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Distribution of Polybrominated Dibenzo-*p*-dioxins and Dibenzofurans and Polybrominated Diphenyl Ethers in a Coal-fired Power Plant and Two Municipal Solid Waste Incinerators

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ABSTRACT

In this study, the distributions of polybrominated dibenzo-*p*-dioxins (PBDD/Fs) and dibenzofurans and polybrominated diphenyl ethers (PBDEs) in the bottom residues of the combustion chambers (BR), the fly ashes from superheaters (SH), economizers (EC), semi-dry scrubbers (SDA), fabric filters (BF), fly-ash pits (FAP) and stack flue gases (SFG) of two municipal solid waste incinerators (MSWIs) and the bottom residue (BR), electrostatic dust precipitators (ESD), and stack flue gases (SFG) of a coal-fired power plant (TPP) were investigated. BR of combustion chambers exhibited the highest content of PBDEs and PBDD/Fs among all the units. The amount of PBDE mass found in bottom residues constituted 99.7% at MWSI-A, and 92.6% at MSWI-B and 75.1% at TPP of the total PBDE discharges, respectively; while the second highest PBDE mass observed in MSWI-A and MSWI-B was from SFG (0.146%) and EC (5.54%), respectively. In TPP, the PBDE distribution was 75.1% in BR, 12.5% in ESD, and 12.4% in SFG. The mean concentrations of PBDEs emitted from SFG of MSWI-A, and MSWI-B were 9.32 ng/Nm^3, and 7.62 ng/Nm^3, respectively; however, that of PBDE discharged from SFG of TPP was only 5.43 ng/Nm^3. The dominant congener found from MSWI-A,MSWI-B and TPP, was BDE-209, accounting for 65.9%, 77.7%, and 77.6% of total PBDE concentrations in SFG, respectively; whereas BDE-206 (6.01%–6.36%) was the second highest congener. Meanwhile, the PBDE emission factors from the stack flue gases were 35.6 ± 10.9 μg/ton-waste at MWSI-A, 47.6 ± 29.4 μg/ton-waste at MSWI-B and 62.9 ± 10.9 μg/ton-coal at TPP of the total PBDEs, respectively; showing the PBDE emission rates and contributions of TPP to the ambient air are actually much higher than those of MSWIs, while the PBDE concentrations in SFG of TPP were lower than MSWIs'. Further investigations on the safety of BR reutilization and the impact of SFG from TPP are strongly advised.

Keywords: Polybrominated diphenyl ethers (PBDEs); Municipal solid waste incinerators; Coal-fired power plant; Ashes; Stack flue gases.

INTRODUCTION

Polybrominated diphenyl ethers (PBDEs), as a group of the cheapest yet effective fire retardants, have been extensively used as additive flame retardants (FRs) in the world since the 1970's (Rahman *et al.* 2001). PBDEs are well known to be a group of persistent organic pollutants, the penta-, octa, and deca-BDEs being the most common products of all the PBDE congeners in the global market. In 2001, deca-BDE accounted for 83% of total worldwide production, followed by penta-BDE (11%), and octa-BDE (6%) (Hites, 2004; La Guardia *et al.*, 2006). Approximately 56,400 metric tons (MT) of PBDEs were produced worldwide in 2003, and the PBDE production rates between 1999 and 2002 were 40,000 to 67,000 MT/year (USEPA, 2010). The European Union banned the manufacturing and usage of commercial penta- and octa-BDE mixtures in August, 2004; the production of deca-BDE mixtures and its usage were also prohibited after July 1, 2008. Approximately 95% of the global production of penta-BDEs, 40% of octa-BDEs, and 44% of deca-BDE were consumed in the Americas (North, South, and Central America) (USEPA, 2010). The USEPA stringently enforced the regulation on manufacturing or importation of commercial penta-BDE and octa-BDE products after January 1, 2005. Moreover, the USEPA announced the phase out of deca-

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BDE in December of 2009, with production, importation, and sales of deca-BDE for most uses in the United States to end by December 31th, 2012, and all uses to end by December 31th, 2013 (USEPA, 2010).

PBDEs are often added at 5–30% weight of the product (Peng *et al.*, 2007); a previous study indicated that the content in different TV housing samples can reach 25,000 mg/g (Kim *et al.*, 2006). Concerns about polybrominated dibenzo-*p*-dioxins and dibenzofurans (PBDD/Fs) have also increased because PBDD/Fs were observed to be released from products containing BFRs during the incineration of product wastes or the processing of PBDE-containing plastics (Sakai *et al.*, 2001; Watanabe and Sakai, 2003; Weber and Kuch, 2003; Lai *et al*., 2007). Moreover, the most commonly used deca-BDE (BDE-209) was found to form photolytically debrominated and nona- to tetra-BDEs as well as some PBDFs (Soderstrom *et al*., 2004). PBDD/Fs have also been reported at average levels of 280,000 ng/g in waste television cabinets manufactured in Japan between 1984 and 1998 (Sakai *et al*., 2001).

The structure of PBDEs is similar to that of polychlorinated biphenyls (PCBs) (Talsness, 2008), but PBDEs are generally more polar than PCBs because of the presence of the oxygen atom and the resulting asymmetry regarding the horizontal axis (Peng *et al*., 2007). The structural similarity also occurred between PCDD/Fs and PBDEs; similar characteristics were also found, such de novo synthesis (Artha *et al*., 2011). It is known to us that PCDD/Fs have been found in various sources, such as crematories, sinter plants and so on (Wang *et al.*, 2003a; Wang *et al.*, 2003b; Lee *et al.*, 2004; Lee *et al.*, 2005; Chen *et al.*, 2011; Huang *et al.*, 2011; Lin *et al*., 2011). PCBs and PCDD/Fs are known to entering soils via dry and wet disposition (Lee *et al*., 1996), and accumulate in animals (Lee *et al*., 2009); these are the characteristics PBDEs also possess.

Once released during production, recycling, or usage, PBDEs tend to persist in both terrestrial and aquatic environments (Hites, 2004; Soderstrom *et al.*, 2004; Mandalakis *et al.*, 2009). Therefore, the uses of unregulated deca-BDE products has caused less-brominated congeners, which are the most highly toxic, to be bio-accumulated in animals (Hale *et al.*, 2001; Darnerud, 2003; La Guardia, *et al.*, 2006; Meng *et al.*, 2007; Kuiper *et al.*, 2008; Chen *et al.*, 2010). According to previous research, PBDEs have been detected in wild animals, and predators, such as peregrine falcon (in eggs) and blue fishes, have higher PBDE burdens than do other susceptible animals (Bocio *et al.*, 2003; Chen *et al.*, 2008). Also, Wang (Wang *et al*., 2010b) stated that PBDE concentrations in the stack flue gases of combustion sources, including waste incinerators, metallurgical processes, power-heating systems, possess high PBDE concentrations revealing that they are not only major PCDD/F emission sources, but also important PBDE emitters to the atmosphere.

Since the 1970's, PBDE concentrations in the breast milk of Swedish mothers has increased almost 100-fold, doubling about every five years from 1972 to 1997 (Noren and Meironyte, 2000). However, a survey from 1973 to 2000 in Japan indicated that PBDE concentrations in the breast milk of Japanese mothers are relatively low (Akutsu *et al.*, 2003). In Taiwan, the conducted research on human breast milk has found that PBDE concentrations are 1.6–2.3 times higher than that of Japanese mothers (Chao *et al.*, 2007; Horng *et al.*, 2010). The bio-accumulating effect in human bodies has become a concern due to the fact that several toxicological effects of PBDE congeners such as neurotoxicity, behavioral changes, and endocrine disruption have been detected in experimental animals, (McDonald, 2002; Darnerud, 2003; Kuiper *et al*., 2008; van der Ven *et al.*, 2009). The major source of human PBDE exposure is through diet, accounting for 73% of daily intake (Bocio *et al*., 2003). Moreover, the major human dietary exposure is through meat products (Bocio *et al.,* 2003; Harrad *et al.*, 2004). However, in a United States study, the major exposure routes were determined to be ingestion and dermal absorption (Johnson-Restrepo and Kannan, 2009). The different results could be attributed to massive usage of PBDEs in the U.S.

In Taiwan, a series of efforts have been launched with regard to building a PCDD/F emission inventory, including mobile sources (Chuang *et al*., 2010), boilers (Chen *et al.*, 2011), and joss papers (Chiu *et al*., 2011; Lo *et al*., 2011), among other possible sources. Also, long term atmospheric PCDD/F monitoring has been done (Wu *et al*., 2010). The main PCDD/F sources in MSWIs were found to be from fly ashes (Chen *et al*., 2008); furthermore, the highest content of PCDD/Fs in the MSWIs studied were found to be the ashes in bag filters (Lin *et al*., 2010). In Taiwan, 72.2% of the electricity comes from thermal power plants, and 67% of those use coal as fuel. Not only have heavily oil-fueled power plants been found to contribute heavy metals in northern Taiwan (Wang *et al*., 2010d), but also coal-fired power plants are known to be very significant sources of PCDD/Fs, accounting for 56% of total PCDD/F emissions in southern Taiwan (Lin *et al*., 2007). However, the major PBDE sources in the MSWIs have rarely been discussed.

The reutilization of bottom residues in MSWIs has become a common idea after the wide deployment of "the most effective technique for PCDD/F emission control" (Buekens and Huang, 1998). However, the bottom residues are industrial wastes which are often buried in landfills, and PBDEs observed at levels of the sum of PBDE-47, -99 and -100 were n.d.–4000 pg/L in the raw landfill leachate (Osako *et al*., 2004). Therefore, the safety of reutilization of bottom residues from MWSIs and TPPs needs to be investigated because the chemical characteristics of PBDEs and PCDD/Fs could be different. Hence, the investigation of PBDE distribution in MSWIs and TPP should not be ignored even though many studies have already been conducted on PBDE toxicology, behavioral characteristics, and fate in the environment.

METHODS

Two continuously operating MSWIs (MSWI-A and MSWI-B) and a coal-fired power plant (TPP) located in southern Taiwan were investigated in 2009. The sampled TPP included the bottom residues (BR) in the combustion chambers, the fly ashes in the electrostatic dust precipitators (ESD) and the stack flue gases (SFG). The combination of air pollution control devices (APCDs) in the TPP was

focused on removing the particulate matters from the stack flue gases. The feeding wastes in both MSWIs were of municipal and industrial origins. The municipal vs. industrial wastes handled were 40% vs. 60% for MSWI-A, and 80% vs. 20% for MSWI-B. The capacity of each furnace in MSWI-A and MSWI-B was 450 and 300 MT/day, respectively. The operating installment for each furnace was a two-stage, starved-air modular type, including its own heat recovery system (a superheater (SH) and an economizer (EC)), semi-dry absorbers (SDA), activated carbon injection systems, fabric filters (BF) and stacks. The combination of the above air pollution control devices, known as ''the most effective technique for PCDD/F emission control'' (Buekens and Huang, 1998), is the most common system among MSWIs in Taiwan.

In order to provide data on the levels of persistent environment pollutants in the surrounding area, samples of the stack flue gas, air pollutant control residues, ashes from the units, ambient air, leaves, soils, and input wastes were collected in the same period of time. Typical ash samples were collected from six different parts of the MSWIs (bottom ashes (BR) from the combustion chambers, fly ashes from the super heaters (SH), economizers (EC), semi-dryer absorbers (SDA), and fabric filters (BF), and the fly ashes in the fly ash pits (FAP). The ashes in the FAPs were the mixtures of those in the SH, EC, SDA, and the BF. The sampling procedures for the stack flue gas, and ashes from the various units complied with the requirements of NIEA A807.74C, and NIEA R119.00C, respectively.

The analytical procedure met the government standard as published in NIEA M802.00B. The samples were pretreated before the analysis. Collected ashes, air-control residues, and soil samples were put on clean utensils or on a clean section of foil, after which their impurities were removed, and the samples were then air-dried or freeze-dried. When the diameters of pellets were greater than 15 mm, the pellets were shattered in order to prevent cementation of the dehydrated solid samples during the air-drying process. The solidified samples were crushed to smaller than 5 mm in diameter before the air-drying. After drying, the samples were sieved with a 2 mm (10 mesh) standard sieve and then ground to pass through an 18 mesh (aperture < 1 mm). The sieved ashes were mixed properly and put into flasks before they were extracted.

The stack flue gas and ambient air samples were placed in a Soxhlet extractor spiked with 30 μL of an internal standard solution (23IS); the samples were extracted for 18 ± 2 hours. The extract was then evaporated off to near dryness and was dissolved in dichloromethane three times before being transferred to a clean tube. Each extract was equally divided into two (A and B) flasks. Flask A was acid-washed, and flask B was stored.

The ash and soil samples were placed in thimble filters and were put in a Soxhlet extractor with a spiked internal standard solution (1613LCS) and were extracted with heat for 22 ± 2 hours. The extract was cooled to room temperature and was then evaporated to near dryness. Leaf samples of about 10 grams were put on a cylinder filter with anhydrous sulfate. The sample was then moved to the middle section of a Soxhlet extractor with 700 mL of mixed acetone/hexane 50/50 (v/v) and 10 μL of LCS. The Soxhlet extraction was initiated with a heating device. After the extraction, the extract was cooled to room temperature and evaporated off to near dryness.

The extracts were treated with sulfuric acid and then shaken in an ultrasonic oscillator. A series of sample cleanup and fraction procedures, including an acidic silica gel column, an acidic alumina column, and activated carbon chromatography, were used to treat the extract. The final extracts were blown with nitrogen to near dryness, and RS (for stack flue gas samples) or ISS (for the rest of samples) were added to the concentrates.

The analyses of PBDEs were carried out by a high-resolution gas chromatographer/high-resolution mass spectrometer (HRGC/HRMS). Each PBDE congener was analyzed. The column equipped by HRGC was heated up from 150°C to 190°C with an increase in temperature of 20 °C/min and was then increased up to 220°C at 1.5 °C/min. The temperature was then increased to 310°C at 3 °C/min and was maintained for 2 minutes. The HRMS was equipped with an electron impact (EI+) source. The analytical mode of the selected ion monitoring (SIM) had a resolution power of 10,000. The temperature of the ion source was 250°C. The detailed analytical procedures have been described in previous researches (Wang *et al.*, 2010b).

RESULTS AND DISCUSSION

PBDE and PBDD/F Concentrations in the Stack Flue Gases

For the purposes of this study, 30 PBDE congeners were selected as the fingerprints of emission sources. Tables 1 and 2 show the mean PBDE and PBDD/F concentrations and relative standard deviations (RSDs) for samples collected in the stack flue gases of MSWI-A, MSWI-B, and TPP, respectively. The results indicated the concentrations of PBDEs emitted from the stack flue gas of MSWI-A, MSWI-B and TPP were 9.32 ng/Nm^3, 7.62 ng/Nm^3, and 5.43 ng/Nm^3, respectively. The results are comparable with our previous research which is focuses on the distribution of PCDD/Fs in MSWI-A, MSWI-B and TPP (Lin *et al.*, 2010). The PBDE levels of MSWI-A were 116 to 132 times higher than that of the PCDD/F TEQs emitted from MWSI-A during the same period. The PBDE levels of MSWI-B were 100–137 times higher than that of PCDD/F TEQs from MWSI-B.

The mean total PBDD/F mass concentrations (sum of 12 congeners) in the stack flue gases of the MSWI-A, MSWI-B and TPP were 26.6 ± 2.60, 168 ± 202, 21.3 ± 15.5 pg/Nm^3, respectively, while the corresponding TEQ concentrations were 3.14 ± 0.146, 13.9 ± 24.9, and 0.222 ± 0.248 pg TEQ/Nm^3, respectively. The international toxic equivalency factors (TEFs) for PBDD/Fs were evaluated with those of PCDD/Fs'. Wang and Chang-Chien (Wang and Chang-Chien, 2007) measured only seven PBDD/F congeners for the mean total PBDD/F concentrations in the stack flue gases of 9 MSWIs, which were 2.28 pg/Nm^3 and 0.557 pg TEQ/Nm^3 on mass and toxicity bases, respectively.

Table 1. PBDE concentrations in the stack flue gases.

	MSWI-A		MSWI-B		TPP	
	Mean (n = 10)	RSD (%)	Mean (n = 10)	RSD (%)	Mean (n = 10)	RSD (%)
BDE-7	0.00586	13.9	0.00344	8.96	0.00303	6.70
BDE-15	0.128	17.9	0.0355	13.7	0.00940	3.94
BDE-17	0.0174	14.3	0.0110	14.7	0.00702	6.28
BDE-28	0.0520	13.7	0.0317	10.4	0.0143	9.54
BDE-49	0.0150	10.9	0.0114	7.58	0.00853	7.02
BDE-71	0.00243	9.6	0.00187	8.74	0.00155	1.36
BDE-47	0.389	15.6	0.115	8.64	0.148	12.9
BDE-66	0.00934	14.2	0.00782	10.2	0.00523	8.30
BDE-77	0.000702	26.6	0.000599	39.0	0.000222	1.36
BDE-100	0.0807	21.8	0.0106	8.82	0.00901	3.22
BDE-119	0.00466	0.634	0.00505	1.02	0.00533	1.35
BDE-99	0.418	19.7	0.0532	9.80	0.0438	6.08
BDE-85	0.0122	22.6	0.00153	31.8	0.000552	16.6
BDE-126	0.0000915	0.644	0.0000992	1.01	0.000105	1.37
BDE-154	0.0573	11.3	0.00833	12.0	0.00721	4.50
BDE-153	0.0902	19.3	0.0224	11.6	0.0171	6.64
BDE-139	0.00788	21.6	0.000699	10.1	0.000690	6.86
BDE-140	0.00344	17.4	0.00179	23.0	0.000933	1.35
BDE-138	0.00937	16.2	0.00352	22.8	0.00180	11.9
BDE-156	0.000268	0.648	0.000291	1.03	0.000307	1.35
BDE-184	0.00255	26.8	0.000923	1.02	0.000976	1.35
BDE-183	0.190	39.4	0.0519	10.9	0.0625	18.1
BDE-191	0.00664	14.8	0.00728	18.1	0.00261	1.35
BDE-197	0.0990	34.2	0.0394	10.4	0.0470	14.1
BDE-203	0.0711	13.5	0.0926	14.9	0.0406	4.88
BDE-196	0.0983	20.4	0.102	12.2	0.0553	8.52
BDE-208	0.282	13.7	0.211	16.9	0.138	5.48
BDE-207	0.553	11.5	0.382	17.0	0.256	5.42
BDE-206	0.568	11.5	0.484	14.8	0.326	6.58
BDE-209	6.13	9.84	5.91	16.3	4.21	7.34
di-octa Br BDEs	1.77	12.7	0.620	10.4	0.493	8.44
nona-deca Br BDEs	7.56	10.08	7.00	16.2	4.94	7.06
Total PBDEs (ng/Nm^3)	9.32	13.9	7.62	8.96	5.43	6.70

PBDE and PBDD/F Contents in Ash Samples

The mean PBDE and PBDD/F contents of ash samples collected from each unit of the MSWIs and TPP are given in Tables 3–12, respectively. MSWI-A and MSWI-B exhibited similar trends with regard to PBDD/F and PBDE content in the ashes. BR exhibited the highest PBDE content (20.4–186 ng/g) and the second highest PBDD/F content (1.58–3.13 ng/g, 0.0279–0.0613 ng TEQ/g) among all the other ashes. BR also contained the highest PBDE content (6.35 ng/g) and PBDD/F content (3.68 pg/g, 0.0342 pg/g TEQ) for TPP. However, PCDD/Fs, whose chemical structure is similar to PBDEs, were found to have the highest concentration in the fly ashes of bag filters in a recent study (Chang *et al*., 2006). In Taiwan, 0.86 million tons of BR are produced from MSWIs each year, and 0.32 million tons of BR are reused for land-filling, road sub-bases and construction blocks, with the remainder sent to landfill sites (Wang *et al*., 2010a).

Emission Factors of PBDEs and PBDD/Fs

Three routes have been considered as the pathway for releasing MSWI substances containing pollutants into the environment, including bottom residues, fly ashes and stack flue gas. The bottom residue route (Route I) includes BR and SH, which are usually collected for landfill or reutilization. The fly ash route (Route II) includes EC, SDA and BF, which are treated as hazardous materials and need to be solidified. Route III is stack flue gases. Tables 13–15 list the mean PBDD/F and PBDE emission factors for each route and the entire MSWI system for MSWI-A, MSWI-B, and TPP, respectively. The total mean emission factors for the MSWI-A, MWSI-B, and TPP were 9.21 ± 9.49 μg TEQ/ton-waste, 7.02 ± 8.33 μg TEQ/ton-waste, and 0.00482 ± 0.00512 μg TEQ/ton-coal for PBDD/Fs, and 24357 ± 8285 μg TEQ/ton-waste, 48711 ± 41889 μg TEQ/ton-waste, and 507 ± 157 μg/ton-coal for PBDEs, respectively. The total PBDE emission factors for the MSWI systems were three orders higher than PBDD/F emission factors. When comparing the emission factors for MSWI-A, MSWI-B, and TPP, MSWI-B with similar operational units to MSWI-A that were fed with a larger percentage of industrial waste, higher PBDE emission factors were obviously observed.

Table 2. PBDD/F concentrations in the stack flue gases.

	MSWI-A		MSWI-B		TPP	
	Mean (n = 10)	RSD (%)	Mean (n = 10)	RSD (%)	Mean (n = 10)	RSD (%)
2,3,7,8,-TeBDD	-	-	0.00574	22.0	-	-
1,2,3,7,8-PeBDD	-	-	0.00260	93.2	-	-
1,2,3,4/6,7,8-HxBDD	0.00149	11.9	0.00421	70.3	0.0018	0.00
1,2,3,7,8,9-HxBDD	-	-	0.00156	7.05	-	-
1,2,3,4,6,7,8-HpBDD	0.00102	17.4	0.00242	69.3	0.000719	0.00
OBDD	0.00424	34.1	0.00261	65.3	0.00143	0.00
2,3,7,8-TeBDF	-	-	0.0360	102	-	-
1,2,3,7,8-PeBDF	-	-	0.0155	97.8	-	-
2,3,4,7,8-PeBDF	-	-	0.00692	91.3	-	-
1,2,3,4,7,8-HxBDF	0.00110	44.9	0.0104	65.7	0.000982	0.00
1,2,3,4,6,7,8-HpBDF	0.0101	17.9	0.0312	20.6	0.014513	41.0
OBDF	0.0160	65.9	0.0527	66.1	0.01099	23.8
PBDDs	0.00499	53.3	0.0148	79.7	0.00395	0.00
PBDFs	0.02285	55.3	0.153	65.7	0.020263	52.0
PBDDs/PBDFs	0.292	39.4	0.0842	30.5	0.237	0.00
Total PBDD/Fs (ng/Nm^3)	0.0266	43.1	0.167	66.8	0.021263	48.6
PBDDs ng TEQ/Nm^3	0.000159	8.04	0.00471	98.1	0.000188	0.00
PBDFs ng TEQ/Nm^3	0.000195	24.5	0.00925	90.4	0.000175	44.7
PBDDs/PBDFs (TEQ)	0.827	-	-	1.07	-	-
Total TEQ (ng TEQ/Nm^3)	0.000314	30.1	0.0139	92.9	0.000222	64.1

Table 3. PBDE content in TPP operating units.

	BR		ESD	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-7	0.000239	1.72	0.000355	10.1
BDE-15	0.00102	0.866	0.00276	2.39
BDE-17	0.000766	8.46	0.00167	6.55
BDE-28	0.00206	0.633	0.00205	1.22
BDE-49	0.00357	1.88	0.00343	9.97
BDE-71	0.000389	0.129	0.00119	12.4
BDE-47	0.0235	1.49	0.0332	3.47
BDE-66	0.00250	2.61	0.00218	6.57
BDE-77	0.000387	3.00	0.000477	8.39
BDE-100	0.00349	11.5	0.00722	6.97
BDE-119	0.000876	10.4	0.00412	12.4
BDE-99	0.0208	1.40	0.0209	2.25
BDE-85	0.000767	6.04	0.000401	3.97
BDE-126	0.0000144	16.4	0.000576	13.8
BDE-154	0.0367	6.38	0.0794	0.227
BDE-153	0.0811	7.64	0.217	15.3
BDE-139	0.00180	4.67	0.00121	7.27
BDE-140	0.00267	3.00	0.00621	11.8
BDE-138	0.00854	12.8	0.0197	17.0
BDE-156	0.0000422	16.3	0.000195	19.2
BDE-184	0.00728	1.04	0.0188	8.94
BDE-183	0.398	13.3	1.30	17.8
BDE-191	0.00399	10.2	0.00878	13.9
BDE-197	0.255	11.0	0.763	17.0
BDE-203	0.0793	10.0	0.217	15.0
BDE-196	0.118	11.2	0.346	16.8
BDE-208	0.0909	5.74	0.0687	10.3
BDE-207	0.323	9.47	0.594	13.7
BDE-206	0.281	6.17	0.203	13.1
BDE-209	4.60	7.06	2.41	3.69
di-octa Br BDEs	1.05	1.72	3.06	10.1

Table 3. *(continued).*

	BR		ESD	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
nona-deca Br BDEs	5.30	0.866	3.28	2.39
Total BDEs (ng/g)	6.35	8.46	6.34	6.55
Total PBDEs (μg/ton-coal)	381	3.53	63.4	1.85

Table 4. PBDE content in MSWI-A operating units (a).

	BR		SH		EC	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-7	0.0845	6.76	0.0565	20.0	0.000335	8.30
BDE-15	0.132	4.09	0.0527	19.8	0.000999	9.04
BDE-17	0.280	4.79	0.107	19.9	0.000918	5.49
BDE-28	0.410	4.83	0.156	19.8	0.00135	3.56
BDE-49	0.480	0.250	0.243	19.9	0.00128	0.156
BDE-71	0.0993	2.97	0.0423	19.9	0.000224	4.43
BDE-47	4.58	4.24	0.665	19.7	0.00855	8.30
BDE-66	0.393	0.204	0.199	20.0	0.000399	16.3
BDE-77	0.0785	8.04	0.0550	20.0	0.000187	8.85
BDE-100	0.648	3.64	0.103	19.9	0.000712	8.37
BDE-119	0.0448	7.05	0.0304	19.9	0.000233	8.58
BDE-99	4.02	1.19	0.886	20.0	0.00274	4.89
BDE-85	0.199	2.75	0.0361	20.0	0.0000112	8.57
BDE-126	0.0195	3.05	0.0161	20.0	0.0000124	15.8
BDE-154	1.02	12.2	0.199	20.0	0.000743	4.74
BDE-153	1.08	6.01	0.701	19.9	0.00122	0.328
BDE-139	0.0869	2.65	0.0492	20.0	0.0000270	8.57
BDE-140	0.0706	2.60	0.0575	20.0	0.0000408	8.58
BDE-138	0.164	8.68	0.118	20.0	0.0000443	8.56
BDE-156	0.00711	5.44	0.00630	20.0	0.0000135	8.55
BDE-184	0.118	13.4	0.0985	20.0	0.000104	15.3
BDE-183	1.90	3.94	1.62	19.8	0.00240	0.833
BDE-191	0.182	12.6	0.149	20.0	0.000114	8.57
BDE-197	2.36	6.37	2.16	19.9	0.00145	3.25
BDE-203	2.52	6.05	2.28	20.0	0.000906	3.19
BDE-196	2.18	5.39	1.93	20.0	0.00130	4.46
BDE-208	6.07	1.93	4.85	20.0	0.00211	0.903
BDE-207	9.54	8.72	6.85	20.0	0.00463	1.02
BDE-206	14.8	1.49	11.7	20.0	0.00469	0.918
BDE-209	108	1.82	73.0	20.0	0.0569	6.31
di-octa Br BDEs	23.2	-	12.0	-	0.0263	
nona-deca Br BDEs	139	-	96.5	-	0.0683	
Total PBDEs (ng/g)	162	6.76	109	19.8	0.0946	3.06
Total PBDEs (μg/ton-waste)	24,300	-	1.00	-	0.946	-

Table 5. PBDE content in MSWI-A operating units (b).

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-7	0.000123	13.1	0.000240	3.47	0.000262	0.727
BDE-15	0.000496	4.18	0.00271	13.2	0.00732	0.874
BDE-17	0.000465	0.108	0.000611	6.91	0.000833	2.53
BDE-28	0.000919	6.33	0.00137	0.513	0.00201	3.54
BDE-49	0.000892	2.15	0.00103	1.49	0.00125	5.22
BDE-71	0.000171	3.51	0.000199	9.99	0.000199	10.3
BDE-47	0.00798	5.31	0.00761	9.43	0.0101	9.58
BDE-66	0.000693	3.95	0.000733	2.48	0.000906	4.08
BDE-77	0.000186	19.4	0.000140	19.2	0.000168	0.833

Table 5. *(continued).*

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-100	0.000704	2.27	0.000712	1.03	0.00111	6.40
BDE-119	0.000233	8.58	0.000233	8.58	0.000233	8.58
BDE-99	0.00508	8.90	0.00319	0.376	0.00443	4.50
BDE-85	0.0000112	8.57	0.0000605	14.7	0.000106	18.8
BDE-126	0.00000455	8.57	0.00000455	8.57	0.00000455	8.57
BDE-154	0.00122	10.6	0.00128	11.2	0.00209	7.66
BDE-153	0.0104	16.7	0.00214	7.01	0.00286	1.12
BDE-139	0.0000687	15.5	0.000203	18.5	0.000345	19.1
BDE-140	0.000356	18.7	0.000130	16.4	0.000356	18.7
BDE-138	0.00177	17.9	0.000351	8.13	0.000503	19.0
BDE-156	0.0000135	8.55	0.0000135	8.55	0.0000135	8.55
BDE-184	0.000207	17.7	0.000188	9.66	0.000262	18.1
BDE-183	0.0169	11.4	0.00403	1.52	0.00859	8.65
BDE-191	0.000513	17.5	0.000114	8.57	0.000766	6.11
BDE-197	0.0121	12.7	0.00256	0.469	0.00704	4.74
BDE-203	0.00485	13.8	0.00180	8.00	0.00533	11.5
BDE-196	0.00740	13.8	0.00212	5.19	0.00508	7.20
BDE-208	0.00688	8.05	0.00335	11.0	0.0104	14.1
BDE-207	0.0217	9.84	0.00732	8.96	0.0286	12.2
BDE-206	0.0173	11.1	0.00777	10.6	0.0281	15.2
BDE-209	0.255	15.2	0.126	14.9	0.315	15.3
di-octa Br BDEs	0.0738	-	0.0338	-	0.0622	-
nona-deca Br BDEs	0.301	-	0.144	-	0.383	-
Total PBDEs (ng/g)	0.375	13.6	0.178	11.8	0.444	12.7
Total PBDEs (μg/ton-waste)	3.75	-	16.1	-	13.3	-

Table 6. PBDE content in MSWI-B operating units (a).

	BR		SH		EC	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-7	0.00849	13.0	0.000504	17.3	0.00111	19.5
BDE-15	0.0562	2.72	0.000416	18.1	0.00194	17.1
BDE-17	0.0918	15.3	0.000658	2.40	0.00651	19.7
BDE-28	0.154	7.49	0.00141	2.55	0.00777	19.1
BDE-49	0.302	12.1	0.000921	11.1	0.0212	19.7
BDE-71	0.0609	15.5	0.00595	19.7	0.00645	19.7
BDE-47	2.99	10.7	0.00698	6.27	0.0592	18.2
BDE-66	0.238	12.7	0.000657	11.7	0.0268	19.8
BDE-77	0.0288	9.29	0.000104	17.3	0.00369	19.9
BDE-100	0.713	13.1	0.000659	7.71	0.0246	19.6
BDE-119	0.0573	19.8	0.000250	6.69	0.0245	19.7
BDE-99	5.17	12.0	0.00393	15.3	0.159	19.7
BDE-85	0.161	10.7	0.0000120	6.67	0.0256	20.0
BDE-126	0.00838	4.11	0.00000490	6.53	0.00215	19.9
BDE-154	1.23	17.5	0.00175	14.3	0.198	19.9
BDE-153	8.20	18.5	0.00321	14.3	0.0999	19.8
BDE-139	0.359	18.3	0.000602	15.5	0.182	20.0
BDE-140	0.173	17.5	0.000933	14.3	0.229	20.0
BDE-138	0.767	17.0	0.000951	13.9	0.137	20.0
BDE-156	0.00572	19.9	0.0000144	6.67	0.0130	20.0
BDE-184	0.239	17.4	0.00111	17.1	0.202	20.0
BDE-183	24.9	19.6	0.00775	14.1	0.856	19.9
BDE-191	1.35	19.4	0.00225	15.9	0.520	20.0
BDE-191	1.35	19.4	0.00225	15.9	0.520	20.0
BDE-197	7.11	19.4	0.00793	14.8	2.46	20.0
BDE-203	1.93	18.0	0.00914	13.3	3.39	20.0

Table 6. *(continued).*

	BR		SH		EC	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-196	4.00	19.0	0.00684	10.4	2.03	20.0
BDE-208	3.14	15.1	0.0205	15.1	8.30	20.0
BDE-207	18.7	18.4	0.0320	14.3	11.6	20.0
BDE-206	14.0	18.2	0.0219	10.7	18.6	20.0
BDE-209	205	16.9	0.322	7.99	221	20.0
di-octa Br BDEs	60.2	-	0.0649	-	10.7	-
nona-deca Br BDEs	241	-	0.397	-	259	-
Total PBDEs (ng/g)	301	17.2	0.461	9.54	270	20.0
Total PBDEs (μg/ton-waste)	45,143	-	4.61		2,701	-

Table 7. PBDE content in MSWI-B operating units (b).

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
BDE-7	0.00553	12.3	0.00895	5.25	0.000444	18.8
BDE-15	0.571	19.9	0.659	3.67	0.110	13.2
BDE-17	0.00934	16.4	0.0294	3.24	0.00359	3.68
BDE-28	0.0869	19.6	0.153	4.00	0.0165	11.3
BDE-49	0.0108	11.4	0.0599	5.00	0.00655	10.2
BDE-71	0.00292	3.29	0.00865	1.43	0.00119	9.47
BDE-47	0.0708	16.7	0.204	0.882	0.0367	7.29
BDE-66	0.0139	9.50	0.0571	6.41	0.00581	1.96
BDE-77	0.00405	13.5	0.0151	4.58	0.00153	0.197
BDE-100	0.0264	18.4	0.0299	1.44	0.00465	1.59
BDE-119	0.00356	13.4	0.00700	8.88	0.00112	0.893
BDE-99	0.0466	7.93	0.187	3.38	0.0259	4.86
BDE-85	0.00521	3.29	0.0108	6.59	0.00147	1.84
BDE-126	0.000699	11.2	0.00373	10.4	0.000184	19.3
BDE-154	3.42	19.9	0.631	17.4	0.562	18.5
BDE-153	0.0498	5.97	0.204	9.51	0.0418	15.7
BDE-139	0.0103	2.04	0.0281	8.26	0.00371	3.56
BDE-140	0.0148	4.86	0.0266	10.6	0.00433	1.92
BDE-138	0.0254	15.7	0.0416	10.6	0.0140	15.1
BDE-156	0.000492	19.2	0.00999	6.04	0.0000192	0
BDE-184	0.00570	7.51	0.0366	18.7	0.00327	12.7
BDE-183	0.0554	3.10	0.399	5.66	0.0493	8.88
BDE-191	0.0218	16.8	0.0316	16.0	0.00554	17.2
BDE-197	0.0646	15.3	0.125	7.28	0.0243	7.22
BDE-203	0.173	18.8	0.112	8.51	0.0270	16.8
BDE-196	0.114	18.2	0.102	7.78	0.0266	14.1
BDE-208	0.296	19.2	0.123	11.5	0.0185	17.2
BDE-207	0.556	19.2	0.215	8.65	0.0490	13.9
BDE-206	0.815	19.5	0.139	0.217	0.0439	18.2
BDE-209	26.4	19.7	1.76	15.1	0.654	18.9
di-octa Br BDEs	4.81	-	3.18	-	0.979	-
nona-deca Br BDEs	28.1	-	2.24	-	0.765	-
Total PBDEs (ng/g)	32.9	14.5	5.41	20.7	1.75	2.58
Total PBDEs (μg/ton-waste)	329	-	487	-	52.4	-

Table 8. PBDD/F content in TPP operating units.

	BR		ESD	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
2,3,7,8,-TeBDD	ND	-	ND	-
1,2,3,7,8-PeBDD	ND	-	ND	-

Table 8. *(continued).*

	BR		ESD	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
1,2,3,4/6,7,8-HxBDD	ND	-	ND	-
1,2,3,7,8,9-HxBDD	ND	-	ND	-
1,2,3,4,6,7,8-HpBDD	ND	-	ND	-
OBDD	ND	-	ND	-
2,3,7,8-TeBDF	ND	-	ND	-
1,2,3,7,8-PeBDF	ND	-	ND	-
2,3,4,7,8-PeBDF	ND	-	ND	-
1,2,3,4,7,8-HxBDF	0.000175	19.2	0.0000304	100
1,2,3,4,6,7,8-HpBDF	0.00147	41.3	0.000886	75.0
OBDF	0.00203	63.9	0.00103	100
PBDDs	ND	-	ND	-
PBDFs	0.00368	51.0	0.00195	88.7
PBDDs/PBDFs	-	-	-	-
PBDD/Fs (ng/g)	0.00368	51.0	0.00195	88.7
PBDDs ng TEQ/g	ND	-	ND	-
PBDFs ng TEQ/g	0.0000342	11.9	0.0000130	82.9
PBDDs/PBDFs (TEQ)	-	-	-	-
Total PBDD/Fs TEQ (ng TEQ/g)	0.0000342	11.9	0.0000130	82.9

Table 9. PBDD/F content in MSWI-A operating units (a).

	BR		SH		EC	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
2,3,7,8,-TeBDD	0.000364	0.55	ND	-	ND	-
1,2,3,7,8-PeBDD	0.0009305	16.1	ND	-	ND	-
1,2,3,4/6,7,8-HxBDD	0.000731	34.8	ND	-	ND	-
1,2,3,7,8,9-HxBDD	0.000424	7.10	ND	-	ND	-
1,2,3,4,6,7,8-HpBDD	0.002655	1.32	ND	-	ND	-
OBDD	0.007595	45.5	ND	-	ND	-
2,3,7,8-TeBDF	0.0152	24.4	ND	-	ND	-
1,2,3,7,8-PeBDF	0.02895	27.5	ND	-	ND	-
2,3,4,7,8-PeBDF	0.0363	62.3	ND	-	ND	-
1,2,3,4,7,8-HxBDF	0.260	41.1	ND	-	ND	-
1,2,3,4,6,7,8-HpBDF	1.17	64.5	0.000431	126	0.000383	86.5
OBDF	1.61	79.0	0.00413	95.0	0.00233	29.6
PBDDs	0.0127	47.9	ND	-	ND	-
PBDFs	3.12	69.5	0.00456	97.9	0.00271	37.6
PBDDs/PBDFs	0.00406	-	-	-	-	-
PBDD/Fs (ng/g)	3.13	69.5	0.00456	97.9	0.00271	37.6
PBDDs ng TEQ/g	0.000978	9.45	-	-	-	-
PBDFs ng TEQ/g	0.0603	52.5	0.00000431	126	0.00000383	86.5
PBDDs/PBDFs (TEQ)	0.0162	-	-	-	-	-
Total PBDD/Fs TEQ (ng TEQ/g)	0.0613	103	0.00000431	126	0.00000383	86.5

Table 10. PBDD/F content in MSWI-A operating units (b).

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
2,3,7,8,-TeBDD	ND	-	ND	-	ND	-
1,2,3,7,8-PeBDD	ND	-	ND	-	ND	-
1,2,3,4/6,7,8-HxBDD	ND	-	ND	-	ND	-
1,2,3,7,8,9-HxBDD	ND	-	ND	-	ND	-
1,2,3,4,6,7,8-HpBDD	0.000108	100	ND	-	0.000820	100
OBDD	0.000925	100	ND	-	0.0114	100
2,3,7,8-TeBDF	0.000056	100	ND	-	0.0000655	100

Table 10. *(continued).*

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
1,2,3,7,8-PeBDF	0.000151	100	ND	-	0.000471	95.9
2,3,4,7,8-PeBDF	ND	-	ND	-	0.000329	85.4
1,2,3,4,7,8-HxBDF	0.00149	100	0.000363	86.8	0.00550	98.3
1,2,3,4,6,7,8-HpBDF	0.0160	93.7	0.000612	137	0.0692	99.5
OBDF	0.0162	86.3	0.00260	106	0.0668	99.2
PBDDs	0.00104	100	ND	-	0.0123	100
PBDFs	0.0338	92.5	0.00322	112	0.142	99.2
PBDDs/PBDFs	0.0306	-	-	-	0.0862	-
PBDD/Fs (ng/g)	0.0349	92.7	0.00322	112	0.155	99.3
PBDDs ng TEQ/g	0.00000201	100	-	-	0.0000197	100
PBDFs ng TEQ/g	0.000338	98.4	0.0000424	167	0.00150	96.6
PBDDs/PBDFs (TEQ)	0.00594	-	-	-	0.0131	-
Total PBDD/Fs TEQ (ng TEQ/g)	0.000340	98.5	0.0000424	167	0.00152	96.6

Table 11. PBDD/F content in MSWI-B operating units (a).

	BR		SH		EC	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
2,3,7,8,-TeBDD	0.000125	100	ND	-	0.000925	100
1,2,3,7,8-PeBDD	0.000148	100	ND	-	0.00222	100
1,2,3,4/6,7,8-HxBDD	0.000306	100	ND	-	0.00245	100
1,2,3,7,8,9-HxBDD	0.000185	100	ND	-	0.00137	100
1,2,3,4,6,7,8-HpBDD	0.00157	100	7.15E-05	100	0.02765	100
OBDD	0.00865	100	0.000263	100	0.1435	100
2,3,7,8-TeBDF	0.00318	52.5	ND	-	0.00615	100
1,2,3,7,8-PeBDF	0.00765	33.4	8.75E-05	100	0.01425	100
2,3,4,7,8-PeBDF	0.0181	49.4	0.0000930	100	0.04075	100
1,2,3,4,7,8-HxBDF	0.108	34.5	0.000944	81.2	0.3635	100
1,2,3,4,6,7,8-HpBDF	0.618	46.6	0.00545	80.9	1.315163	100
OBDF	0.818	33.4	0.00298	29.8	3.265	100
PBDDs	0.0110	50	0.000335	100	0.178	100
PBDFs	1.57	38.9	0.00956	65.0	5.00	100
PBDDs/PBDFs	0.00697	-	0.0350	-	0.0356	-
PBDD/Fs (ng/g)	1.58	39.5	0.00991	65.7	5.20	100
PBDDs ng TEQ/g	0.000272	100	9.8E-07	100	0.00284	100
PBDFs ng TEQ/g	0.0276	42.3	0.000203	85.0	0.0745	100
PBDDs/PBDFs (TEQ)	0.00987	-	0.00484	-	0.0381	-
Total PBDD/Fs TEQ (ng TEQ/g)	0.0279	42.9	0.000204	85.0	0.0775	100

Table 12. PBDD/F content in MSWI-B operating units (b).

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
2,3,7,8,-TeBDD	0.000298	100	0.00115	75.4	0.000197	100
1,2,3,7,8-PeBDD	0.000186	100	0.00114	78.0	ND	-
1,2,3,4/6,7,8-HxBDD	0.00163	100	0.00204	15.7	0.000715	100
1,2,3,7,8,9-HxBDD	0.000960	100	0.00137	8.76	0.000372	100
1,2,3,4,6,7,8-HpBDD	0.00844	96.6	0.00718	17.4	0.00312	88.1
OBDD	0.00210	22.0	0.0125	20.8	0.000351	100
PBDDs	0.0136	85.6	0.0254	31.2	0.00475	77.5
2,3,7,8-TeBDF	0.000778	8.94	0.00232	37.6	0.000387	100
1,2,3,7,8-PeBDF	0.00200	14.3	0.0115	76.4	0.000709	35.3
2,3,4,7,8-PeBDF	0.00174	49.2	0.0189	77.0	0.00107	31.3
1,2,3,4,7,8-HxBDF	0.0125	38.9	0.0742	81.8	0.00248	32.5
1,2,3,4,6,7,8-HpBDF	0.0552	78.3	0.154	73.1	0.00603	54.2

Table 12. *(continued).*

	SDA		BF		FAP	
	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)	Mean (n = 2)	RPD (%)
OBDF	0.116	93.9	0.0127	33.9	0.00710	100
PBDFs	0.187	84.1	0.274	70.5	0.0178	68.3
PBDDs/PBDFs	0.0727	-	0.0925	-	0.267	-
PBDD/Fs (ng/g)	0.201	73.5	0.299	65.9	0.0226	37.5
PBDDs ng TEQ/g	0.000737	99.4	0.00214	62.5	0.000337	98.9
PBDFs ng TEQ/g	0.00296	49.9	0.0192	77.6	0.000922	36.7
PBDDs/PBDFs (TEQ)	0.249	-	0.111	-	0.365	-
Total PBDD/Fs TEQ (ng TEQ/g)	0.003695	20.2	0.0214	76.1	0.00126	1.59

Table 13. PBDE and PBDD/F emission factors in the MSWI-A.

		Route 1	Route 2	Route 3
		BR + SH	EC + SDA + BF	SFG
PBDEs	Σ2-8 Br BDEs	3480 ± 120	4.04 ± 0.641	6.88 ± 2.21
	Σ9-10 Br BDEs	20790 ± 8150	16.7 ± 11.6	28.7 ± 8.70
	Total BDEs (μg/ton-waste)	24301 ± 8262	20.8 ± 12.2	35.6 ± 10.9
PBDD/Fs	Total PBDD/Fs (μg/ton-waste)	470 ± 653	0.440 ± 0.783	0.133 ± 0.0896
	Total TEQ (μg TEQ/ton-waste)	9.20 ± 9.48	0.00726 ± 0.0131	0.00103 ± 0.000756

Table 14. P PBDE and PBDD/F emission factors in the MSWI-B.

		Route 1	Route 2	Route 3
		BR + SH	EC + SDA + BF	SFG
PBDEs	Σ2-8 Br BDEs	9028 ± 8071	441 ± 200	3.90 ± 1.75
	Σ9-10 Br BDEs	36116 ± 30806	3073 ± 2972	43.7 ± 27.7
	Total BDEs (μg/ton-waste)	45147 ± 38870	3517 ± 2990	47.6 ± 29.4
PBDD/Fs	Total PBDD/Fs (μg/ton-waste)	237 ± 186	80.9 ± 120	1.26 ± 1.65
	Total TEQ (μg TEQ/ton-waste)	4.18 ± 3.59	2.74 ± 4.56	0.101 ± 0.183

Table 15. PBDE and PBDD/F emission factors in the TPP.

		Route 1	Route 2	Route 3
		BR	ESD	SFG
PBDEs	Σ2-8 Br BDEs	63.2 ± 32.2	30.6 ± 24.6	5.69 ± 1.77
	Σ9-10 Br BDEs	318 ± 102	32.8 ± 12.9	57.2 ± 9.04
	Total BDEs (μg/ton-coal)	381 ± 134	63.4 ± 11.7	62.9 ± 10.9
PBDD/Fs	Total PBDD/Fs (μg/ton-coal)	0.333 ± 0.333	0.00221 ± 0.00221	0.246 ± 0.168
	Total TEQ (μg TEQ/ton-coal)	0.00229 ± 0.00229	0.0000221 ± 0.0000221	0.00251 ± 0.00281

Distribution of PBDEs and PBDD/Fs

Tables 16–18 list the PBDD/F and PBDE distributions (%) among the different ashes and the stack flue gases for MSWI-A, MSWI-B and TPP which were obtained from each emission factor from BR, SH, EC, SDA, BF and stack flue gas divided by the total emission factors of the MSWI-A, MSWI-B, and TPP, respectively.

In MSWI-A and MSWI-B, the weights of the bottom residues were 15% and 12.5%, and the weights of fly ashes were 8.3% and 6.3% of the solid waste feeds, respectively. In TPP, 1.46% by weight of coal became bottom residue, and 5.56% became fly ashes. BR exhibited much higher PBDD/F and PBDE distributions than those of other ashes, even higher than those of the BF in the MSWIs. Only less than 5% of the total PBDD/F TEQs and less than 1% of PBDEs were emitted from the stack flue gases. However, 51.2% PBDD/F TEQs and 12.5% PBDEs were emitted into the atmosphere. According to Tables 5–7, different PBDE emitting scenarios for MSWIs and TPP could be discerned. The concentration of PBDEs in TPP was lower than that found in MSWIs; however, the emission rate of PBDEs was the highest in TPP as compared to that found in MSWIs. The extreme outcomes indicated that even though the PBDE concentration in the TPP was low, the emission was still noticeable. The combination of dry scrubbers, activated carbon injections, and bag filters installed in MSWIs has served as the most effective technique for the control of PCDD/Fs and PCDD/F-like compounds. However, the largest emission factors in MSWI-A, MSWI-B and TPP were bottom residue, accounting for 99.7%, 92.6% and

Table 16. PBDE and PBDD/F Distributions (%) in the MSWI-A.

		SFG	BR	SH	EC	SDA	BF
PBDEs	Σ2-8 Br BDEs	0.197 ± 0.0632	99.7 ± 3.44	0.00937 ± 0.00483	0.00753 ± 0.000829	0.0211 ± 0.0110	0.0871 ± 0.00658
	Σ9-10 Br BDEs	0.138 ± 0.0417	99.8 ± 39.1	0.00324 ± 0.000951	0.00328 ± 0.000833	0.0144 ± 0.0104	0.0624 ± 0.0444
	Total BDE	0.146 ± 0.0447	99.8 ± 33.9	0.00411 ± 0.000117	0.00388 ± 0.000594	0.0154 ± 0.0105	0.0661 ± 0.0391
PBDD/Fs	Mass	0.0283 ± 0.0190	99.88 ± 139	0.00916 ± 0.00115	0.000814 ± 0.000704	0.0741 ± 0.138	0.0186 ± 0.0279
	Total TEQ	0.0141 ± 0.0103	99.9 ± 103	0.000468 ± 0.00059	0.000416 ± 0.00036	0.0369 ± 0.0727	0.0415 ± 0.693

Table 17. PBDE and PBDD/F Distributions (%) in the MSWI-B.

		SFG	BR	SH	EC	SDA	BF
PBDEs	Σ2-8 Br BDEs	0.0412 ± 0.0184	95.3 ± 85.2	0.00685 ± 0.00435	1.13 ± 1.13	0.508 ± 0.403	3.02 ± 0.576
	Σ9-10 Br BDEs	0.111 ± 0.705	92.0 ± 78.5	0.0101 ± 0.00455	6.60 ± 6.60	0.716 ± 0.705	0.512 ± 0.267
	Total BDEs	0.0977 ± 0.0603	92.7 ± 79.8	0.00946 ± 0.00451	5.54 ± 5.54	0.675 ± 0.490	1.00 ± 0.104
PBDD/Fs	Mass	0.393 ± 0.516	74.2 ± 58.1	0.0310 ± 0.0413	16.3 ± 32.6	0.630 ± 0.913	8.43 ± 4.20
	Total TEQ	1.43 ± 2.60	59.5 ± 51.1	0.0290 ± 0.0494	11.0 ± 22.1	0.527 ± 0.212	27.5 ± 42.6

Table 18. PBDE and PBDD/F Distributions (%) in the TPP.

		SFG	BR	ESD
PBDEs	Σ2-8 Br BDEs	5.72 ± 1.78	63.5 ± 32.4	30.76 ± 24.8
	Σ9-10 Br BDEs	14.0 ± 2.22	77.9 ± 25.1	8.04 ± 3.16
	Total BDEs	12.4 ± 2.15	75.1 ± 26.5	12.5 ± 2.31
PBDD/Fs	Mass	42.3 ± 28.9	57.3 ± 57.3	0.380 ± 0.380
	Total TEQ	52.1 ± 58.3	47.49 ± 47.49	0.458 ± 0.458

75.1% of the PBDE emissions, respectively. The results can be compared with a previous study where 99.2% of PBDE emissions was also found in the bottom residue of an MSWI (Wang *et al.,* 2010a); however, another study for a large scale MSWI states otherwise; only 57.8% of PBDEs was found in the ash combination of BR and SH (Wang *et al.*, 2010c). The dominating congener in each unit was BDE-209. However, the content of highly brominated PBDE (nona- and deca-BDEs) was found to decrease with temperature in each APCD unit, especially in the case of MSWI-B, where nona-and deca-BDEs consisted of 86.1%, 95.9%, 85.4%, and 41.3% PBDEs in SH, EC, SDA, and BF, respectively.

Only 0.15% or lower PBDE mass escaped into the environment for every ton of wastes treated. The absence of adequate air pollution control devices for PBDE in PP led to a 12.4 % PBDE dispersal into the atmosphere for each ton of coal burnt; the percentage of PBDEs emitted from TPP was 80-120 times higher than those from MSWI-A and MSWI-B. The necessity of adding effective PCDD/F control devices, such as activated carbon and bag filters, to remove PBDEs in the coal-fired power plant has to be further investigated in order to mitigate the PBDE emission from TPP. The PBDE mass distribution pattern was very similar in each MSWI; however, the resemblance between the MSWIs is unapparent. The different PBDE emission characteristics between the MSWIs and the coal-fired power plant should be noticed. The PBDE emission rate was found to be high in the coal-fired power plant and low in the MSWIs, whereas the emitting PBDE concentration was high in MSWIs and low in the coal-fired power plant. Thus, the PBDE contribution of the coal-fired power plant still needs to be assessed because the average amount of coal burnt in the TPP was 16,442 tons/day, while the solid waste burnt in the MSWIs was 1,140–1,185 tons/day. The estimated mass of PBDEs emitted by considering the high amount of coal burnt by PP would be 11,900 μg/hr, which is comparable with those of the PCDD/Fs emitted from the MSWIs (669–830 μg/hr). Thus, the PBDE emission rate of a TPP is 14.4–17.8 times of those associated with MSWIs.

Congener Profiles of PBDEs and PBDD/Fs

Figs. 1 and 2 show the profiles of individual PBDE fractions obtained from the respective flue gases of MSWI-A, MSWI-B, and TPP, respectively. The only dominant congener found from MSWI-A was BDE-209, accounting for 65.9% of total PBDE concentrations in the stack flue gases; BDE-206 and BDE-207 were the second and third most abundant congeners, but these two species comprised only 6.1% and 5.94% of all of the PBDEs, respectively. The dominant congener in MSWI-B, as in MSWI-A, was BDE-209, which constituted 77.7% of all PBDEs in the stack flue gas; the second and third highest congeners were also BDE-206 and BDE-207, accounting for 6.36% and 5.02% of all PBDEs in the stack flue gas, respectively. The congener pattern for TPP was similar to that of MSWI-A and MSWI-B, with BDE-209 (77.6%) as the dominant congener, followed by BDE-206 (6.01%) and BDE-207 (4.72%).

The PBDD/F and PBDE congener profiles in each unit of MSWI-A, MSWI-B and TPP are illustrated in Figs. 3–12,

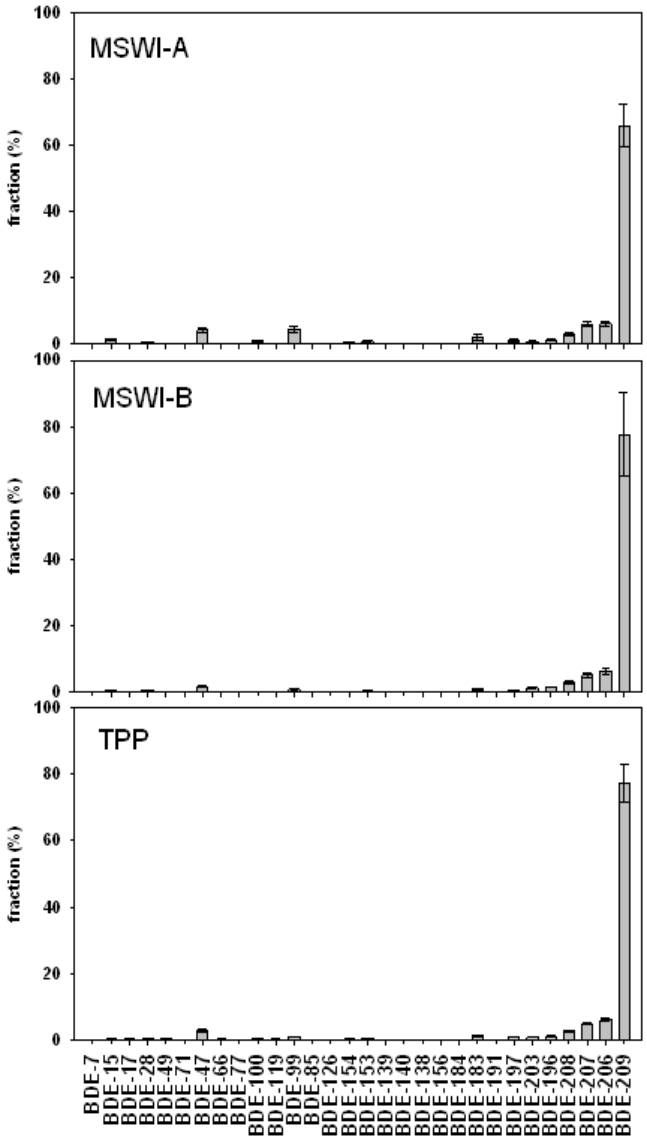

Fig. 1. PBDE congener profiles in the stack flue gases.

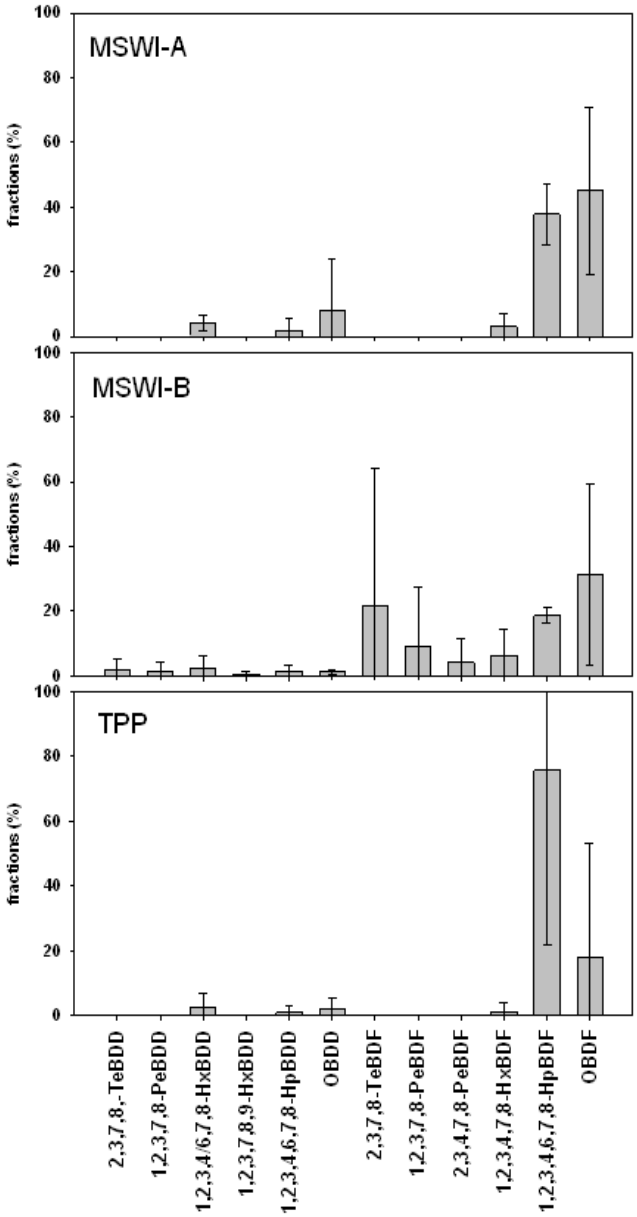

Fig. 2. PBDD/F congener profiles in the stack flue gases.

respectively. The stack flue gases of MSWIs and TPP contained abundances of highly brominated-substituted congeners, like OBDF, and 1,2,3,4,6,7,8-HpCDF, while OBDD, 1,2,3,4,6,7,8-HpBDD were found to be minor. In the case of PBDEs, the most dominant PBDE congeners in the MSWI stack flue gases were highly brominated-substituted congeners, especially BDE-209. All the other species were minor when compared to BDE-209. However, the levels of BDE-154 in the SDA, BF and FAP of MSWI-B were found to be much higher than was the case in any other unit.

Trends of PBDEs and PBDD/Fs among the Ashes

The elevated PBDE content in the BR showed that the PBDEs in the feeding waste may not be completely destroyed, although research (Sakai, *et al.,* 2001) has reported that the

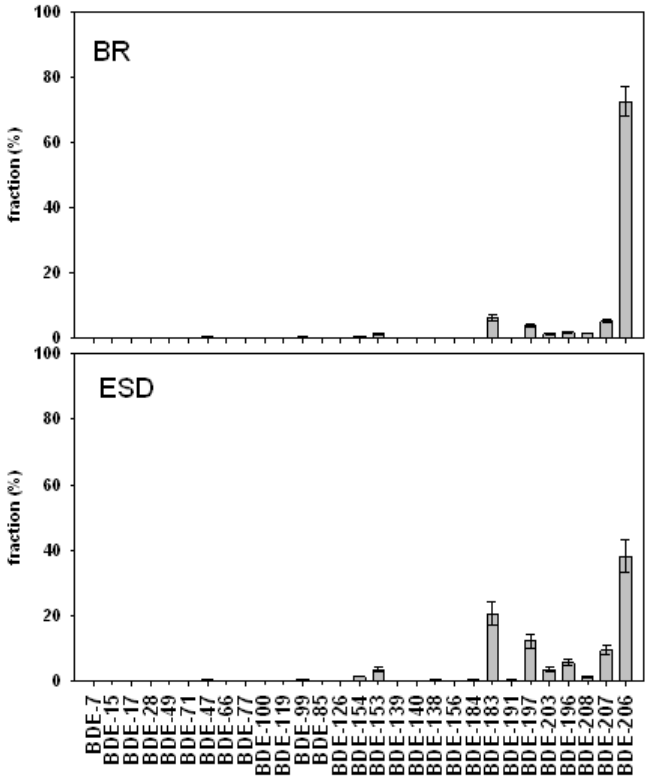

Fig. 3. PBDE congener profiles of the ashes in the TPP operating units

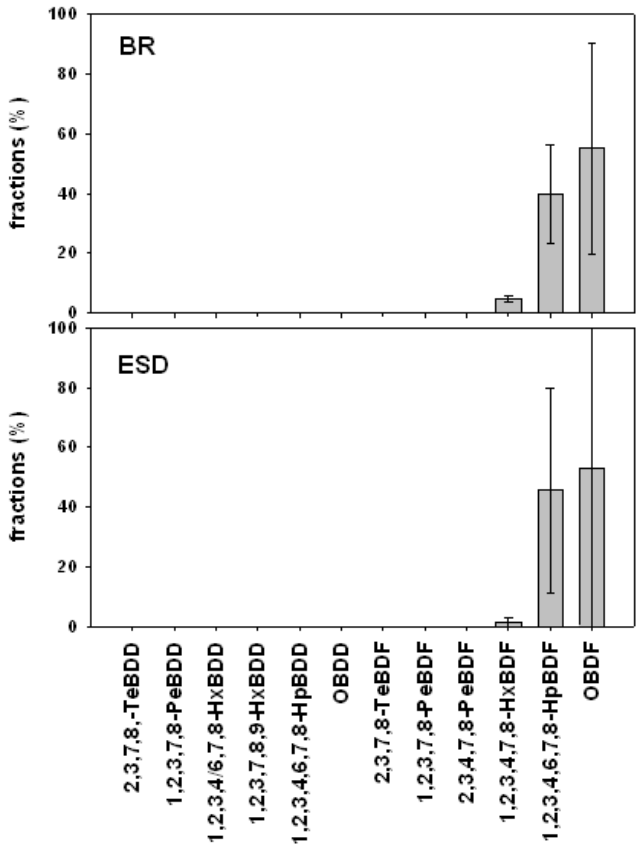

Fig. 4. PBDD/F congener profiles of the ashes in the TPP operating units

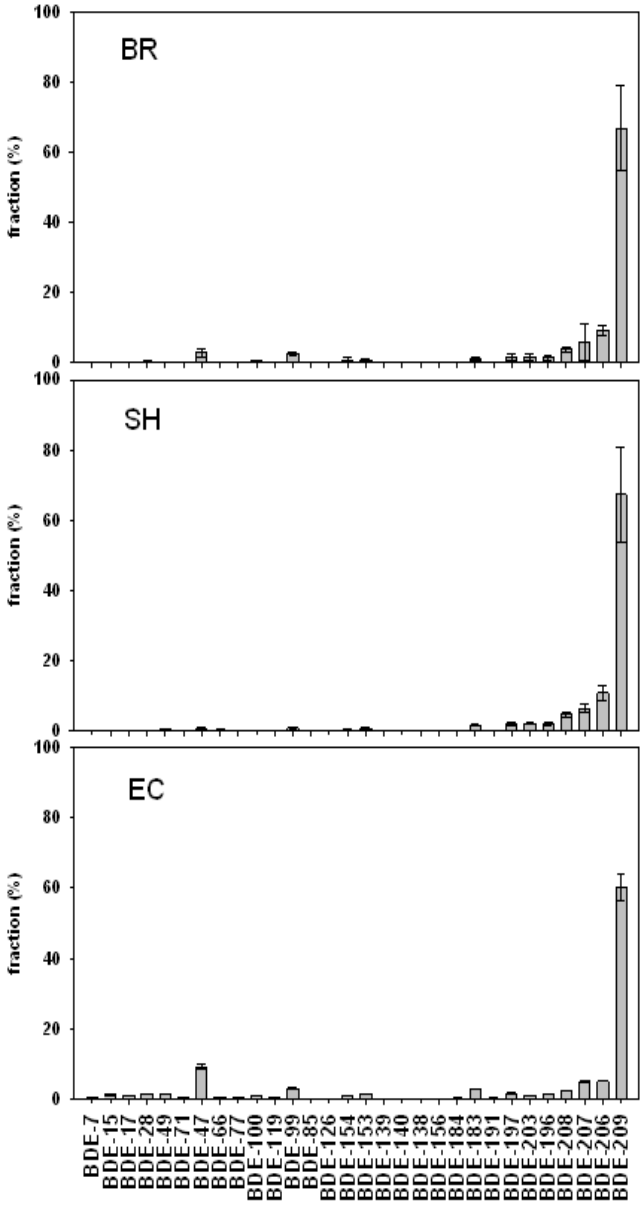

Fig. 5. PBDE congener profiles of the ashes in the MSWI-A operating units (a).

destruction rates of PBDEs has reached 99.9% in a laboratory scale incinerator. The most dominant PBDE congeners in the BR are highly brominated-substituted congeners, especially BDE-209, which is still a common commercial product in the market. The elevated content of PBDD/Fs and PBDE in the BR could be similar, coming from PBDD/F-containing wastes incompletely destroyed. Another reason for the higher PBDD/F contents in the BR could be the pyrolysis and thermolysis of BFR-containing wastes in the furnaces. However, the PBDD/F yields from the thermolysis of Tetrabromobisphenol A (TBBP-A) have been found to be orders of magnitudes lower than that from PBDEs (Weber and Kuch, 2003). The "steric crowding" of bromine atoms in BDE-209 suggest that the formation of the highly brominated-substituted PBDD/Fs from PBDEs was not favorable in BR (Weber and Kuch, 2003). Consequently,

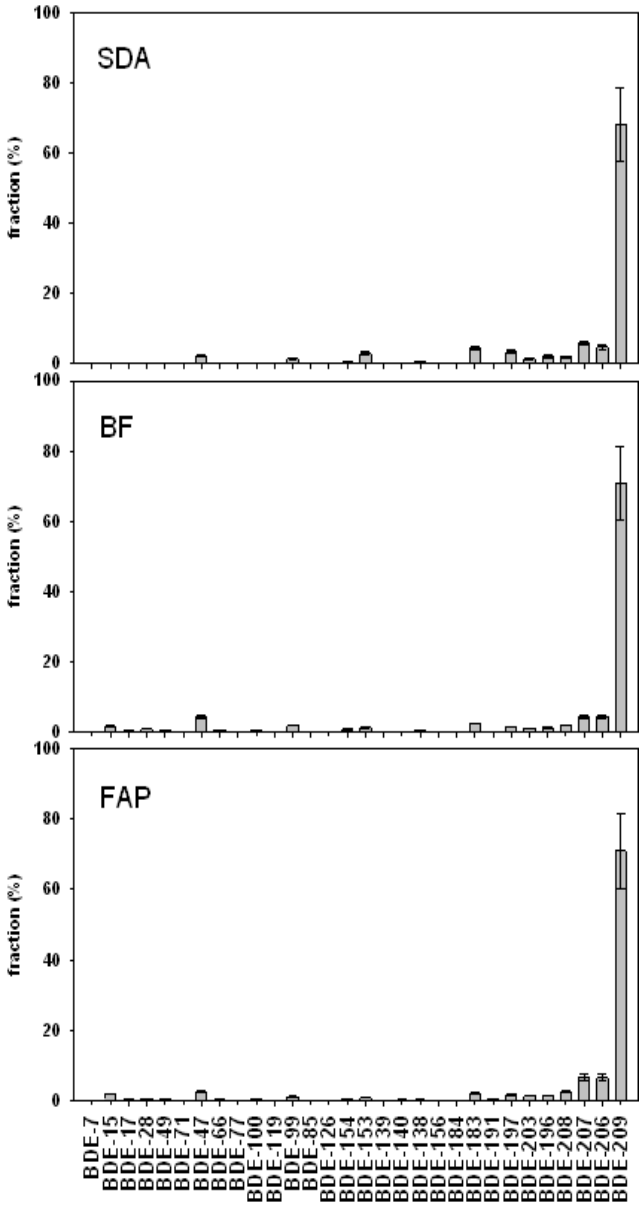

Fig. 6. PBDE congener profiles of the ashes in the MSWI-A operating units (b).

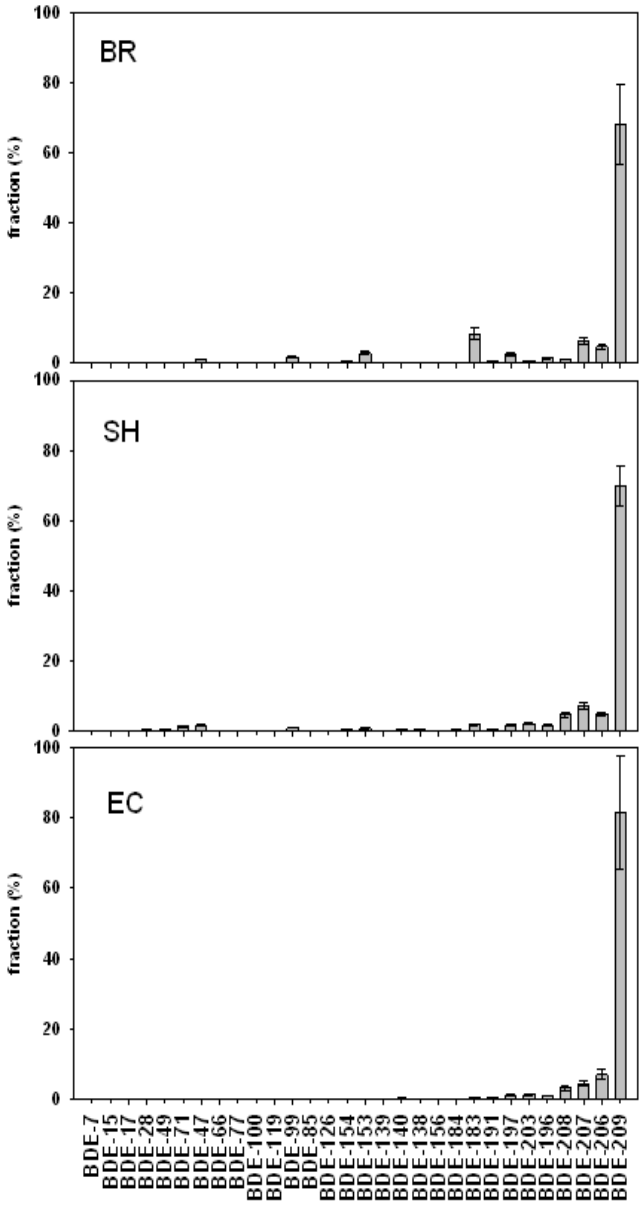

Fig. 7. PBDE congener profiles of the ashes in the MSWI-B operating units (a).

the elevated PBDD/F content in the BR should be the feeding waste containing PBDD/Fs that was not completely destroyed. The remained PBDD/F and PBDE content left in the BR was even higher than that found in the BF containing activated carbon which could adsorb gas-phase PBDD/Fs and PBDEs.

Influence of the Feeding Wastes of the MSWIs

The tremendous differences in PBDE content for MSWIs and TPP proved the feeding characteristics do have a direct influence on the PBDE content in bottom residue, fly ashes, and stack flue gases. In view that no brominated flame retardant was sprayed on the coals burnt as TPP fuel, we speculated that the heat-resistant plastic used in the combustion system of the TPP or the precursor compounds in the coals reacting with gaseous inhalation which may contain bromine-rich sea spray (the TPP is located near the coastline) could be the source of the PBDEs and PBDD/Fs found in the stack flue gas and ash samples. It is possible that the type of the feeding wastes have more influence than the types of furnaces. The higher PBDE content in the TPP ESD as compared to the PBDE content in both MSWIs revealed that operating temperature in the ESD was more suitable for the precursors of PBDEs than for those of BF.

The results showed that further study is needed with regard to reduction of PBDE and PBDD/F contributions from MSWIs and TPP, including the prevention of high PBDE-containing wastes into incinerators, an increase in the removal efficiency of PBDEs and PBDD/Fs by APCDs, and a reduction in PBDE and PBDD/F leaching through reutilization of BR. Vitrification of ashes was proven to be an effective method to stabilize heavy metals (Li *et al*., 2003;

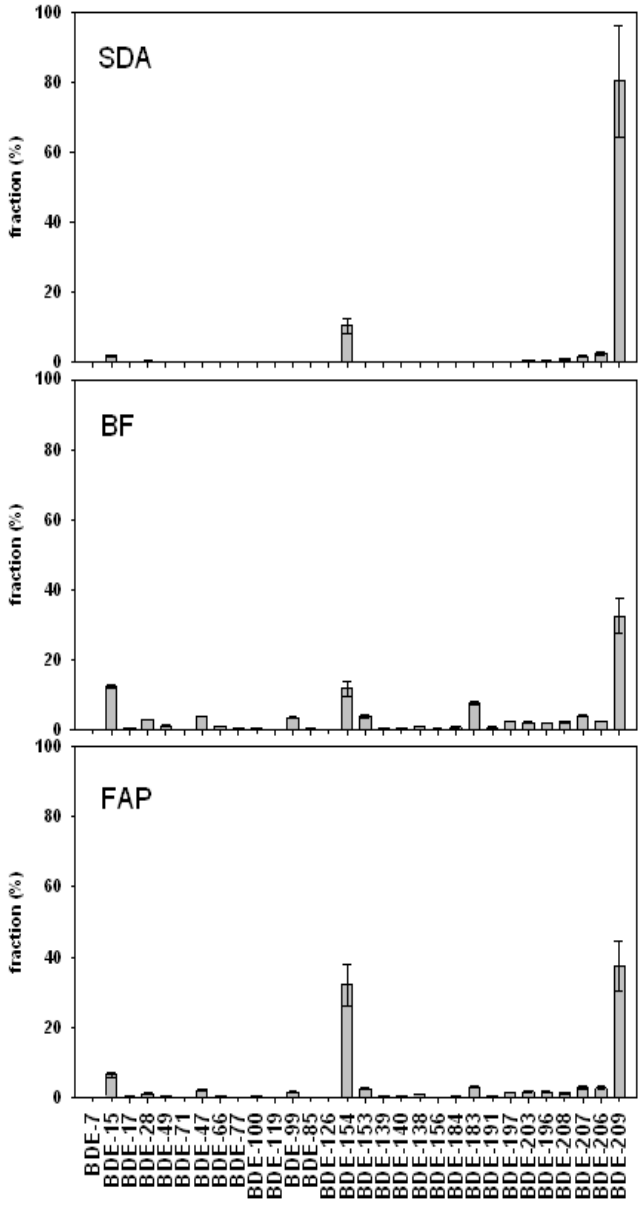

Fig. 8. PBDE congener profiles of the ashes in the MSWI-B operating units (b).

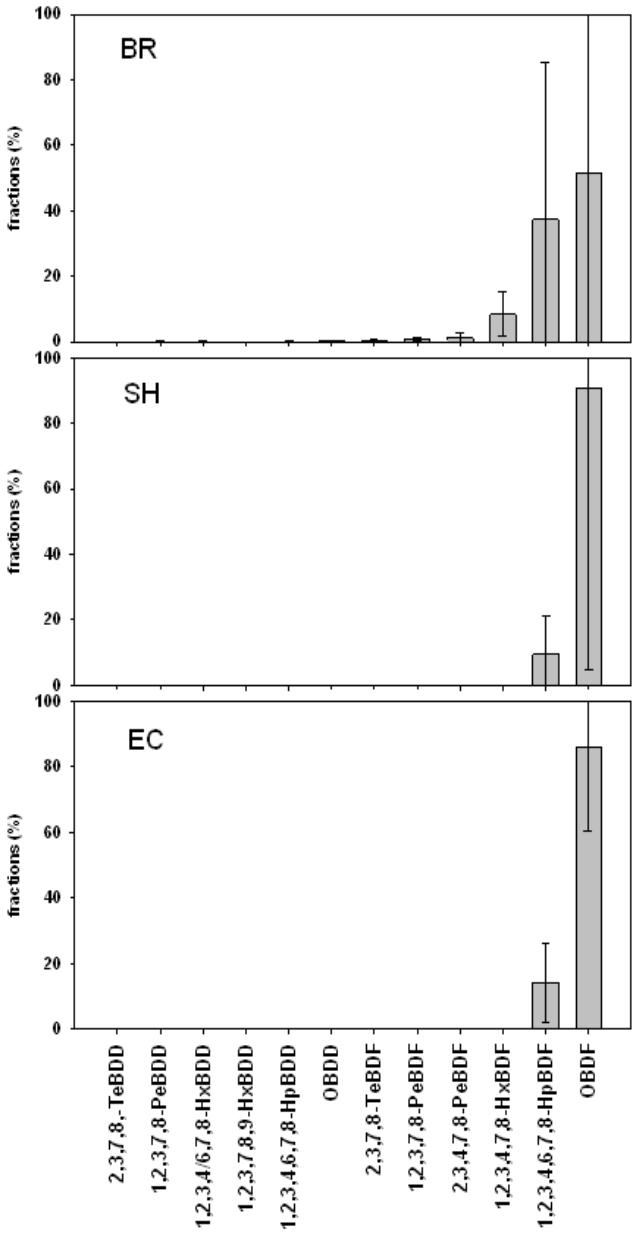

Fig. 9. PBDD/F congener profiles of the ashes in the MSWI-A operating units (a).

Li *et al*., 2007); this technique should be considered to prevent the release of PBDEs in ashes into the environment.

Contribution of PBDEs to the Environment

The PBDD/F emission factors based on the whole system was much smaller than that of the PBDEs, showing that the possible influences on the environment caused by PBDD/Fs is not significant when compared to the impact of PBDEs. Therefore, the potential impact on the environment caused by PBDEs from both MSWIs and TPPs needs further investigation. Although the PBDE content in the TPP stack flue gases was much lower than that of the MSWIs, the PBDE emission rates were 669, 830, and 11900 μg/hr for MSWI-A, MSWI-B, and the TPP, respectively. The summarized PBDE emission factors for the stack flue gases were, i.e., 35.6, and 47.6 μg/ton-waste for MSWI-A and MSWI-B, respectively and 62.9 μg/ton-coal for the TPP. Therefore, the PBDE contribution from TPPs should not be ignored, especially in the gaseous phase. The reutilization of MSWI and TPP BR could transport PBDEs into the environment and therefore should not be ignored from the point of the developing PBDE inventory.

CONCLUSIONS

The elevated PBDE and PBDD/F content in BR indicated that PBDEs in the feeding wastes were not destroyed completely. The bottom residues of combustion chambers exhibited the highest content of PBDEs and PBDD/Fs among all the units. The amount of PBDE mass found in bottom residues constituted 99.7% at MWSI-A, and 92.6%

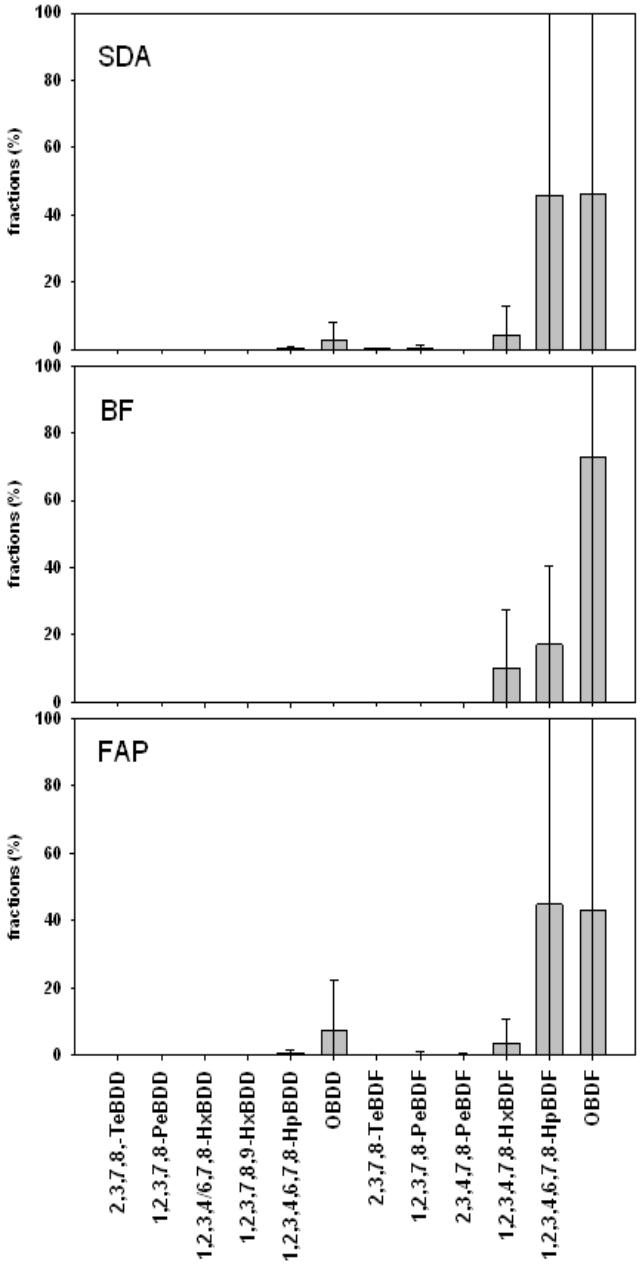

Fig. 10. PBDD/F congener profiles of the ashes in the MSWI-A operating units (b).

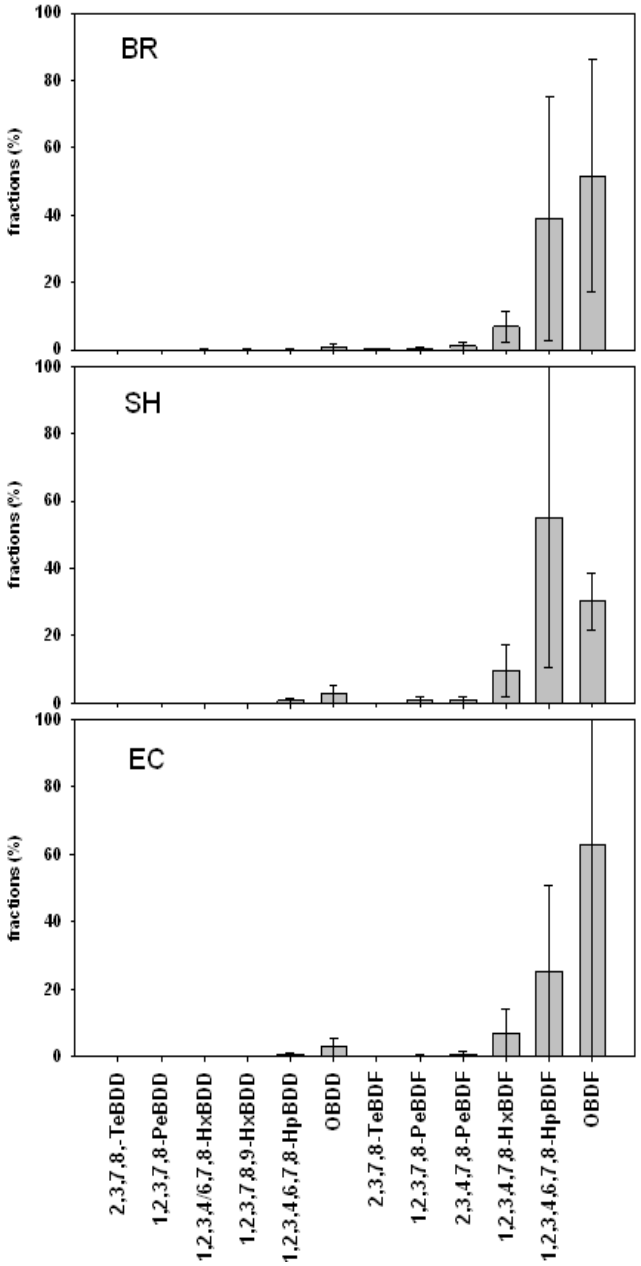

Fig. 11. PBDD/F congener profiles of the ashes in the MSWI-B operating units (a).

at MSWI-B, and 75.1% at TPP of the total PBDE mass discharges, respectively. The second highest PBDE mass observed in MSWI-A and MSWI-B was from the stack flue gases (0.146%) and the economizer (5.54%), respectively, while the PBDE distribution in TPP was 75.1% in BR, 12.5% in ESD, and 12.4% in SFG. Therefore, the bottom residues of MWSI-A, MSWI-B, and TPP accounted for majority of the total PBDE mass discharges. The most pronounced difference between the PBDE discharges from the bottom residues of MSWI-A and MSWI-B and TPP was attributed to the characteristics of feeding materials. The mean concentrations of PBDEs emitted from the stack flue gas of MSWI-A, and MSWI-B were 9.32 ng/Nm^3, and 7.62 ng/Nm^3, respectively; however, that of PBDEs discharged from the stack flue gases of TPP was only 5.43 ng/Nm^3. Meanwhile, the PBDE emission factors from the stack flue gases were 35.6 ± 10.9 μg/ton-waste at MWSI-A, 47.6 ± 29.4 μg/ton-waste at MSWI-B and 62.9 ± 10.9 μg/ton-coal at TPP of the total PBDEs, respectively. The above results show that the PBDE emission rates and contributions of gases of TPP were lower than MSWIs'. The consequences indicated that it is crucial to carefully treat the bottom residues at MWSIs in order to prevent the PBDEs from entering the environment, and the PBDE emission rates from the TPP were also found to be of great significance. Therefore, TPPs should not be ignored in PBDE emission inventories. However, further investigations are still required for the technique of PBDE and PBDD/F controls.

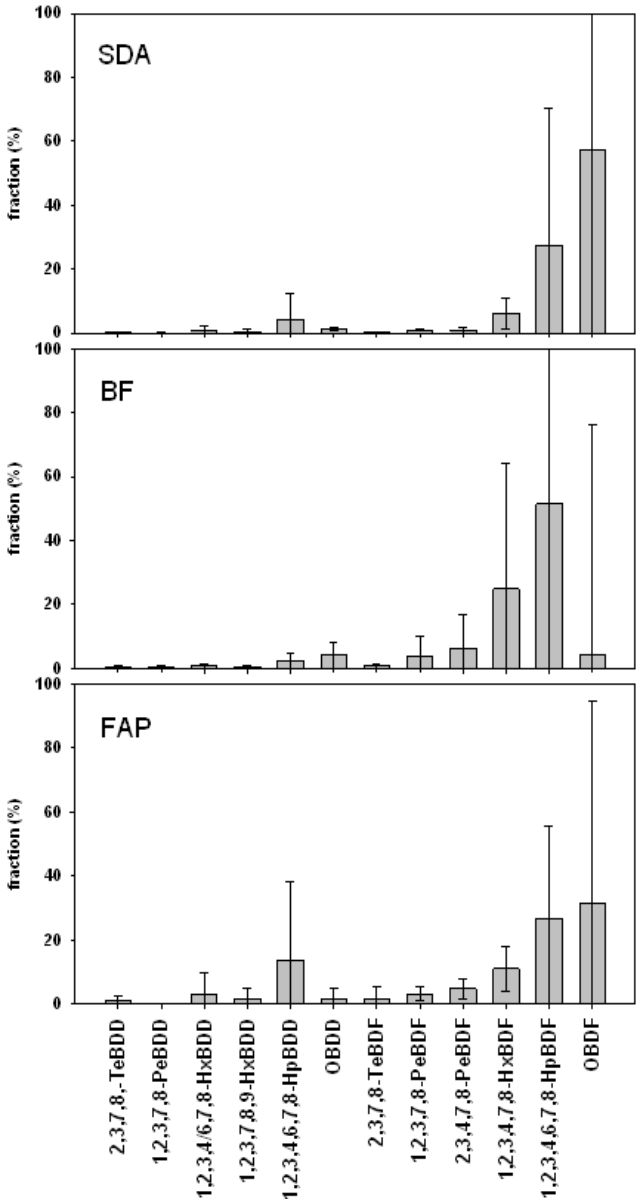

Fig. 12. PBDD/F congener profiles of the ashes in the MSWI-B operating units (b).

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