acute lead poisoning can cause myriad adverse health effects including abdominal pain, hemolytic anemia, and neuropathy. Lead poisoning has, in very rare cases, progressed to encephalopathy and coma [Moline and Landrigan 2005].

People with chronic lead poisoning, which is more likely at current occupational exposure levels, may not have symptoms or they may have nonspecific symptoms that may not be recognized as being associated with lead exposure. These symptoms include headache, joint and muscle aches, weakness, fatigue, irritability, depression, constipation, anorexia, and abdominal discomfort [Moline and Landrigan 2005].

The National Toxicology Program (NTP) recently released a monograph on the health effects of low-level lead exposure [NTP 2012]. For adults, the NTP concluded the following about the evidence regarding health effects of lead (Table B1).

Table B1. Evidence regarding health effects of lead in adults

Health area	NTP conclusion	Principal health effects	Blood lead evidence
Neurological	Sufficient	Increased incidence of essential tremor	Yes, < 10 µg/dL
	Limited	Psychiatric effects, decreased hearing, decreased cognitive function, increased incidence of amyotrophic lateral sclerosis	Yes, < 10 µg/dL
	Limited	Increased incidence of essential tremor	Yes, < 5 µg/dL
Immune	Inadequate		Unclear
Cardiovascular	Sufficient	Increased blood pressure and increased risk of hypertension	Yes, < 10 µg/dL
	Limited	Increased cardiovascular-related mortality and electrocardiography abnormalities	Yes, < 10 µg/dL
Renal	Sufficient	Decreased glomerular filtration rate	Yes, < 5 µg/dL
Reproductive	Sufficient	Women: reduced fetal growth	Yes, < 5 µg/dL
	Sufficient	Men: adverse changes in sperm parameters and increased time to pregnancy	Yes, ≥ 15–20 µg/dL
	Limited	Women: increase in spontaneous abortion and preterm birth	Yes, < 10 µg/dL
	Limited	Men: decreased fertility	Yes, ≥ 10 µg/dL
	Limited	Men: spontaneous abortion	Yes, ≥ 31 µg/dL
	Inadequate	Women and Men: stillbirth, endocrine effects, birth defects	Unclear

Various organizations have assessed the relationship between lead exposure and cancer. According to the Agency for Toxic Substances and Disease Registry (ATSDR) [2007] and NTP [2016], inorganic lead compounds are reasonably anticipated to cause cancer in humans. Through the International Agency for Research on Cancer (IARC), the World Health Organization (WHO) classifies inorganic lead as probably carcinogenic to humans [IARC 2006a]. Some studies show a relationship between lead and stomach cancer, and these findings are less likely to be affected by the other exposures. The results of studies looking at other cancers, including brain, kidney, bladder, colon, and rectum, are mixed.

Medical Management

To prevent acute and chronic health effects, a panel of experts convened by the Association of Occupational and Environmental Clinics published guidelines for the management of adult lead exposure [Kosnett et al. 2007]. The panel recommended BLL testing for all lead-exposed employees, regardless of the airborne lead concentration. These recommendations do not apply to pregnant women, who should avoid BLLs > 5 µg/dL. Removal from lead exposure should be considered if control measures over an extended period do not decrease BLLs to < 10 µg/dL or an employee has a medical condition that would increase the risk of adverse health effects from lead exposure. These guidelines were endorsed by the Council of State and Territorial Epidemiologists (CSTE) and the CDPH in 2009 [CDPH 2009; CSTE 2009]. CSTE published updated guidelines in 2013 to reflect the new definition of an elevated BLL in adults of 5 µg/dL [CSTE 2015]. The CDPH recommended keeping BLLs below 5 to 10 µg/dL in 2013 [Billingsley 2013] and updated their medical management guidelines in 2014 [CDPH 2014]. In 2015, NIOSH designated 5 µg/dL of whole blood, in a venous blood sample, as the reference BLL for adults. An elevated BLL is defined as a BLL ≥ 5 µg/dL. In 2016, the American College of Occupational and Environmental Medicine (ACOEM) released a position statement entitled "Workplace Lead Exposure," which reinforces the guidelines and recommendations above [Holland and Cawthorn 2016]. Table B2 incorporates recommendations from the expert panel guidelines and those from CDPH, CSTE, and ACOEM.

Table B2. Health-based medical surveillance recommendations for lead-exposed employees

Category of exposure	Recommendations
All lead exposed workers	• Baseline or preplacement medical history and physical examination, baseline BLL, and serum creatinine
BLL < 5 µg/dL	• BLL monthly for first 3 months placement, or upon change in task to higher exposure, then BLL every 6 months; if BLL increases ≥ 5 µg/dL, evaluate exposure and protective measures, and increase monitoring if indicated
BLL 5–9 µg/dL	• Discuss health risks • Minimize exposure • Consider removal for pregnancy and certain medical conditions • BLL monthly for first 3 months placement or every 2 months for the first 6 months placement, or upon change in task to higher exposure, then BLL every 6 months; if BLL increases ≥ 5 µg/dL, evaluate exposure and protective measures, and increase monitoring if indicated
BLL 10–19 µg/dL	• Discuss health risks • Decrease exposure • Remove from exposure for pregnancy • Consider removal for certain medical conditions or BLL ≥ 10 µg/dL for extended period • BLL every 3 months; evaluate exposure, engineering controls, and work practices; consider removal. • Revert to BLL every 6 months after 3 BLLs < 10 µg/dL
BLL 20–29 µg/dL	• Remove from exposure for pregnancy • Remove from exposure if repeat BLL measured in 4 weeks remains ≥ 20 µg/dL • Annual lead medical exam recommended • Monthly BLL testing • Consider return to work after 2 BLLs < 15 µg/dL a month apart, then monitor as above
BLL 30–49 µg/dL	• Remove from exposure • Prompt medical evaluation • Monthly BLL testing • Consider return to work after 2 BLLs < 15 µg/dL a month apart, then monitor as above
BLL 50–79 µg/dL	• Remove from exposure • Prompt medical evaluation • Consider chelation with significant symptoms
BLL ≥ 80 µg/dL	• Remove from exposure • Urgent medical evaluation • Chelation may be indicated

Adapted from Kosnett et al. 2007, CSTE 2015, and CDPH 2014

Take-home Contamination

Occupational exposures to lead can result in exposures to household members, including children, from take-home contamination. Take-home contamination occurs when lead dust is transferred from the workplace on employees' skin, clothing, shoes, and other personal items to their vehicle and home [CDC 2009, 2015].

The CDC considers a BLL in children of 5 µg/dL or higher as a reference level above which public health actions should be initiated, and states that no safe BLL in children has been identified [CDC 2013a].

The U.S. Congress passed the Workers' Family Protection Act in 1992 (29 U.S.C. 671a). The Act required NIOSH to study take-home contamination from workplace chemicals and substances, including lead. NIOSH found that take-home exposure is a widespread problem [NIOSH 1995]. Workplace measures effective in preventing take-home exposures were (1) reducing exposure in the workplace, (2) changing clothes before going home and leaving soiled clothing at work for laundering, (3) storing street clothes in areas separate from work clothes, (4) showering before leaving work, and (5) prohibiting removal of toxic substances or contaminated items from the workplace. NIOSH noted that preventing take-home exposure is critical because decontaminating homes and vehicles is not always effective. Normal house cleaning and laundry methods are inadequate, and decontamination can expose the people doing the cleaning and laundry.

Silver

Silver is a white, lustrous metal. Silver has been used in the production of electrical contacts and solder. The accumulation of a body burden of silver may, over time, result in a condition known as argyria. This condition, the primary health effect seen after prolonged silver exposure, has been described as a blue-grey discoloration of the skin and eyes [ACGIH 2019].

The NIOSH REL and OSHA PEL for silver metal dust and soluble compounds is 0.01 milligrams per cubic meter (mg/m^3) (as silver) as an 8-hour TWA [NIOSH 2007]. The ACGIH TLV for silver metal dust and fume of 0.1 mg/m^3 as an 8-hour TWA and is recommended to prevent argyria [ACGIH 2019]. Based on the current TLV, a minimum of 24 years of uninterrupted workplace exposure has been estimated for workers to retain sufficient silver to develop signs of argyria.

Beryllium, Cadmium, Chromium, Nickel, Manganese, and Cobalt

Below is a table summarizing the OELs for the other common metals found in electronic scrap recycling, as well as a discussion of the potential health effects from exposure to these elements.

Table B3. Chemical health effects

Chemicals	Health effects	IARC	OEL (μg/m³)
Beryllium	• Beryllium exposure may cause dermatitis, lung inflammation, and chronic beryllium disease in humans [Proctor et al. 1991] • Exposure to beryllium can lead to sensitization • Exposure also slightly increases the risk for lung cancer [Schubauer-Berigan et al. 2010]	Group 1: carcinogenic to humans [IARC 2012]	OSHA PEL: 2.0 NIOSH REL: 0.5 ACGIH TLV: 0.05
Cadmium	• Long-term occupational exposure to cadmium is associated with increased occurrence of lung cancer, kidney damage, and chronic obstructive lung disease [WHO 1992]	Group 1: carcinogenic to humans [IARC 2012]	OSHA PEL: 5.0 NIOSH REL: Cancer ACGIH TLV: 10 (2 respirable fraction)
Chromium	• The toxic effects of chromium exposure, including lung and nasal cancer, are primarily related to hexavalent chromium • Skin exposure to chromium dust can cause skin irritation and skin ulceration, and allergic contact dermatitis	Group 1: carcinogenic to humans [IARC 2012]	OSHA PEL: 1,000 NIOSH REL: 500 ACGIH TLV: 500
Cobalt	• Exposure to elevated levels of cobalt can cause gastrointestinal irritation, nausea, and vomiting • Inhaled cobalt can lead to lung damage • Skin exposure can cause irritant and allergic contact dermatitis [Vincoli 1997]	Group 2B: possibly carcinogenic to humans [IARC 2006b]	OSHA PEL: 100 NIOSH REL: 50 ACGIH TLV: 20
Manganese	• Subclinical neurological effects, such as decreased performance on neurobehavioral tests; significantly poorer eye-hand coordination, hand steadiness, and reaction time; poorer postural stability; and lower levels of cognitive flexibility	None	OSHA PEL: 5,000 NIOSH REL: 1,000 ACGIH TLV: 100
Nickel	• Allergic contact dermatitis, respiratory irritation, chronic bronchitis, asthma, reduced lung function	Nickel compounds, Group 1: carcinogenic to humans; paranasal sinus, nasal cavity, and lung	OSHA PEL: 1,000 NIOSH REL: 15 ACGIH TLV: 1,500

IARC = International Agency for Research on Cancer

Flame Retardants

Flame retardants are added to manufactured materials, surface finishes, and coatings to inhibit, suppress, or delay the production of flames and impede the spread of fire. In 1975, California Technical Bill 117 required that upholstered furniture filling, which is usually polyurethane foam, meet an open flame test. Manufacturers added chemical flame retardants to foam to meet this standard. While the standard only applied in California, manufacturers sold Technical Bill 117-compliant products across North America to avoid having double inventory and to minimize liability. California updated the standard in 2014 (TB117-2013). While it does not ban flame retardants, flammability safety standards can now be met without them.

PBDEs were used in a variety of products from the 1980s until recently. All PBDEs have a common structure of brominated diphenyl ether molecules with 1–10 bromine atoms attached. PBDEs have 209 different structural variations possible [Lorber 2008]. The manufacturing and import of the PentaBDE and OctaBDE formulations were phased out in 2004 in the United States, and the production of DecaBDE ended in 2013. Manufacturers of flame retardants have introduced replacements for the PBDEs, but the toxicity of the replacements has not been well characterized [Allen et al. 2013]. These replacement compounds include novel brominated flame retardants like EH-TBB and BEH-TEBP, and phosphorus flame retardants like TDCIPP and TPHP.

PBDEs have a molecular structure similar to thyroid hormones [McDonald 2002]. Some human epidemiologic studies have shown an association between exposure to PBDEs and changes in male reproductive hormones, semen quality, thyroid homeostasis, and hormone levels and fertility in women; cryptorchidism (undescended testicles); low birth weight and length; delayed motor skills; and decreased IQ [Abdallah et al. 2015; Czerska et al. 2013; Dallaire et al. 2009; Dishaw et al. 2014; Grant et al. 2013].

TPHP, BEH-TEBP, EH-TBB, and isopropylated triphenyl phosphate isomers are components of Firemaster 550, which appears to be the second most common flame retardant mixture currently applied to foam, after TDCIPP [Hoffman et al. 2014]. Studies indicate that BEH-TEBP may affect thyroid hormones [Johnson et al. 2013]. TCEP and TCIPP are also used in some polyurethane foam. Some phosphorus flame retardants have been associated with decreased fertility, reduced sperm motility, altered reproductive and thyroid hormones, and cancer in humans [Dishaw et al. 2014; Meeker and Stapleton 2010; Meeker et al. 2013a,b; van der Veen and de Boer 2012].

Exposure to flame retardants in indoor environments like homes, schools, and offices is thought to be mainly from ingestion of dust, primarily during the transfer of the flame retardants from hands to mouth, with dermal absorption the next most important route of exposure [Abdallah et al. 2015]. In contrast, a recent study estimated that inhalation exposure exceeded intake from ingestion of some chlorinated organophosphate flame retardants [Schreder et al. 2016]. Experimental data using human skin equivalent tissue demonstrate that absorption through skin increased as the number of bromine atoms decreased for PBDEs [Abdallah et al. 2015]. Animal studies show that TDCIPP is easily absorbed through the skin and gastrointestinal tract [Nomeir et al. 1981], and recent studies of human ex vivo skin showed absorption of 28% for TCEP, 25% for TCIPP, and 13% for TDCIPP [Abdallah et al. 2016].

Only two of the flame retardants have OSHA PELs: TPHP and TCP. The OSHA PEL for TPHP is 3,000,000 ng/m^3 (3 mg/m^3) while the PEL for tri-o-cresyl phosphate (one of the isomers of TCP) is 100,000 ng/m^3 (0.1 mg/m^3). The NIOSH REL and ACGIH TLV for TPHP are also 3 mg/m^3. The NIOSH REL and ACGIH TLV are also 0.1 mg/m^3. In addition, ATSDR [2004] recommends that if dust levels of PentaBDE and OctaBDE exceed 5,000,000 ng/m^3 (5 mg/m^3), then periodic air monitoring should be required.

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Acknowledgments

Availability of Report

Copies of this report have been sent to the employer and employees at the facility. The state and local health department and the Occupational Safety and Health Administration Regional Office have also received a copy. This report is not copyrighted and may be freely reproduced.

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