Supporting Information

MANUSCRIPT TITLE: Emissions and Occupational Exposure Risk of Halogenated Flame Retardants from Primitive Recycling of E-Waste

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Text S1. Experimental Setup and Sampling, Sample Extraction and Purification.

Three plastic casings (A1−A3) and three printed circuit boards (B1−B3) were elected from 161 e-waste samples from e-waste dismantling workshops and a resource utilization company in Guangdong Province, China, for chamber experiments. These plastic casings and printed circuit boards were composition of televisions or computers, detailed product information can be obtained in our previous work.[1] Raw materials were cleaned and smashed into pieces (830–1700 μm) before extraction and simulation. Thermal treatment (at 300 °C) and open burning (~ 800−1350 °C) were conducted in a stainless steel chamber (500 mm length × 500 mm width × 1500 mm height). The inner walls of the apparatus were buffed to reduce adsorption, rinsed with acetone after each experiment, and these rinsing samples were collected. The air flowed through the inlet purifying unit into the chamber, and finally to a Micro-Orifice Uniform Deposit Impactor (MOUDI; MSP Corporation, Shoreview, MN), which collected particulate samples in 11 size fractions (i.e., >18, 10−18, 5.6−10, 3.2−5.6, 1.8−3.2, 1.0−1.8, 0.56−1.0, 0.32−0.56, 0.18−0.32, 0.10−0.18, and 0.056−0.10 μm), followed by a polyurethane foam plug (PUF; 6.5 cm diameter × 8.0 cm; density: 0.03 g cm^{-3}) for collection of gaseous samples at the chamber outlet, at a constant flow rate of 30 L min^{-1}. The sampling duration were in cohesion with the progression of the experiments and continued for another 180 min after the experiments were completed. Schematic diagram showing the simulation experiment setup for measuring emissions of FRs from e-waste processing can be obtained in our previous work.[1]

Raw e-waste samples were extracted by 20 mL of toluene for 30 min with an ultrasonic extractor three times, while a mixture of *n*-hexane, dichloromethane, and acetone (2:2:1 in volume) was applied in the ultrasonic extraction of airborne particle and residual ash samples. Soxhlet extraction by the above-mentioned solvent mixture lasting for 48 h were applied for the extraction of PUF plugs. Each extract was concentrated to approximately 1 mL in *n*-hexane by a pressure blowing concentrator and then purified on a silica gel column

(i.d.=1.0 cm) consisted of neutral silica gel (12 cm) and anhydrous sodium sulfate (1 cm) from bottom to top. The column was eluded with 45 mL of *n*-hexane, and 50 mL of dichloromethane in sequence.

The first fraction containing AHFRs was then concentrated to 100 μL and purified by another glass column (i.d.=0.23 cm) packed with 5 cm sulfuric acid silica (44% sulfuric acid, w/w) and 1 cm anhydrous sodium sulfate with an eluate of 1.5 mL *n*-hexane. The second fraction containing BPhs was then concentrated to 100 μL in hexane and spiked with internal standards (fluorene-d_{10}, pyrene-d_{10}) before instrumental analysis. And then this fraction containing TBBPA and HBCDs was evaporated to near-dryness under a gentle N_2 stream and re-dissolved in 100 μL methanol. Finally, internal standards (d_{10}-labeled TBBPA, d_{18}-labeled α-, β-, and γ-HBCD) were added before liquid chromatography/mass spectrometry analysis.

Text S2. Instrumental Analysis

Concentrations of AHFRs were determined with a Shimadzu Model 2010 Plus gas chromatograph coupled with a Model QP2010 Ultra mass spectrometer in the negative chemical ionization mode. A DB-5MS capillary column (30 m × 0.25 mm i.d. with 0.25 μm film thickness) was used for chromatographic separation for all but DBDPE which was separated on a DB-5HT capillary column (15 m × 0.25 mm i.d. with 0.1 μm film thickness). Concentrations of BPhs were quantified with an Agilent 7890B gas chromatograph coupled to a 5977 mass spectrometer in the electron impact ionization mode, coupled with a HP-5MS capillary column (30 m × 0.25 mm i.d. with 0.25 μm film thickness).

The analysis of TBBPA and HBCDs were conducted by a Shimadzu LC-30AD liquid chromatography (LC) system coupled to an AB SCIEX Triple QUAD 5500 electrospray triple quadrupole mass spectrometer. An Agilent Eclipse Plus C18 column (100 mm × 4.6 mm i.d., 3.5 μm) was applied to separate TBBPA and the HBCD diastereoisomers. The flow rate was set at 0.3 mL min−1 with an injection volume of 2 μL. The mass spectrometer was

operated in the electrospray ionization (ESI) negative ion mode. The ions were selected at the ([M-H]−) transition of m/z 640.6/79, 652.6/79, and 657.6/79 for HBCD, 13C12-labeled HBCD, and d18-labeled HBCD isomers, respectively. The ions m/z 542.8/79 for TBBPA, m/z 554.8/79 for 13C12-labeled TBBPA, and m/z 551.8/79 for d10-labeled TBBPA were monitored.

A DB-5MS capillary column (30 m × 0.25 mm i.d. with 0.25 μm film thickness) was used for chromatographic separation for TBECH, HCDBCO, HBB, TBB, TDBPP, BTBPE, TBPH, Dec-602, Dec-603, Dec-604, *syn*-DP, and *anti*-DP, with temperature program increasing from 110 °C (held for 1 min) to 200 °C (held for 1 min) at 12 °C min^{-1}, then increasing at 5 °C min^{-1} to 240 °C (held for 5 min), increasing at 2 °C min^{-1} to 280 °C (held for 5 min), and finally increasing at 30 °C min^{-1} to 310 °C (held for 10 min).

For DBDPE, a DB-5HT capillary column (15 m × 0.25 mm i.d. with 0.1 μm film thickness) was used, with temperature program increasing from 100 °C (held for 2 min) to 255 °C at 25 °C min^{-1}, then increasing at 1 °C min^{-1} to 265 °C, and finally increasing at 25 °C min^{-1} to 325 °C (held for 6 min). Carrier gas was ultrahigh purity helium at a flow rate of 1.5 mL min^{-1}. The ion source and quadrupole temperatures were set at 200 and 150 °C, respectively.

The concentrations of 4-BPh, 2,4-DBPh, 2,6-DBPh, and 2,4,6-TBPh were quantified with an Agilent 7890B gas chromatograph coupled to a 5977 mass spectrometer in the electron impact ionization mode. A HP-5MS capillary column (30 m × 0.25 mm i.d. with 0.25 μm film thickness) was applied for their separation with temperature program increasing from 60 °C (held for 1 min) at 30 °C min^{-1} to 200 °C, then increasing at 15 °C min^{-1} to 278 °C, and finally increasing at 25 °C min^{-1} to 300 (held for 14 min).

An Agilent Eclipse Plus C18 column (100 mm × 4.6 mm i.d., 3.5 μm, Agilent, CA) was used to separate the TBBPA and HBCD diastereoisomers. The mobile phases A (30:70 methanol/water) and B (30:70 methanol/acetonitrile) were used, starting at 20:80 A/B (held

for 2 min) and increasing to 0:100 A/B over 4 min (held for 2 min) followed by a return to 20:80 A/B over 2 min (held for 10 min).

Text S3. The Estimation of the Concentration of Particulate and Gaseous FRs in Workshop Air based on the EFs

The estimation was based on information of informal e-waste dismantling workshops in Guiyu. According to the data, there are more than 5,500 household workshops in Guiyu Town, which are engaged in the dismantling and processing of e-waste, with annual dismantling e-waste amount reached 1.55 million tons.[2, 3] Thus the recycling amount for a workshop per day (W_j, g d^{-1}) is estimated by:

$$W_j = W_{annual} \times f_j \div 5500 \div 365 \quad \text{(S1)}$$

where f_j is the fraction of plastics or printed circuit boards to the total dismantling amount of e-waste in Guiyu, assumed to be consistent with those in formal recycling company (29.55% and 4.73%, respectively).[4]

As estimated for the dismantling procedure of waste printed circuit boards in facilities by Guo et al.,[5] after 20–30 s of heating time, the solder on the waste printed circuit boards melted, and the worker started to manually remove the electrical components, such as knock and pull lasting about 20 s. The thermal process was assumed to similar to this process in informal workshops and concentration of FRs in the workshop was assumed to be uniform and steady during this cycle. Thus the concentration of FRs accumulated in air after one-day dismantling was estimated by:

$$C_{j,i} = EF_{j,I} \times t \times W_j \div V \quad \text{(S2)}$$

where $EF_{j,I}$ is the emission factors (ng g^{-1} s^{-1}) for size-fractioned particulate or gaseous FRs in the thermal treatment of plastic casings or printed circuit boards; t is the heating lasting time (30 s); V is the volume of a workshop which was normally around 100

m^2 with an average height of 3.5 m, thus with a volume at 350 m^3. The FR concentrations in air were supposed to accumulate in a liner increase, thus the average value per day was applied in the health assessment.

Text S4. Exposure and Health Assessment of Flame retardants

To estimate the deposition efficiency and flux of inhaled HFRs in the human respiratory tract, we adopted the simplified equations based on the International Commission on Radiological Protection model (ICRP).[6, 7] The model calculates the deposition fractions of inhaled particles in three main regions of the human respiratory tract, i.e., head airways (HA, including nose, mouse, pharynx, and larynx), tracheobronchial region (TB), and alveolar region (AR).

The particle deposition efficiency in the head airway (DF_{HA}) was estimated by:

$$DF_{\mathrm{HA},i} = IF_{\mathrm{i}} \times \left(\frac{1}{1+\exp(6.84+1.183\ln D_{\mathrm{p,i}})} + \frac{1}{1+\exp(0.924-1.885\ln D_{\mathrm{p,i}})}\right) \quad \text{(S3)}$$

where $D_{\mathrm{p,i}}$ (μm) is geometric mean diameter of the particle at stage i, and this value for the first stage (D_{p} > 18 μm) was assumed to be 20 μm; and IF was inhalable fraction of all particles, estimated by:

$$IF = 1 - 0.5\left(1 - \frac{1}{1+0.00076\, D_{\mathrm{p,i}}^{2.8}}\right) \quad \text{(S4)}$$

The particle deposition efficiency in the tracheobronchial region (DF_{TB}) was calculated by:

$$DF_{\mathrm{TB,i}} = \frac{0.00352}{D_{\mathrm{p,i}}} \times \left(\exp(-0.234(\ln D_{\mathrm{p,i}} + 3.40)^2) + 63.9\exp(-0.819(\ln D_{\mathrm{p,i}} - 1.61)^2)\right) \quad \text{(S5)}$$

The particle deposition efficiency in the alveolar region (DF_{AR}) was estimated by:

$$DF_{\mathrm{AR,i}} = \frac{0.0155}{D_{\mathrm{p,i}}} \times (\exp(-0.416(\ln D_{\mathrm{p,i}} + 2.84)^2) + 19.11\exp(-0.482(\ln D_{\mathrm{p,i}} - 1.362)^2))$$

(S6)

The total deposition efficiency (DF_{Total}) of particle in the human respiratory tract was the sum of the three region deposition efficiencies.

The deposition flux (D, pg h^{-1}) of particle-bound HFRs in the respiratory tract was estimated by:

$$D_{\mathrm{j}} = \sum \left(DF_{\mathrm{j,i}} \times C_{\mathrm{i}}\right) \times V \quad \text{(S7)}$$

where $DF_{j,i}$ is the particle deposition efficiency in each region for $D_{p,i}$; C_i is FR concentration in particle $D_{p,i}$ (pg m^{-3}); and V is the breathing rate (0.54 m^3 h^{-1} at the sitting level of exercise).

Inhalation intake flux of gaseous (D_g) was estimated by the following:

$$D_{\mathrm{g}} = \sum C_{\mathrm{i}} \times V \quad \text{(S8)}$$

Dermal intake of particulate and gaseous FRs was assessed using the formula proposed by Weschler and Nazaroff as followed:[8]

$$D_{\mathrm{erm,p}} = \sum C_{\mathrm{i}} \times k_{\mathrm{p\_d}} \times BSA \quad \text{(S9)}$$

$$D_{\mathrm{erm,g}} = C_{\mathrm{g}} \times k_{\mathrm{p\_g}} \times BSA \quad \text{(S10)}$$

where BSA is the body surface area, and 3300 cm^2 for adults[9] was adopt in this study; k_{p_d} and k_{p_g} are the transdermal permeability coefficients (m h^{-1}) of target FRs in the particulate and gaseous phases, and 0.13 and 0.34 m h^{-1} were adopt from literature,[10] respectively.

The total exposure (EI, ng kg^{-1} day^{-1}) of FRs for the worker was estimated by:

$$EI = \frac{\sum D_{\mathrm{i}} \times T}{BW} \quad \text{(S11)}$$

where T is is the daily exposure time (h d^{-1}) which was assumed to be 8 h; BW is the body weight of an adult worker assumed to be 60 kg at an average level.

Monte Carlo simulation was used to evaluate the uncertainty and variability of intake amounts of FRs via dermal and inhalation pathways. The concentration of individual FR was assumed to be lognormal distributed with average value and standard deviation obtained in our studies.

Table S1. The Concentrations of Halogenated Flame Retardants in Plastic Casings (A1−A3) and Printed Circuit Boards (B1−B3).

	A1		A2		A3		B1		B2		B3	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
α-HBCD	1.1×10^4	680	6.2×10^3	280	3.4×10^3	310	120	13	170	9.6	430	52
β-HBCD	3.4×10^3	160	1.8×10^3	99	240	47	<RL [a]	<RL	<RL	<RL	88	10
γ-HBCD	1.3×10^3	89	660	85	560	34	14	2.0	21	4.2	280	38
TBBPA	4.2×10^5	1.3×10^4	2.0×10^5	9.6×10^3	1.3×10^5	$1.2E\times 10^4$	2.7×10^4	4.5×10^3	1.7×10^5	4.4×10^4	1.0×10^5	4.7×10^3
TBECH	850	38	320	35	<RL	<RL	<RL	<RL	<RL	<RL	<RL	<RL
HBB	350	23	190	36	150	31	33	24	<RL	<RL	30	9.2
DBDPE	2.8×10^4	4.7×10^3	5.6×10^4	5.7×10^4	2.0×10^4	3.8×10^3	<RL	<RL	<RL	<RL	7.2×10^3	510
Dec-602	200	7.0	40	6.8	36	5.1	<RL	<RL	<RL	<RL	<RL	<RL
Dec-604	280	90	93	24	130	20	<RL	<RL	<RL	<RL	<RL	<RL
syn-DP	1.1×10^4	920	3.8×10^3	660	320	89	<RL	<RL	<RL	<RL	<RL	<RL
anti-DP	6.3×10^4	4.5×10^3	2.3×10^4	4.6×10^3	1.6×10^3	450	<RL	<RL	<RL	<RL	<RL	<RL

4-BPh	650	42	<RL	<RL	<RL	<RL	180	55	140	35	850	100
2,4-DBPh	640	83	220	42	240	47	51	10	140	71	10	15
2,6-DBPh	1.1×10^3	15	600	110	550	84	110	92	850	190	210	100
2,4,6-TBPh	2.4×10^4	5.0×10^3	1.2×10^4	160	1.6×10^4	1.8×10^3	9.8×10^3	1.8×10^3	7.8×10^3	1.5×10^3	4.0×10^3	960
$\sum_{15}$HFR	$5.7E \times 10^5$	1.3×10^4	3.0×10^5	4.6×10^4	1.3×10^5	5.2×10^4	7.1×10^4	5.0×10^4	1.8×10^5	4.4×10^4	1.2×10^5	4.2×10^3

[a] The concentration is below the reporting limits.

Table S2. Emission Factors (EFs) of 15 Kinds of Halogenated Flame Retardants (ng g^{-1}) from the Thermal Treatment (T) and Open Burning (B) of Plastic Casings (A1−A3) and Printed Circuit Boards (B1−B3).

	A1		A2		A3		B1		B2		B3	
	T	B	T	B	T	B	T	B	T	B	T	B
α-HBCD	3.6×10^3	3.7×10^3	155	85	5.0×10^3	198	240	100	210	200	270	240
β-HBCD	280	310	100	150	540	6.3	93	45	190	100	170	67
γ-HBCD	3.2×10^3	1.7×10^3	25	11	5.0×10^3	250	580	27	190	55	220	77
TBBPA	1.3×10^5	6.1×10^4	1.7×10^4	446	3.6×10^4	140	5.4×10^4	1.1×10^4	3.8×10^5	2.8×10^4	3.2×10^5	1.6×10^4
TBECH	21	<RL [a]	3.9	<RL	10	<RL	2.4	<RL	0.69	<RL	1.5	<RL
HBB	230	120	92	3.0	8.6	27	6.5	16	13	15	1.2	290
DBDPE	4.4×10^3	1.2×10^4	2.7×10^3	1.1×10^3	9.7×10^3	780	<RL	<RL	<RL	<RL	6.0×10^3	1.7×10^3
Dec-602	90	65	6.6	<RL	2.9	<RL	<RL	<RL	<RL	<RL	<RL	<RL
Dec-604	99	<RL	2.0	<RL	50	<RL	<RL	<RL	<RL	<RL	<RL	<RL
syn-DP	2.8×10^3	1.2×10^3	470	<RL	280	<RL	<RL	<RL	<RL	<RL	<RL	<RL

anti-DP	9.6×10^3	7.5×10^3	2.1×10^3	4.2	97	<RL	<RL	<RL	<RL	<RL	<RL	<RL
4-BPh	990	1.6×10^3	480	930	390	1.1×10^3	500	1.4×10^3	940	2.8×10^3	1.3×10^3	3.1×10^3
2,4-DBPh	1.1×10^3	1.9×10^3	240	1.6×10^3	1.0×10^3	1.6×10^3	1.9×10^3	3.3×10^3	1.4×10^3	2.2×10^3	1.8×10^3	3.2×10^3
2,6-DBPh	1.7×10^3	3.1×10^3	470	2.4×10^3	990	2.9×10^3	2.7×10^3	4.2×10^3	3.2×10^3	4.5×10^3	4.0×10^3	5.8×10^3
2,4,6-TBPh	6.5×10^3	6.5×10^3	2.0×10^3	2.1×10^3	8.2×10^3	3.1×10^3	9.2×10^3	4.7×10^3	4.7×10^3	1.9×10^3	4.6×10^3	2.5×10^3
$\sum_{15}$HFR	1.6×10^5	1.0×10^5	2.6×10^4	8.8×10^3	6.7×10^4	1.0×10^4	7.0×10^4	2.5×10^4	3.9×10^5	4.0×10^4	3.4×10^5	3.3×10^4

[a] The concentration of HFRs in after-treatment products were below reporting limits.

Table S3. Output over Input Mass Ratios by Thermal Process (T) and Open Burning (B) of Plastic Casings (A1−A3) and Printed Circuit Boards (B1−B3).

	A1		A2		A3		B1		B2		B3	
	T	B	T	B	T	B	T	B	T	B	T	B
α-HBCD	0.33	0.34	0.03	0.01	1.32	1.09	2.06	0.89	1.22	1.15	0.64	0.57
β-HBCD	0.08	0.09	0.06	0.08	1.78	0.26	– [a]	–	–	–	1.92	0.77
γ-HBCD	2.52	1.32	0.04	0.02	8.15	6.76	42.0	1.92	9.01	2.68	0.78	0.27
TBBPA	0.30	0.15	0.09	2.3×10^{-3}	0.25	0.01	2.04	0.42	2.28	0.17	3.10	0.16
TBECH	0.02	< RL [b]	0.01	< RL	–	–	–	–	–	–	–	–
HBB	0.65	0.34	0.47	0.02	0.05	0.18	0.19	0.49	–	–	0.04	9.75
DBDPE	0.16	0.43	0.05	0.02	0.48	0.04	–	–	–	–	0.84	0.24
Dec-602	0.44	0.32	0.17	< RL	0.08	< RL	–	–	–	–	–	–
Dec-604	0.35	< RL	0.02	< RL	0.37	< RL	–	–	–	–	–	–
syn-DP	0.25	0.11	0.12	< RL	0.87	< RL	–	–	–	–	–	–

229	*anti*-DP	0.15	0.12	0.09	1.9×10^{-4}	0.06	< RL	–	–	–	–	–	–
230	4-BPh	1.52	2.50	–	–	–	–	2.76	7.78	6.93	20.9	1.56	3.71
231	2,4-DBPh	1.71	2.94	1.12	7.48	4.33	6.96	37	65	9.79	15.5	174	312
232	2,6-DBPh	1.53	2.71	0.79	3.96	1.80	5.32	24	38	3.74	5.30	19	27
233	2,4,6-TBPh	0.28	0.27	0.16	0.17	0.51	0.19	0.94	0.48	0.59	0.24	1.15	0.63
234	$\sum_{15}$HFR	0.29	0.18	0.09	0.03	0.36	0.21	1.89	0.69	2.22	0.23	2.91	0.29

235 [a] Invalid. The concentrations are below the reporting limits in raw materials and the output over input mass ratio therefore could not be

236 calculated;

237 [b] The concentration of HFRs in after-treatment products were below reporting limits.

Table S4. Relative abundance of individual halogenated flame retardant derived from thermal treatment (T) and open burning (B) of plastic casings (A1−A3) and printed circuit boards (B1−B3).

	A1		A2		A3		B1		B2		B3	
	T	B	T	B	T	B	T	B	T	B	T	B
α -HBCD	2.2	3.7	0.59	0.96	7.55	1.9	0.34	0.41	0.05	0.50	0.08	0.73
β -HBCD	0.17	0.30	0.40	1.72	0.81	0.06	0.13	0.18	0.05	0.25	0.05	0.20
γ -HBCD	2.0	1.7	0.10	0.13	7.4	2.5	0.84	0.11	0.05	0.14	0.06	0.23
TBBPA	79	61	67	5.1	53	1.4	78	45	97	70	95	49
TBECH	0.01	– [a]	0.01	–	0.02	–	3.5×10^{-3}	–	1.8×10^{-4}	–	4.3×10^{-4}	–
HBB	0.14	0.12	0.35	0.03	0.01	0.27	0.01	0.07	3.3×10^{-3}	0.04	3.6×10^{-4}	0.87
DBDPE	2.7	12	10	12	15	7.7	–	–	–	–	1.8	5.1
Dec-602	0.06	0.06	0.03	–	4.4×10^{-3}	–	–	–	–	–	–	–
Dec-604	0.06	–	0.01	–	0.08	–	–	–	–	–	–	–
syn-DP	1.7	1.2	1.8	–	0.42	–	–	–	–	–	–	–

254	*anti*-DP	5.9	7.4	7.8	0.05	0.14	–	–	–	–	–	–	–
255	4-BPh	0.61	1.6	1.8	10	0.58	11	0.72	5.6	0.24	7.1	0.39	9.4
256	2,4-DBPh	0.67	1.9	0.92	18	1.5	16	2.8	13	0.36	5.6	0.52	9.6
257	2,6-DBPh	1.1	3.0	1.8	27	1.5	29	3.9	17	0.81	11	1.2	17
258	2,4-TBPh	4.0	6.4	7.5	24	12	31	13	19	1.2	4.8	1.4	7.6

259 [a] The concentration of HFRs in after-treatment products were below reporting limits.

Table S5. Geometric Mean Diameter (GMD, μm) [a] and Geometric Standard Deviations (GSD, μm) [b] of Particle-Bound HFRs Calculated for Particles Released by Thermal Process of Plastic Casings (A1−A3) and Printed Circuit Boards (B1−B3).

	A1		A2		A3		B1		B2		B3	
	GMD	GSD	GMD	GSD	GMD	GSD	GMD	GSD	GMD	GSD	GMD	GSD
α-HBCD	0.85	1.70	0.78	2.33	0.73	1.70	0.37	1.65	0.45	1.65	0.52	1.60
β-HBCD	1.00	1.76	0.66	1.98	1.11	1.66	0.42	1.63	0.48	1.64	0.53	1.67
γ-HBCD	0.86	1.72	0.83	2.00	0.82	1.69	0.44	1.70	0.49	1.62	0.60	1.52
TBBPA	1.12	2.02	0.75	2.07	0.78	1.63	0.48	1.96	0.48	1.65	0.56	1.64
TBECH	– [c]	–	1.34	1.00	–	–	–	–	–	–	–	–
HBB	0.83	2.09	0.64	1.89	–	–	–	–	0.57	1.33	–	–
DBDPE	0.88	2.95	0.67	2.48	0.73	2.45	–	–	–	–	0.48	2.14
Dec-602	0.85	1.98	0.58	2.19	1.34	1.00	–	–	–	–	–	–
Dec-604	0.75	1.74	1.34	1.00	0.75	1.00	–	–	–	–	–	–
syn-DP	0.82	1.87	0.65	1.82	0.76	1.59	–	–	–	–	–	–

anti-DP	0.75	1.90	0.65	1.78	1.04	1.34	–	–	–	–	–	–
4-BPh	1.00	2.49	0.72	3.36	–	–	–	–	–	–	–	–
2,4-DBPh	0.78	1.78	0.55	1.69	0.77	1.62	0.50	1.56	0.41	1.63	0.63	1.42
2,6-DBPh	0.78	1.42	0.72	1.59	0.73	1.41	0.46	1.89	0.47	1.81	0.56	1.69
2,4,6-TBPh	0.81	2.37	0.66	2.11	0.72	1.94	0.57	2.42	0.49	2.15	0.64	1.87
$\sum_{15}$HFR	1.06	2.04	0.73	2.10	0.77	1.78	0.48	2.01	0.48	1.65	0.56	1.65

[a] Calculated as $\log \mathrm{GMD} = \frac{\sum (C_\mathrm{i} \times \log D_{\mathrm{p,i}})}{\sum C_\mathrm{i}}$; where C_i is the concentration of target compound in size class i and $D_{\mathrm{p,i}}$ is the geometric mean particle diameter collected on stage i;

[b] Calculated as $\log \mathrm{GSD} = \sqrt{\frac{\sum [C_\mathrm{i} \times (\log D_{\mathrm{p,i}} - \log \mathrm{GMD})^2]}{\sum C_\mathrm{i}}}$;

[c] Invalid for calculation.

Table S6. Geometric Mean Diameter (GMD, µm) [a] and Geometric Standard Deviations (GSD, µm) [b] of Particle-Bound Halogenated Flame Retardants Calculated for Particles Released by Open Burning of Plastic Casings (A1−A3) and Printed Circuit Boards (B1−B3).

	A1		A2		A3		B1		B2		B3	
	GMD	GSD	GMD	GSD	GMD	GSD	GMD	GSD	GMD	GSD	GMD	GSD
α-HBCD	1.02	1.95	0.49	1.78	0.46	1.71	0.53	1.76	0.69	1.92	0.63	1.83
β-HBCD	– [c]	–	0.58	2.20	–	–	0.75	1.00	0.57	1.92	0.62	1.78
γ-HBCD	0.95	2.15	0.47	1.80	0.77	1.92	0.78	1.16	0.55	1.76	0.73	1.83
TBBPA	1.08	1.71	0.62	2.12	0.72	2.26	0.61	1.81	0.58	2.11	0.62	1.82
TBECH	–	–	–	–	–	–	–	–	–	–	–	–
HBB	1.57	2.32	0.42	1.00	0.63	2.76	0.35	2.11	0.57	2.02	0.64	1.88
DBDPE	0.95	1.33	0.45	1.39	2.40	1.00	–	–	–	–	0.61	1.93
Dec-602	–	–	–	–	–	–	–	–	–	–	–	–
Dec-604	–	–	–	–	–	–	–	–	–	–	–	–
syn-DP	–	–	–	–	–	–	–	–	–	–	–	–

anti-DP	1.10	1.32	0.42	1.00	–	–	–	–	–	–	–	–
4-BPh	1.10	2.60	0.55	1.81	0.40	1.80	0.47	1.63	0.47	1.72	0.60	1.79
2,4-DBPh	1.24	2.18	–	–	0.33	1.32	0.47	1.64	0.43	1.60	0.48	1.52
2,6-DBPh	–	–	–	–	–	–	0.75	1.00	0.41	1.61	0.55	1.63
2,4,6-TBPh	0.87	3.04	0.74	3.35	0.38	2.26	0.50	2.01	0.50	1.67	0.56	1.72
$\sum_{15}$HFR	0.99	2.57	0.50	1.83	0.47	2.41	0.61	1.82	0.57	2.10	0.62	1.82

[a] Calculated as $\log \mathrm{GMD} = \frac{\sum (C_\mathrm{i} \times \log D_\mathrm{p,i})}{\sum C_\mathrm{i}}$; where C_i is the concentration of target compound in size class i and $D_\mathrm{p,i}$ is the geometric mean particle diameter collected on stage i;

[b] Calculated as $\log \mathrm{GSD} = \sqrt{\frac{\sum [C_\mathrm{i} \times (\log D_\mathrm{p,i} - \log \mathrm{GMD})^2]}{\sum C_\mathrm{i}}}$;

[c] Invalid for calculation.

Table S7. Daily Intake (ng d^{-1}) of Particle-bound and Gaseous Flame Retardants in the Thermal Treatment of E-waste through Inhalation and Dermal Absorption, and the Estimated Daily Intake Dose (EDI, ng kg^{-1} d^{-1}) and Their Reference Dose (RfD, ng kg^{-1} d^{-1}).

	Inhalation			Dermal			Total	EDI	RfD
	Particle	Gas	Total	Particle	Gas	Total			
HBCDs	2.1E4±4.4E3	0±0	2.1E4±4.4E3	4.5E3±1.6E3	0±0	4.5E3±1.6E3	2.6E4±4.7E3	430±78	5000 [a]
TBBPA	3.4E5±7.0E4	6.04±1.95	3.4E5±6.9E4	7.4E4±2.7E4	1.26±0.39	7.4E4±2.7E4	4.1E5±7.5E4	6.9E3±1240	10^6 [a]
TBECH	4.3±2.91	0±0	4.3±2.93	0.59±0.4	0±0	0.6±0.42	4.9±2.98	0.08±0.04	– [b]
HBB	350±85	0±0	350±85	75±32	0±0	75±32	430±90	7.1±1.5	–
DBDPE	1.2E4±2.7E3	0±0	1.2E4±2.7E3	2.5E3±1.1E3	0±0	2.5E3±1.1E3	1.5E4±2.9E3	240±48	330000 [c]
Dec-602	130±360	0±0	130±360	25±15	0±0	25±15	150±320	2.5±5.3	–
Dec-604	170±41	0±0	170±41	39±14	0±0	39±14	210±45	3.5±0.74	–
DP	1.4E4±4.3E3	0±0	1.4E4±4.3E3	3.1E3±1.7E3	0±0	3.1E3±1.7E3	1.7E4±4.5E3	280±76	1.02E7 [d]
4-BPh	530±143.61	4.5E3±990	5.1E3±1.0E3	120±49	950±210	1.1E3±210	6.1E3±1.2E3	10±20	–
2,4-BPh	790±200	8.6E3±1.6E3	9.4E3±1.6E3	170±65	1.8E3±330	2.0E53±330	1.1E4±1.9E3	190±31	–

2,6-DBPh	690±230	1.3E4±1.9E3	1.4E4±1.9E3	170±68	2.8E3±410	3.0E3±420	1.7E4±2.4E3	280±40	–
2,4,6-TBPh	1.2E4±2.2E3	1.7E4±2.8E3	2.9E4±3.6E3	2.8E3±920	3.4E3±590	6.3E3±1.1E3	3.5E4±4.2E3	590±69	–
∑HFR	4.0E5±7.7E4	4.3E4±6.7E3	4.5E5±7.7E4	8.7E4±2.9E4	8.9E3±1.4E3	9.7E4±2.9E4	5.4E5±8.2E4	9.0E3±1.4E3	
BDE-7	230±39	11±7.3	240±41	56±18	2.27±1.54	58±18	300±44	5.0±0.73	–
BDE-15	164±19	79±27	240±33	40±7.1	16±5.7	56±8.9	300±38	5.0±0.64	–
BDE-17	57±8.5	0.26±0.18	57±8.5	14±2.9	0.05±0.03	14±3.0	71±9.0	1.2±0.14	100 [e]
BDE-28	63±12	2.8±1.9	66±12	21±6.2	0.58±0.39	21±6.3	87±14	1.4±0.22	100 [e]
BDE-47	283±68	2.8±1.9	280±66	88±39	0.57±0.39	89±38	370±77	6.3±1.3	100 [e]
BDE-49	410±74	0±0	410±73	89±24	0±0	89±23	500±77	8.3±1.3	100 [e]
BDE-66	268±87	0.53±0.36	270±86	72±25	0.11±0.07	72±25	340±90	5.7±1.5	100 [e]
BDE-71	430±85	17±1.9	450±86	110±38	3.6±0.39	110±39	560±94	9.3±1.6	100 [e]
BDE-77	380±140	0±0	380±140	87±47	0±0	87±47	460±140	7.7±2.4	100 [e]
BDE-85	100±24	0±0	100±24	24±8.8	0±0	24±8.8	130±26	2.1±0.42	100[d]
BDE-99	740±170	0±0	740±170	170±61	0±0	170±61	910±190	15±3.1	100 [e]
BDE-100	800±260	5.3±1.3	810±270	180±94	1.1±0.26	180±92	990±280	16.6±4.7	100 [e]
BDE-119	1.6E3±490	0.69±0.47	1.6e3±490	370±170	0.14±0.09	370±170	2.0E3±500	33±8.3	100 [e]

BDE-126	150±35	0±0	150±35	35±14	0±0	35±14	180±37	3.0±0.62	100 [e]
BDE-138	2.8E3±940	0±0	2.8E3±940	540±210	0±0	540±210	3.3E3±950	55±16	200 [e]
BDE-153	1.5E4±3.3E3	0±0	1.5E4±3.3E3	3.1E3±330	0±0	3.1E3±330	1.8E4±3.2E3	290±54	200 [e]
BDE-154	4.9E3±1.4E3	0±0	4.9E3±1.4E3	1.0E3±340	0±0	1.0E3±340	5.9E4±1.4E3	99±24	200 [e]
BDE-156	1.4E3±470	0±0	1.4E3±470	310±150	0±0	310±150	1.7E3±490	28±8.3	200 [e]
BDE-180	8.7E4±1.5E4	0±0	8.7E4±1.5E4	1.9E4±5.0E3	0±0	1.9E4±5.0E3	1.0E5±1.6E4	1.8E3±260	200 [e]
BDE-183	6.8E4±1.5E3	0±0	6.8E4±1.5E3	1.4E4±4.7E3	0±0	1.4E4±4.6E3	8.2E3±1.6E3	1.4E3±270	200 [e]
BDE-184	9.7E3±3.3E3	0±0	9.7E3±3.3E3	1.9E3±790	0±0	1.9E3±790	1.2E4±3.5E3	190±58	200 [e]
BDE-194	4.1E3±1.0E3	0±0	4.1E3±1.0E3	860±320	0±0	860±320	5.0E3±1.1E3	83±18	3000 [e]
BDE-195	4.7E3±1.8E3	0±0	4.7E3±1.8E3	1.1E3±550	0±0	1.1E3±550	5.8E3±1.9E3	97±32	3000 [e]
BDE-196	1.7E4±4.0E3	0±0	1.7E4±4.0E3	3.7E3±1.3E3	0±0	3.7E3±1.3E3	2.1E4±4.2E3	350±71	3000 [e]
BDE-197	1.3E4±2.9E3	0±0	1.3E4±2.9E3	2.8E3±920	0±0	2.8E3±920	1.6E4±3.0E3	270±50	3000 [e]
BDE-198 [f]	1.2E4±4.4E3	0±0	1.2E4±4.4E3	2.7E3±1.1E3	0±0	2.7E3±1.1E3	1.4E4±4.7E3	240±78	3000 [e]
BDE-201	1.3E4±3.4E3	0±0	1.3E4±3.4E3	2.9E3±1.2E3	0±0	2.9E3±1.2E3	1.6E4±3.7E3	270±61	3000 [e]
BDE-202	5.1E3±1.4E3	0±0	5.1E3±1.4E3	1.1E3±450	0±0	1.1E3±450	6.2E3±1.5E3	100±24	3000 [e]
BDE-204	1.4E34±420	0±0	1.4E34±420	300±130	0±0	300±130	1.7E3±440	29±7.4	3000 [e]

BDE-205	205±75	0±0	205±75	432±25	0±0	432±25	248±78	4.1±1.3	3000 [e]
BDE-206	2.2E4±5.3E3	0±0	2.2E4±5.3E3	4.7E3±1.7E3	0±0	4.7E3±1.7E3	2.7E4±5.6E3	450±94	3000 [e]
BDE-207	2.8E4±6.8E3	0±0	2.8E4±6.8E3	5.9E3±2.2E3	0±0	5.9E3±2.2E3	3.4E4±7.2E3	570±120	3000 [e]
BDE-208	1.7E4±4.2E3	0±0	1.7E4±4.2E3	3.7E3±1.4E3	0±0	3.7E3±1.4E3	2.1E4±4.4E3	350±73	3000 [e]
BDE-209	2.9E4±5.9E3	0±0	2.9E4±5.9E3	6.2E3±2.2E3	0±0	6.2E3±2.2E3	3.5E4±6.3E3	590±100	7000 [e]
∑PBDE	3.6E5±7.2E4	120±27	3.6E5±7.2E4	7.7E4±2.3E3	25±5.6	7.7E4±2.3E3	4.4E5±7.6E4	7.3E3±1.3E3	–
TIBP	120±29	0±0	120±29	28±19	0±0	28±20	150±35	2.5±0.58	–
TNBP	370±45	0±0	370±45	71±19	0±0	71±19	440±49	7.4±0.81	24000 [c]
TCEP	1.1E5±1.6E4	0±0	1.1E5±1.6E4	2.6E4±4.8E3	0±0	2.6E4±4.8E3	1.4E5±1.6E4	2.3E3±270	22000 [c]
TCIPP	8.4E4±1.3E4	3.0E3±720	8.7E4±1.3E4	1.6E4±4.9E3	610±150	1.7E4±4.8E3	1.E5±1.4E4	1.7E3±230	80000 [c]
TDCIPP	4.2E4±1.5E4	0±0	4.2E4±1.5E4	8.7E3±5.8E3	0±0	8.7E3±5.8E3	5.1E4±1.6E4	850±270	15000 [c]
TPHP	1.0E5±2.6E4	330±230	1.0E5±2.6E4	2.1E4±9.6E3	69±46	2.1E4±9.6E3	1.2E5±2.7E4	2.1E3±460	70000 [c]
EHDPP	3.5E3±490	0±0	3.5E3±490	760±150	0±0	760±150	4.3E3±510	71±8.6	–
ToCP	1.3E3±360	0±0	1.3E3±360	270±120	0±0	270±120	1.6E3±370	27±6.3	13000 [c]
∑OPFR	3.5E5±3.7E4	3.5E3±660	3.5E5±3.7E4	7.3E4±9.4E3	730±130	7.4E4±9.4E3	4.2E5±3.8E4	7.0E3±630	

[a] Data from Wang et al.;[11]

376 [b] Reference dose is unavailable;

377 [c] Data from Ali et al.;[12]

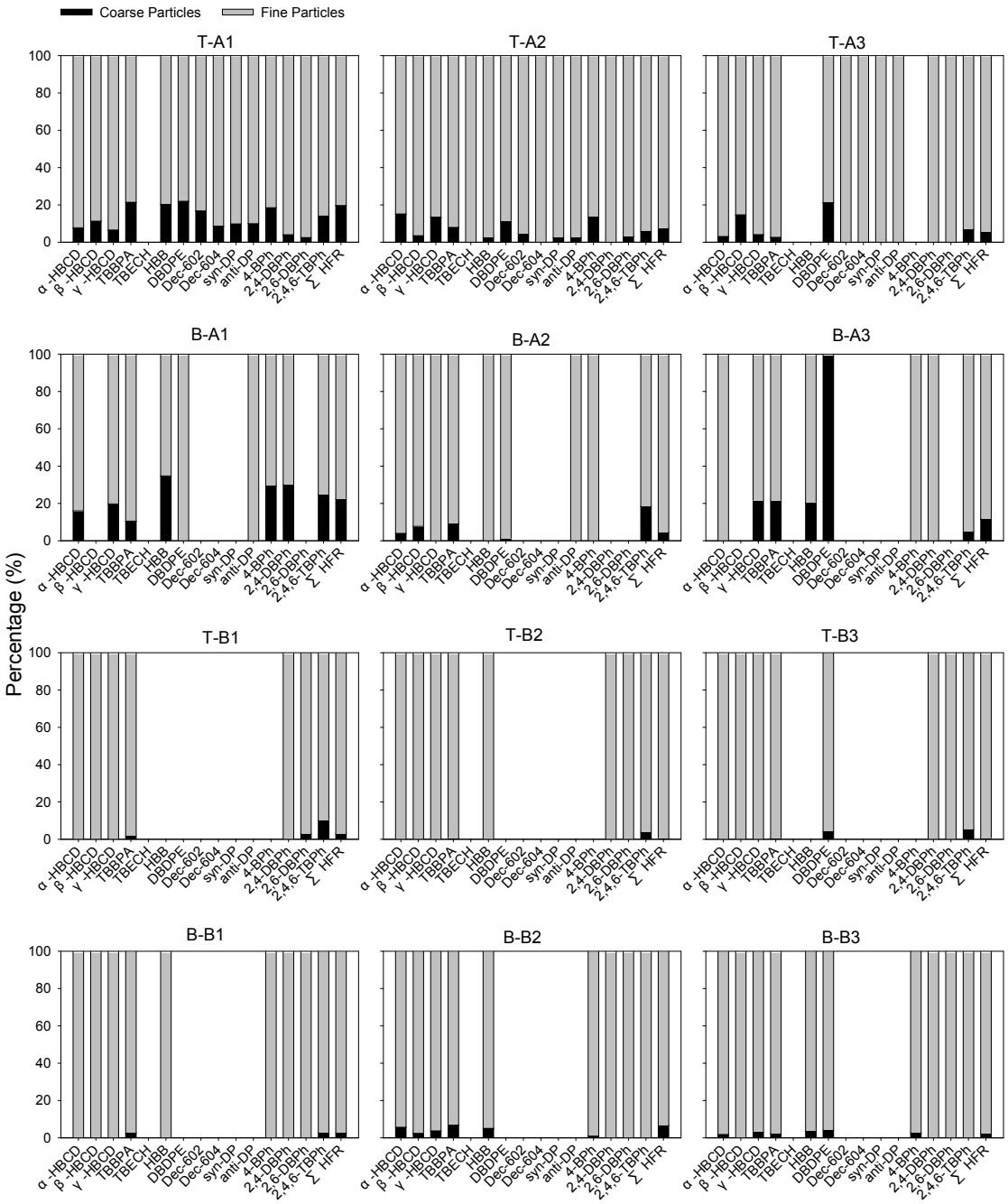
378 [d] Data from Wang et al.;[13]

379 [e] Reference dose for some BDEs were suggested by the United States Environmental Protection Agency Integrated Risk Information System

380 (https://cfpub.epa.gov/ncea/iris_drafts/AtoZ.cfm) and other BDE congers were assumed to be equivalent reference dose of BDE congers with the

381 same number of bromine atoms;

382 [f] The sum of BDE-198, -203, -199, and -200.



383

384 **Figure S1. The relative abundances of particle-bound halogenated flame retardants on**

385 **coarse (D_p > 1.8 μm) and fine particles (D_p < 1.8 μm).**

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