



## A preliminary investigation of unintentional POP emissions from thermal wire reclamation at industrial scrap metal recycling parks in China

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### ABSTRACT

Thermal wire reclamation is considered to be a potential source of unintentional persistent organic pollutants (unintentional POPs). In this study, unintentional POP concentrations, including PCDD/Fs, dioxin like PCBs (dl-PCBs), polychlorinated naphthalenes (PCNs), hexachlorobenzene (HxCBz) and pentachlorobenzene (PeCBz), were quantified in flue gas and residual ash emissions from thermal wire reclamation at scrap metal dismantling parks in Zhejiang Province, China. The total average TEQ emissions of the investigated unintentional POPs from flue gas and residual ash in two typical scrap metal recycling plants ranged from 13.1 to 48.3 ng TEQ N m<sup>-3</sup> and 0.08 to 2.8 ng TEQ g<sup>-1</sup>, respectively. The dominant PCDD/F congeners were OCDD, 1,2,3,4,6,7,8-HpCDD, OCDF and 1,2,3,4,6,7,8-HpCDF, while PCB-126 and PCB-169 were the main contributors to the toxicity of the dl-PCBs. There were clear differences in the distribution dl-PCBs congeners contributing to the TEQ concentrations in the flue gas samples from the two plants. The PCN TEQs were dominated by PCN-66/67 and PCN-73. Although thermal wire reclamation in incinerators has been proposed as an alternative to open burning, there are still considerable environmental risks associated with regulated incinerators, and unintentional POP emissions from thermal wire reclamation sites need to be controlled by local government agencies.

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### 1. Introduction

Unintentional persistent organic pollutants (unintentional POPs), such as polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs), polychlorinated naphthalenes (PCNs), hexachlorobenzene (HxCBz) and pentachlorobenzene (PeCBz) are damaging to human health and the environment because of their toxicological and ecotoxicological effects [1,2]. Once released into various environmental compartments such as air, water, soil, sediment and food, they can be dispersed on global scale and pose serious health and environmental risks [3,4]. Thus, issues associated with unintentional POP formation, emission, transport, abatement, and environmental risk assessment have been intensively investigated [5–9]. Over the past decade, many sources of PCDD/Fs have been documented in national inventories, as required of signatories to the Stockholm Convention on Persistent Organic Pollutants [10]. In 2007, China established a National Implementation Plan (NIP) for the implementation of the Stockholm Convention. The report identifies that the major potential sources of PCDD/F releases to the air are

ferrous and non-ferrous metal production (2486.2 g TEQ yr<sup>-1</sup>), power and heat generation (1304.4 g TEQ yr<sup>-1</sup>) and waste incineration (610.5 g TEQ yr<sup>-1</sup>) [11]. Investigations have also been conducted on various anthropogenic combustion and thermal related sources, which are widely recognized as the major PCDD/Fs formation and emission pathway. However, there are still large uncertainties with regard to the environmental fluxes of PCDD/Fs for sources such as thermal wire reclamation and open burning processes. The open burning of waste wire for metal reclamation has been very common in recent decades in China. Strict environmental protection laws and regulations have now been implemented in China, and the open burning of waste wire is forbidden. Thermal wire reclamation in incinerators has been proposed as an alternative to open burning, but the environmental risks associated with this technique have not been evaluated.

There are various techniques used for thermal wire reclamation in different countries. Currently, there is little information on PCDD/F emissions from commercial scrap wire recovery facilities in developed countries [12–15], and studies on environmental releases of PCDD/Fs from thermal wire reclamation developing countries are also scarce. Additionally, there is almost no information available on emissions to the air of dioxin like PCBs (dl-PCBs), PCNs, PeCBz and HxCBz from thermal wire reclamation. Thus, the development of unintentional POP inventories from thermal

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wire reclamation is crucial for the evaluation of unintentional POP releases from scrap metal dismantling and recycling industries.

In recent years, the importation, disassembly and processing of scrap metal in China has developed rapidly, with millions of tons of copper, steel and aluminum recovered each year by dismantling and recycling waste electric motors, waste wire and cables, and waste hardware. In general, the waste is shipped from developed countries such as Japan, USA, the EU and Australia to mainland China, and scrap metal imports play an important role in the Chinese metal recycling industry. The scrap metal recycling industry has led to significant social and economic benefits due to increased revenue and local employment. However, years of open burning of scrap metal and the dumping of processed materials has released huge amounts of contaminants into the environment. To regulate scrap metal dismantling activities and control pollutant emissions, two main industrial scrap metal dismantling and recycling parks in Zhejiang Province were established by the local government. Factories with disassembly licenses were moved into the industrial parks. The waste is dismantled as follows: first, most of the waste hardware and cables are dismantled using mechanical tools to recycle steel, copper, aluminum and plastic; second, the difficult to disassemble scrap metal, such as enameled wires and electronic motors, are burned in furnaces to facilitate metal recovery. It is the second step, the disassembly and incineration of enamel wires and electronic motors that can lead to unintentional POP releases with serious risks to human health and the environment. During this process, all the ingredients for unintentional POP formation are present, including carbon (in the wire sheaths), chlorine (PVC) and catalysts (Cu or Zn). Consequently, investigations into the concentrations and profiles of unintentional POPs from the incinerators at thermal wire reclamation factories would be very helpful in understanding the sources and exposure risks associated with these compounds.

The objective of this study was to provide a preliminary characterization of the emission concentrations of unintentional POPs and their toxic equivalents to improve understanding of the level of unintentional POP emissions from thermal wire reclamation in China. A further objective was to present and discuss the unintentional POP emissions profiles, which may provide useful information for establishing POP inventories for the thermal wire reclamation industry. After considerable investigation, two typical scrap metal dismantling factories were selected in the secondary resources industrial recycling parks in Zhejiang Province, China. These plants varied in scale, technological level and raw materials, allowing us to obtain credible and representative data.

## 2. Experimental

### 2.1. Sample collection

Zhejiang Province is a major scrap metal dismantling and processing area in China and has been for several decades. There are two secondary resource importing and processing parks with scrap metal import licenses issued by the Ministry of Environmental Protection (MEP) in China. After considerable investigation, combustion of scrap metal consists of smoldering and cracking in a furnace fitted with afterburners. In this study, five flue gas and two mixed residual ash samples were collected from two typical metal scrap dismantling plants: one plant burns waste electronic motors in Ningbo City (P1); and the other burns waste enameled wires in Taizhou City (P2). The approximate composition and content of waste electric motors and enameled wires from the two plants are provided in Table S1. The details schematic diagram of the incinerator and disposal procedure of thermal wire reclamation are given and supplemented in Fig. A and Supplementary

**Table 1**

Basic operating conditions at the scrap metal disassembly and processing plants.

Denotation	P1	P2
Operating mode	Batch	Batch
Air pollution control device (APCD)	Water-cooling	No
Feeding materials	Electric motors	Enamel wires
Run time (h/batch)	5	3
Capacity (tons batch <sup>-1</sup> )	19	30
Auxiliary fuel	Heavy oil	Heavy oil
Flue gas temperature of sampling point (°C)	60.3	506.8
Temperature of PCC <sup>a</sup> (°C)	205–658	220–560
Temperature of SCC <sup>b</sup> (°C)	680–1025	310–720
O <sub>2</sub> content of flue gas in PCC (%)	5	8
O <sub>2</sub> content of flue gas in SCC (%)	12	10
Average flue gas flow (Nm <sup>3</sup> /h)	5954	4927
O <sub>2</sub> content in flue gas of sampling point (%)	16.8	14
CO <sub>2</sub> content in flue gas of sampling point (%)	2.4	4
Moisture content in flue gas of sampling point (%)	8.4	2.8
The volume of flue gas samples (Nm <sup>3</sup> )	1.9–2.6	1.9–2.4

<sup>a</sup> Primary combustion chamber.

<sup>b</sup> Secondary combustion chamber.

Information, respectively. In P1, the waste electric motors were combusted in a cracking furnace. The furnace was equipped with two subsidiary combustion burners including a primary combustion chamber (PCC) and a secondary combustion chamber (SCC). Following the SCC was a flue gas cleaning system consisting of an afterburner and water-cooling equipment. The temperature of the flue gas was higher than 1000 °C in the afterburner and the temperature of the flue gas at the sampling point, after water-cooling, was lower than 100 °C. In P2, mostly waste enameled wires and a few waste rotors were burned in an incinerator. The generated flue gas from the SCC in the plant, however, was directly emitted to the atmosphere through an exhaust funnel with a 10-m stack. The temperature of the flue gas at the sampling point was higher than 500 °C. The collected flue gas samples passed through the whole combustion process in each plant. In each of the two plants, one composite residual ash sample was collected. The ash samples were collected from areas with different burning conditions and raw materials within the plants are detailed in Table 1.

The flue gas samples were collected with an automatic isokinetic sampling system (Isostack Basic, TECORA, Italy). The selected sampling points at each plant were located downstream of the secondary combustion chamber or water-cooling device. Prior to collection, the O<sub>2</sub> and CO<sub>2</sub> contents, and flue gas temperature at the sampling points were measured using a Testo 355 flue gas analyzer (Testo, Germany). The sampling system consisted of a filter (25 mm i.d., 90 mm length, silica glass microfiber thimble, Whatman, UK), a condensing system, and an adsorbing resin (Amberlite XAD-2, Supleco, USA). The resin was spiked with a <sup>13</sup>C<sub>12</sub>-labeled PCDD/Fs internal standard before sampling was initiated. The residual ash samples were collected from the bottom of the furnaces after combustion.

### 2.2. Sample extraction and analysis

The samples were analyzed for PCDD/Fs and dl-PCBs in accordance with US EPA Methods 23 and 1668A. The flue gas and about 2–3 g of residual ash samples were pretreated and analyzed for specific PCDD/F and dl-PCB congeners. The samples were spiked with known amounts of <sup>13</sup>C<sub>12</sub>-labeled internal standards before extraction. The sample extraction, cleanup and instrumental analysis for PCDD/Fs and dl-PCBs determination are described in detail by Ba et al. [16]. The extraction and cleanup of PCNs, HxCBz and PeCBz

**Table 2**  
Concentrations and TEQs of unintentional POPs in flue gas and residual ash released from thermal wire reclamation ( $\text{ng N m}^{-3}$  or  $\text{ng g}^{-1}$ ).

	P1		Residual ash	P2		Residual ash
	Flue gas ( $n=3$ )			Flue gas ( $n=2$ )		
	Mean	Range		Mean	Range	
$\Sigma$ PCDD/Fs	1253	1143–1407	4.6	208	100–316	50.2
$\Sigma$ dl-PCBs	593	281–982	13.6	197	187–207	25.3
$\Sigma$ PCNs	8650	2045–14,490	66	2715	2635–2780	195
HxCBz	126	105–144	16.5	46.2	41.3–51.2	23
PeCBz	309	252–354	10.7	112	103–121	50.9
$\Sigma$ WHO-TEQ (PCDD/Fs)	47.1	22.1–72.4	0.06	11.3	6.4–16.2	2.6
$\Sigma$ WHO-TEQ (dl-PCBs)	1.1	0.4–1.8	0.008	1.7	1.3–2.1	0.2
$\Sigma$ TEQ (dl-PCNs)	0.1	0.06–0.2	0.007	0.09	0.08–0.09	0.004
TEQ (HxCBz)	0.01	0.01–0.01	0.001	0.005	0.004–0.006	0.002

in the flue gas and residual ash samples used the same procedures as the analysis of dl-PCBs with the samples spiked with known amounts of  $^{13}\text{C}$ -labeled standards before extraction. The sample extraction, cleanup and instrumental analysis for PCNs, HxCBz and PeCBz determination are described by Nie et al. [17]. In this study, blank samples were analyzed with samples. The recoveries of  $^{13}\text{C}_{12}$ -labeled PCDD/F internal standards were 48–134%. The recoveries of  $^{13}\text{C}_{12}$ -labeled PCB standards were 32–123%. The recoveries of  $^{13}\text{C}_{10}$ -labeled PCN standards were 33–122%. The recoveries of  $^{13}\text{C}_6$ -PeCBz and  $^{13}\text{C}_6$ -HxCBz were 45–89% and 63–92%, respectively.

### 3. Results and discussion

#### 3.1. Concentrations of unintentional POPs emitted from thermal wire reclamation

The concentrations and TEQs of the unintentional POPs in flue gas and residual ash samples are summarized in Table 2. For congeners with concentrations below the limit of detection (LOD), a value of half the LOD was used to calculate the total concentration and the TEQ. The WHO-TEF<sub>2005</sub> values reported by Van den Berg et al. [18] were used to calculate the TEQs for the PCDD/Fs and dl-PCBs. The TEQs for the dioxin like PCNs (dl-PCNs) and HxCBz were calculated based on the relative potency factors (RPFs) reported by Noma et al. [19] and van Birgelen [20], respectively.

Table 2 shows that the average WHO-TEQ values of PCDD/Fs measured in the flue gas samples at P1 and P2 in this study were 47.1 and 11.3  $\text{ng TEQ N m}^{-3}$ , respectively. At P1, the WHO-TEQ values for PCDD/Fs ranged from 22.1 to 72.4  $\text{ng TEQ N m}^{-3}$  and while the WHO-TEQ range at P2 was from 6.4 to 16.2  $\text{ng TEQ N m}^{-3}$ . The mean PCDD/F TEQ values from flue gases in this study were higher than the values reported by Bremmer et al. for metal recovery from burning electromotors (1.3  $\text{ng I-TEQ N m}^{-3}$ ) and burning stripped cables with grease (3.8  $\text{ng I-TEQ N m}^{-3}$ ) [12]. Studies have shown that the combustion of plastics, particularly PVC, in the presence of a copper catalyst can generate PCDD/Fs [21,22]. High PCDD/F TEQs were observed in this study partly due to the PVC, oil and grease content in scrap metal. The dust, organic and inorganic compounds in the flue gas were also determined and presented in Table S2. The dust concentrations were highly correlated with the removal efficiency of the air pollution control devices and the average dust concentrations in flue gas from P1 and P2 were 94.6 and 87  $\text{mg m}^{-3}$ , respectively. Organic compounds, such as benzene, toluene and dimethylbenzene, in flue gas at P1 were higher than at P2. The concentrations of PCDD/Fs in flue gas released from the two plants were different, likely because of variations in the organic compounds present in the raw materials.

The average PCDD/F WHO-TEQs in the residual ash samples from P1 and P2 were 0.06 and 2.6  $\text{ng TEQ g}^{-1}$ , respectively. The total organic carbon concentrations (TOC, wt%) in the residual ash

from P1 and P2 were 0.42 and 3.64, respectively. Simultaneously, the elemental analysis of residual ash from the two plants was given in Table S3 and Fig. B. These results indicated that the large increase in PCDD/F concentrations from P2 could be the result of high concentrations of carbon, chlorine, Fe and Cu in the residual ash. The PCDD/F emissions levels in this study have been compared with emission levels measured at scrap wire and scrap metal incineration sites. Huang et al. reported PCDD/F TEQ values ranging from 0.03  $\text{ng TEQ/g dw}$  to 13.5  $\text{ng TEQ/g dw}$  in soil samples from metal reclamation incineration sites in Taiwan [23]. Vanwijnen et al. measured soil samples collected around small-scale illegal scrap wire and car incineration sites in the Netherlands, and found total PCDD/F TEQ concentrations of 0.06–98  $\text{ng I-TEQ/g dw}$  [24]. Harnly et al. analyzed soil/ash mixtures from three historical metal recovery facilities near a California desert town, and found mean PCDD/F TEQ concentrations of 0.2–2.9  $\text{ng I-TEQ g}^{-1}$ , with a significantly higher value (19  $\mu\text{g I-TEQ g}^{-1}$ ) found in the fly ash at the metal recovery sites, originating from the burning of electrical wires, transformers, capacitors and automobile engines [25].

Studies on dl-PCBs from thermal wire reclamation were limited. The total dl-PCB WHO-TEQs from the flue gas samples at P1 and P2 ranged from 0.4 to 1.8  $\text{ng WHO-TEQ N m}^{-3}$  and from 1.3 to 2.1  $\text{ng WHO-TEQ N m}^{-3}$ , respectively. The average dl-PCB TEQ concentrations from flue gas samples at P1 and P2 were 1.1 and 1.7  $\text{ng WHO-TEQ N m}^{-3}$ , respectively. As with the PCDD/Fs, the mean dl-PCB TEQs in flue gas released from thermal wire reclamation were much higher than the values reported by Ba et al. in stack gases released from secondary aluminum and copper metallurgy (0.019 and 0.023  $\text{ng TEQ N m}^{-3}$ , respectively) [16], and by Wang et al. in the flue gas of a municipal solid waste incinerator (5.5  $\text{pg WHO-TEQ N m}^{-3}$ ) [26]. In this study, the average dl-PCB concentrations in the residual ash samples from P1 and P2 were 13.6 and 25.3  $\text{ng g}^{-1}$ , respectively (Table 2). These levels were far lower than the dl-PCB concentrations in soils collected from a metal reclamation incineration site in Taiwan (0.45–77  $\mu\text{g/g dw}$ ) [23].

PCNs are a candidate POP class and have been proposed for inclusion into the UN-ECE POP protocol [27], due to the increasing public attention associated with PCN pollution. In this study, the average PCN concentrations and TEQs from the flue gas emissions from P1 and P2 ranged from 8650 to 2715  $\text{ng N m}^{-3}$  and from 0.1 to 0.09  $\text{ng TEQ N m}^{-3}$ , respectively. Although the total PCN concentrations were much higher than the total 2378-PCDD/Fs concentrations, the PCN TEQs were lower than the PCDD/Fs TEQs due to the lower RPFs of PCNs. The PCN concentrations emitted from flue gas during the thermal wire reclamation process were higher than from other industrial sources, including municipal waste incineration (MWI), the coking industry, and secondary copper and lead smelting [28–30]. This indicates that thermal wire reclamation might be an important PCN emission source in the scrap metal dismantling industry. A clear difference in the

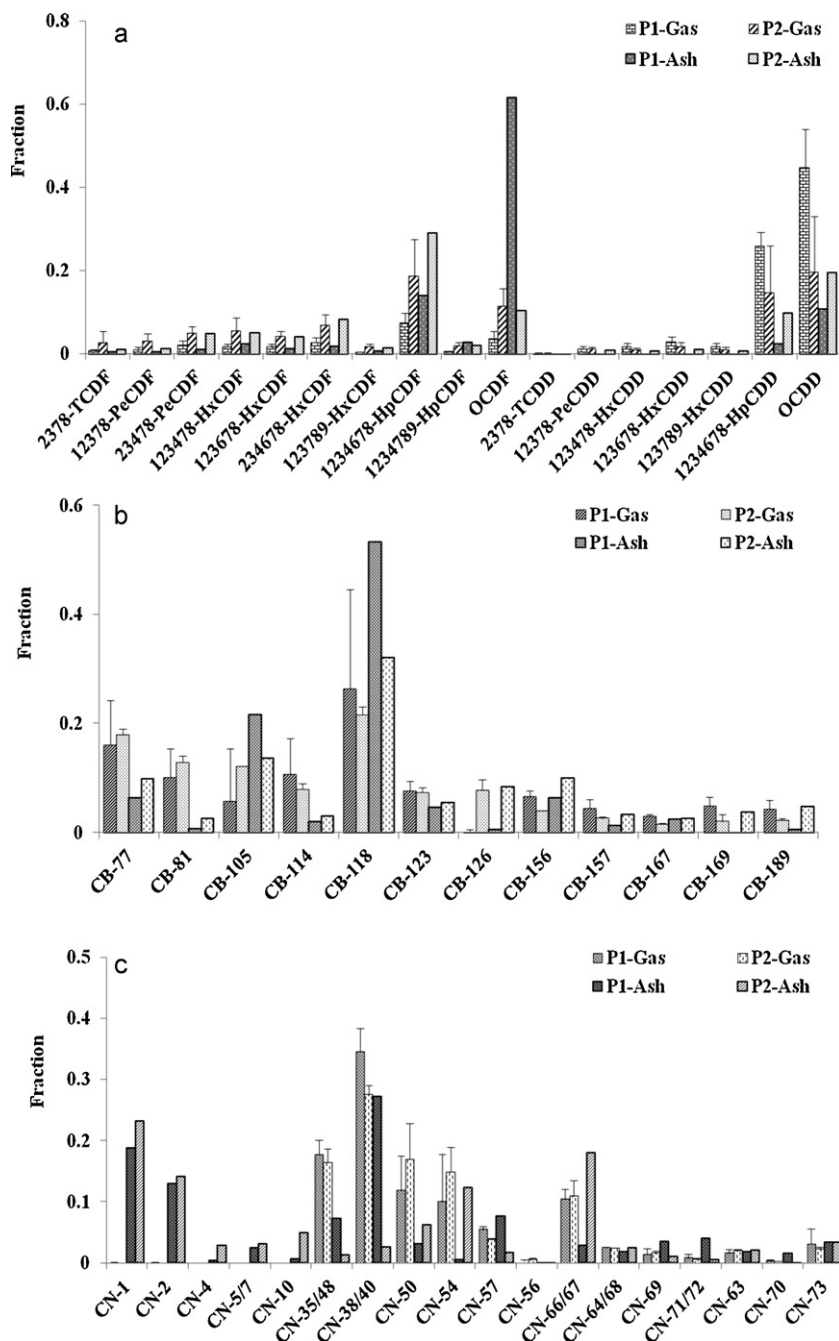


Fig. 1. PCDD/F (a), dl-PCB (b) and dl-PCN (c) congener concentrations in flue gas and residual ash from thermal wire reclamation.

homologue distributions between the flue gas and residual ash samples was observed and is shown in Fig. 2b. The predominant PCN in flue gas was tri-CN, which accounted for 56–73% of the total PCNs, followed by tetra-CN (23–37%), with the sum of the triCNs and tetraCNs accounted for about 80% of the total PCNs in flue gas. However, in the residual ash mono-CN to penta-CN was the dominant homologues.

No studies have been reported on HxCBz and PeCBz emissions from flue gas during thermal wire reclamation, although the sources and environmental levels of PeCBz and HxCBz have attracted attention due to their inclusion into the Stockholm Convention. In this study, the average HxCBz concentrations from flue gas samples at P1 and P2 were 126 and 46.2 ng N m<sup>-3</sup>, respectively, which are much higher than concentrations measured during the combustion of firewood and pellets (ND – 1.1 ng N m<sup>-3</sup>) and

copper smelting-H<sub>2</sub>SO<sub>4</sub> production (1.57 ng N m<sup>-3</sup>), but are lower than iron ore sintering (613.1 and 1491 ng N m<sup>-3</sup>) [31,32]. The HxCBz TEQs in flue gas and residual ash samples from thermal wire reclamation were in the range of 0.004–0.01 ng TEQ N m<sup>-3</sup> and 0.001–0.002 ng TEQ g<sup>-1</sup>, respectively. The TEQ contribution from HxCBz is very small compared to the contribution from PCDD/Fs.

As shown in Table 2, the average PeCBz concentrations in flue gas samples from thermal wire reclamation at the two plants ranged from 112 to 309 ng N m<sup>-3</sup>, lower concentrations than measured during aluminum smelting (10.34 μg m<sup>-3</sup>) and hospital waste incineration (1.83–9.59 μg N m<sup>-3</sup>) [33,34], but higher than a waste incineration pilot plant (87.21 ng N m<sup>-3</sup>) [35]. The PeCBz concentrations in residual ash from P1 and P2 were 10.7 and 50.9 ng g<sup>-1</sup>, respectively.



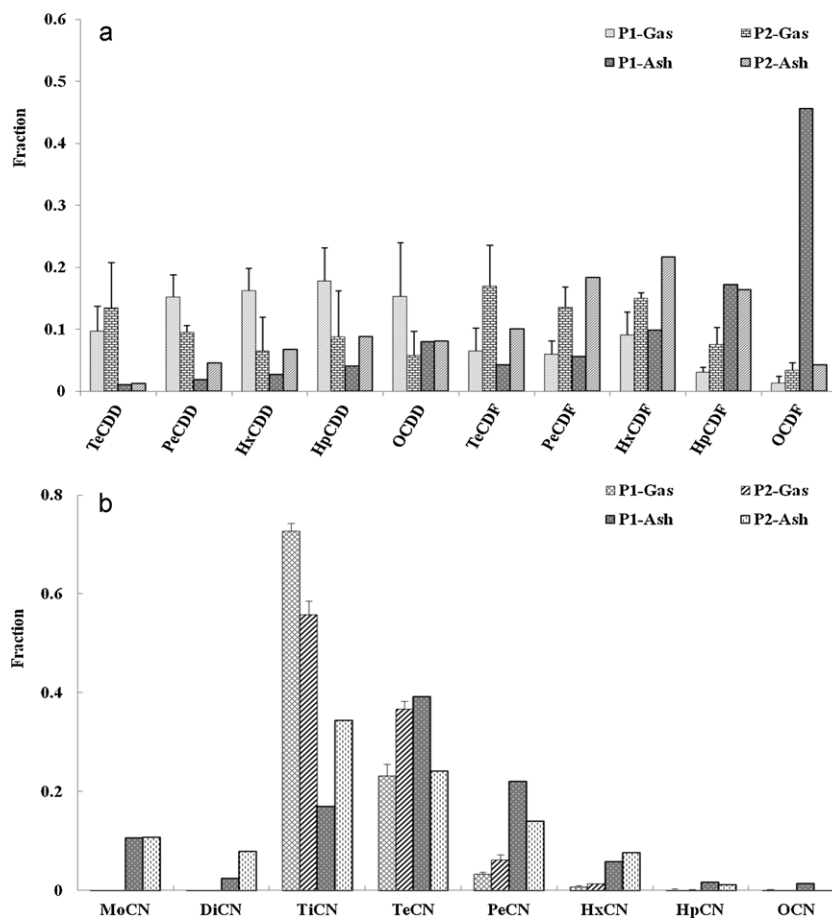


Fig. 2. PCDD/F (a) and PCN (b) homologue profiles in flue gas and residual ash from thermal wire reclamation.

### 3.2. Unintentional POP congener profiles in emissions from thermal wire reclamation

The PCDD/F, dl-PCB and dl-PCN congener profiles were used as fingerprints for emissions from thermal wire reclamation. Fig. 1a clearly shows the PCDD/F congener profiles detected in flue gas and residual ash from thermal wire reclamation. This shows that OCDD, 1,2,3,4,6,7,8-HpCDD, OCDF and 1,2,3,4,6,7,8-HpCDF were the dominant congeners, and this is very similar to the congener profiles in flue gas reported by Gullett et al. for the open burning of insulated wire [13]. The fingerprints from the residual ash in the study were similar at both sites and also similar to soil/ash and fly ash samples from open burning metal recovery sites [25,36]. Different PCDD/Fs homologue profiles are normally correlated with different PCDD/Fs formation pathways. The PCDD/F homologue profiles in the flue gas and residual ash samples in this study are shown in Fig. 2a. The results show that the homologue profiles for residual ash in the two plants were similar for the PCDDs and the PCDFs. In addition, in the flue gas at P1 (burning waste electronic motors), the percentage of PCDDs was somewhat higher than the percentage of PCDFs for the tetra- to octa-substituted PCDD/Fs. However, the opposite pattern was observed in the flue gas from P2 (burning waste enameled wires).

Researchers have often noted that total PCDF concentrations in samples from combustion sources will be equal to or greater than total PCDD concentrations [13,37]. The PCDF to PCDD ratio ( $R_{DF/DD}$ ) can indicate different PCDD/F formation mechanisms. The  $R_{DF/DD}$  values from flue gas and residual ash samples were calculated and are shown in Fig. C in the Supplementary Material.  $R_{DF/DD}$  values  $>1$  were observed in all the residual ash and flue gas samples from P2

which operates with oxygen-enriched combustion. This high ratio is similar to ratios measured in soils from metal recovery facilities and open burning sites [25]. However, a much lower  $R_{DF/DD}$  of 0.4 was obtained from the flue gas at P1, which operates in a low oxygen environment. This value was similar to ratios measured in soil/ash from waste railroad car incineration [25,37]. In summary, the PCDD/F characteristics and distribution indicate that different formation mechanisms may occur in the flue gases at the two plants.

PCB-118 is generally considered to be the dominant congener among the dl-PCBs for many thermal related sources [38–41]. The concentrations of the dl-PCB congeners are shown in Fig. 1b. PCB-118 was found to have the highest concentration followed by PCB-77 and PCB-105. These three congeners together comprised more than 45% of the total dl-PCB concentrations in both flue gas and residual ash. However, in the flue gas, high concentrations of PCB-81 and PCB-114 were also measured, accounting for about 10% each. For the dl-PCBs TEQ values, PCB-126 and PCB-169 were the two main contributors to the toxicity from PCBs in flue gas and residual ash due to their higher TEF values when compared with other dl-PCB congeners (Fig. D.1 in the Supplementary Information). PCB-126 was the greatest contributor to the dl-PCBs toxicity in residual ash, contributing more than 85% of the total dl-PCBs TEQ, followed by PCB-169. However, there the contributions of the different congeners to the dl-PCB TEQ concentrations in the flue gas samples were different at the two sites. The most toxic dl-PCB congeners in P1 were PCB-169 (80.1%) and PCB-126 (16.2%), while in P2 the toxicity contributions were PCB-169 (6.9%) and PCB-126 (92.2%), indicating that different pathways for dl-PCB formation may occur in the flue gas. The reasons for the different pathways

may include differences in the types of furnaces, combustion materials and combustion systems at the two plants.

The concentration patterns of the dl-PCN congeners in flue gas and residual ash are shown in Fig. 1c. The congener patterns in flue gas were quite similar in both plants. The most abundant dl-PCN congeners were PCN-38/40, followed by PCN-35/48, PCN-50, PCN-54 and PCN-66/67. However, the distribution patterns of dl-PCN in the residual ash are different at the two sites. The most abundant dl-PCNs at P1 were PCN-38/40 (27.2%), PCN-1 (18.7%) and PCN-2 (13%), while at P2 the most abundant dl-PCNs were PCN-1 (23.2%), PCN-2 (14.2%), PCN-54 (12.3%) and PCN-66/67 (18.1%). Several congeners are commonly found associated with thermal-related processes, including PCN-35/48, PCN-38/40, PCN-50, PCN-54, PCN-66/67 and PCN-73 [42,43], and were also observed associated with thermal wire reclamation. The TEQ patterns for the dl-PCNs congeners in flue gas and residual ash are shown in Fig. D.3. PCN-66/67 and PCN-73 were the two dominant contributors to the dl-PCN TEQs in flue gas and residual ash, accounting for more than 50% of the total TEQ from PCNs due to their relatively high RPFs compared with other PCN congeners. In addition to PCN-66/67 and PCN-73, PCN-69 and PCN-63 also contributed to the toxicity of the dl-PCNs.

#### 4. Conclusions

This study quantified the emissions of unintentional POPs from regulated thermal wire reclamation processes at industrial scrap metal recycling parks in China. High concentrations of unintentional POPs were measured after the burning of waste enamel wires and waste electronic motors. The measured concentrations were higher than those measured for other industrial sources such as municipal waste incineration, coking and non-ferrous metal smelting, indicating that thermal wire reclamation could be an important unintentional POP emission source during the scrap metal dismantling process. Although thermal wire reclamation in these industrial parks has been proposed as an alternative to the open burning of waste, the techniques used still pose considerable environmental risks. The results of this study suggest the emission of unintentional POPs from thermal wire reclamation need to be considered by local government agencies. Further investigations into the emission of unintentional POPs from thermal wire reclamation in China are required to improve the knowledge in this area.

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#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2012.02.062.

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