



## Destruction and formation of PCDD/Fs in a fluidised bed combustor co-incinerating automotive shredder residue with refuse derived fuel and wastewater treatment sludge

J. Van Caneghem<sup>a,\*</sup>, I. Vermeulen<sup>a</sup>, C. Block<sup>a,b</sup>, A. Van Brecht<sup>c</sup>, P. Van Royen<sup>d</sup>, M. Jaspers<sup>d</sup>, G. Wauters<sup>c</sup>, C. Vandecasteele<sup>a</sup>

<sup>a</sup> Department of Chemical Engineering, University of Leuven, W. De Croylaen 46, 3001 Heverlee, Belgium

<sup>b</sup> Leuven Engineering College Group T, Department of Chemical Engineering, Vesaliusstraat 13, 3000 Leuven, Belgium

<sup>c</sup> Indaver NV, Dijle 17a, 2800 Mechelen, Belgium

<sup>d</sup> Indaver NV, Poldervlietweg 5, Haven 550, 2030 Antwerpen, Belgium

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### ABSTRACT

During an eight day trial automotive shredder residue (ASR) was added to the usual waste feed of a Fluidized Bed Combustor (FBC) for waste-to-energy conversion; the input waste mix consisted of 25% ASR, 25% refuse-derived fuel (RDF) and 50% wastewater treatment (WWT) sludge. All inputs and outputs were sampled and the concentration of the 17 PCDD/Fs with TEF-values was determined in order to obtain "PCDD/F fingerprints". The ASR contained approximately 9000 ng PCDD/Fs/kg<sub>DW</sub>, six times more than the RDF and 10 times more than the WWT sludge. The fingerprint of ASR and RDF was dominated by HpCDD and OCDD, which accounted for 90% of the total PCDD/F content, whereas the WWT sludge contained relatively more HpCDFs and OCDF (together 70%). The flue gas cleaning residue (FGCR) and fly and boiler ash contained approximately 30,000 and 2500 ng PCDD/Fs/kg<sub>DW</sub>, respectively. The fingerprints of these outputs were also dominated by HpCDFs and OCDF. The bottom ash contained only OCDD and OCDF, in total 8 ng PCDD/Fs/kg<sub>DW</sub>. From the comparison of the bottom ash fingerprints with the fingerprints of the other output fractions and of the inputs, it could be concluded that the PCDD/Fs in the waste were destroyed and new PCDD/Fs were formed in the post combustion process by de novo synthesis. During the ASR-co-incineration, the PCDD/F congener concentrations in the fly and boiler ash, FGCR and flue gas were 1.25–10 times higher compared to the same output fractions generated during incineration of the usual waste mix (70% RDF and 30% WWT sludge). The concentration of the higher chlorinated PCDD/Fs increased most. As these congeners have the lowest TEF-factors, the total PCDD/F output, expressed in kg TEQ/year, of the FBC did not increase significantly when ASR was co-incinerated. Due to the relatively high copper levels in the ASR, the copper concentrations in the FBCs outputs increased. As copper catalysis the de novo syntheses, this could explain the increase in PCDD/F concentrations in these outputs.

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### 1. Introduction

In a waste incineration process, waste, for the sake of clarity called primary waste, is transformed into other waste, called secondary waste, under emission of CO<sub>2</sub> and pollutants. State-of-the-art waste incineration aims not only at reducing the primary waste volume but also at destroying the toxic organic substances in this waste and at recovering energy. Waste may contain indeed highly toxic persistent organic pollutants (POPs) such as polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans

(PCDD/Fs) and polychlorinated biphenyls (PCBs) and a wide range of other toxic substances e.g., polyaromatic hydrocarbons (PAHs), phthalates and polybrominated diphenylethers (PBDEs) [1–7]. However, during the cooling of the combustion gases, new POPs, mainly PCDD/Fs and PCBs are formed from precursors or through de novo synthesis [2,3,8–11]. These PCDD/Fs and PCBs are not only present in the flue gases emitted at the stack, but also in the secondary waste, predominantly in the fly and boiler ash and in the flue gas cleaning residue (FGCR).

Automotive shredder residue (ASR) is a waste stream known to contain high concentrations of PCDD/Fs, PCBs and also plasticizers such as di-2-ethylhexyl-phtalate (DEHP) [12–15]. ASR is the fraction that remains at the end of the end-of-life vehicle's (ELV's) dismantling and recycling process, typically consisting of

\* Corresponding author. Tel.: +32 16 322353; fax: +32 16 322991.

E-mail address: [jo.vanCaneghem@cit.kuleuven.be](mailto:jo.vanCaneghem@cit.kuleuven.be) (J. Van Caneghem).

dismantling of reusable and/or hazardous parts, shredding of the car hulk followed by mechanical recovery of metals and in some cases plastics. It is a heterogeneous mixture of inert and combustible materials (both representing about 50%) including plastics, glass, fabric, wood, rubber, etc. ASR accounts for 10–25% of the initial ELV's mass and is mostly sent to landfill [16–20]. The European directive 2000/53/EC, which was adopted in 2000, implies a “reuse and recovery” rate for ELVs of 95% to be reached by the year 2015. One of the options to increase the actual average European “reuse and recovery” rate of approximately 78% is incineration of ASR with energy-recovery [16]. In order to investigate the feasibility of co-incineration in an existing installation, ASR was added to the usual waste feed of the SLECO Fluidized Bed Combustor (FBC) for waste-to-energy conversion during an eight day trial. The usual waste feed consists of household and similar non-hazardous waste (in the trial refuse-derived fuel (RDF) was processed) and of wastewater treatment (WWT) sludge. In addition to previous work by Van Caneghem et al. [21], reporting measured PCDD/F, dioxin-like PCB, PCB and PAH concentrations in all input and output streams of the FBC and discussing the mass balance of these pollutants, this paper focuses on the PCDD/F fingerprints of the different input wastes and of the output fractions of the FBC. The objectives are:

- to investigate the differences between the PCDD/F-fingerprints of the inputs (RDF, WWT sludge and ASR)
- to investigate the differences between the PCDD/F-fingerprints of these inputs and the PCDD/F-fingerprints of the outputs (fly and boiler ash, FGCR, flue gas and bottom ash) of the FBC, in order to check the theory that the PCDD/Fs in the waste are destroyed during incineration and that in the flue gases new PCDD/Fs are formed
- to determine the major PCDD/F formation mechanism
- to investigate the influence of the high PCDD/F and copper concentration in the ASR on the PCDD/F-fingerprint of the output streams

## 2. Methods and materials

### 2.1. Installation

The installation in which the experiment was carried out was described in previous work of the authors [21,22]. In the FBC high calorific RDF from mechanical biological treatment of municipal solid waste (MSW) affords the heat necessary for drying and incinerating low calorific WWT sludge and for steam and electricity generation. The installation, constructed in 2005–2006 in Doel in Flanders, Belgium, has an annual capacity of  $466 \times 10^3$  t of mixed waste, making it the largest and most recent FBC built for this purpose in Europe. In 2008,  $313 \times 10^3$  t of RDF and  $134 \times 10^3$  t of WWT sludge (on average 25% of dry matter) were incinerated. The FBC is of the ROWITEC internal rotating fluid bed type in which a sand mass is fluidized by hot air. The RDF is shredded and iron parts are removed before it is introduced in the fluidized sand bed, together with the WWT sludge. In the freeboard, a gas temperature of at least 850 °C, a residence time of at least 2 s and an oxygen excess of at least 6% are maintained to ensure proper burn-out. The energy is recovered in a vertical boiler. The produced superheated steam (40 bar, 400 °C) is sent to a turbine (capacity of 34 MW) for electricity production. The flue gas is dedusted in an electrostatic precipitator and flows through a flue gas cleaning installation consisting of a semi-dry Circoclear reactor, a baghouse filter and a caustic soda scrubber. A mixture of clay and activated carbon particles (Dioxorb<sup>®</sup>) is injected in the semi-dry reactor to adsorb PCDD/Fs. At the bottom of the FBC, the sand and ashes are removed after which the sand is sieved of and sent back into the incinerator.

### 2.2. Input waste streams

The RDF incinerated in the FBC is one of the remaining fractions of mechanical biological treatment of Flemish MSW. In Flanders, separate collection systems exist for organic kitchen and garden waste, glass, paper and cardboard, metal packaging (tins and cans), drink packaging and hazardous wastes (e.g., motor oil, batteries, paint, pesticides, solvents). The “residual household waste” consists mainly of non-sorted organic waste (approximately 30%), plastic packaging (approximately 15%) and paper and cardboard (approximately 10%) [23]. It is generally incinerated directly, typically in a grate furnace, but part of it undergoes mechanical biological treatment (MBT). The MBT-process of interest here, consists of biological drying (the shredded waste is put in an insulated bunker during one week and is dried by the heat resulting from largely aerobic biological activity) during which the mass is reduced by 25–30%, followed by mechanical, magnetic, eddy-current and hand separation. The resulting output streams are inert materials (sand, china, glass) accounting for 10–15% of the initial waste mass, metals (5% of the initial waste mass) and RDF containing mainly plastics, paper and dried organic material (55% of the initial waste mass). The RDF “as received (AR)” has an average lower heating value (LHV) of 12 MJ/kg.

The second waste stream incinerated in the FBC is WWT sludge. Approximately  $270 \times 10^3$  t (dry matter) of sludge are produced in Flanders each year, approximately 37% is sewage water treatment sludge and approximately 47% is industrial WWT sludge. On average, 69% of the sludge is (co-) incinerated [24]. The sludge incinerated in the FBC mainly comes from industrial and municipal biological wastewater treatment plants. It is a mixture of dewatered and digested sludge with an average dry matter content of 24%. The average LHV (AR) of the sludge incinerated in the FBC is 2 MJ/kg.

The co-incinerated ASR consists of the “heavy” ASR fraction, which is the remaining fraction after separation of ferrous, non-ferrous and plastic materials and does not include the fluff collected by the air suction installation at the main shredder. It contains a mixture of combustible (mainly PU-foam, plastic fibres and foil) and inert materials (sand, small stones, iron and rust particles). The ASR particle size was reduced in order to make it suitable for injection in the FBC. The average ash content of the incinerated ASR is 53%, the average LHV (AR) is 19 MJ/kg.

In order to maintain a stable temperature in the steam boiler, practice has shown that the input waste mix should have a LHV (AR) of approximately 8.5 MJ/kg. During the co-incineration experiment this was obtained by mixing 25% (mass%) RDF, 25% ASR and 50% of WWT sludge. The usual waste mix of the FBC consists of 70% RDF and 30% WWT sludge.

### 2.3. Sampling and analysis

The concentration of the 7 PCDDs and 10 PCDFs with TEF-values was determined on samples taken on site of the FBC plant during the experimental co-incineration of ASR, conducted from 17 to 24 November 2008.

The flue gas was monitored with equipment located on a measuring platform at the stack. The flue gases were sampled continuously during the eight days of the trial using sampling equipment of the AMESA (Adsorption Method for Sampling) type, according to the EN 1948-1 standard as described in [25]. PCDD/Fs were subsequently determined by a certified laboratory by GC-MS according to the EN 1948-2 standard. Clean-up was performed using a multi-layer column of modified silica gel, followed by an aluminium oxide and activated carbon column. The detection limit was 0.001 ng/Nm<sup>3</sup>. The certified laboratory has to participate

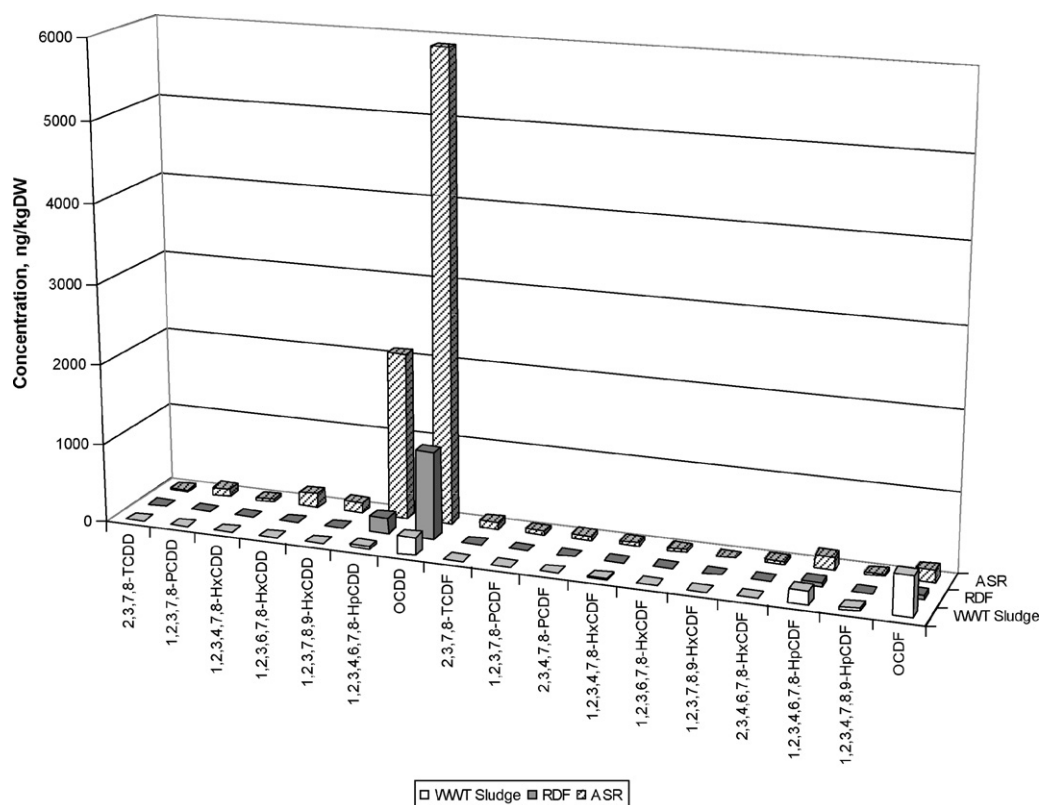


Fig. 1. PCDD/F congener concentrations in the different input wastes of the FBC.

regularly in government-organised inter-comparisons in order to demonstrate quality.

The different waste types incinerated in the FBC were already mixed and homogenized at the production location before transport to the plant. On both 18 and 20 November 2008, a representative 5-l sample was taken from each truck load of the waste streams. On each day, about 20, 25 and 50 truck loads of ASR, RDF and WWT sludge were delivered, respectively. At the end of the day, the samples of each waste stream were thoroughly mixed and shredded. Part of this shredded mixture was sent to the certified lab for analysis. In this way, the measured POP concentrations could be considered average concentrations for the wastes delivered that day. In the FBC the input wastes are thoroughly mixed and the solid residues of the combustion process are representative of this mixture. On 18 and 20 November 2008, the residues were sampled at different times and the samples were mixed thoroughly before analysis. PCDD/F concentrations were determined by GC–MS after soxhlet extraction according to the German AbfKlärV, Annex1 [26]. The detection limit was 1 ng/kg<sub>DW</sub>.

### 3. Results and discussion

#### 3.1. PCDD/F fingerprints of the input wastes

During the eight day trial, a mixture of 25% ASR, 25% RDF and 50% WWT sludge was incinerated in the FBC. Fig. 1 shows the individual concentration (ng/kg<sub>DW</sub>) of the 17 PCDD/F congeners in these three waste types. Because of the large differences in the congener concentrations in the ASR and WWT sludge, Fig. 2 also shows these concentrations expressed as a percentage of the total PCDD/F concentration in the respective waste types. The ASR contains approximately 9000 ng PCDD/Fs/kg<sub>DW</sub>, six times more than the RDF

and 10 times more than the WWT sludge. The PCDD/F-fingerprint of the ASR is clearly dominated by the higher chlorinated PCDD congeners. Indeed, approximately 90% of the total PCDD/F content of the ASR is accounted for by hepta- and octa-CDD; the PCDFs represent only approximately 3%, with hepta-CDFs and octa-CDF being most abundant. The PCDD/F-fingerprint of the RDF is very similar to the one of ASR: only hepta-CDD (approximately 14%), octa-CDD (approximately 78%), 1,2,3,4,6,7,8-heptaCDF (approximately 4%) and octa-CDF (approximately 4%) are present in concentrations above the detection limit. Hedman et al. [27] reported a PCDD/F fingerprint of the textile and leather fraction of RDF from MSW and the relative contribution of the different congeners to the total PCDD/F content corresponds very well to the PCDD/F fingerprints of the ASR and RDF reported here. In general ASR can contain up to 40% of textile and leather, which suggests that this fraction might be an important contamination source of PCDD/Fs in ASR [20,28,29]. The RDF analysed by Hedman et al. [27] contained on average 13% textile and leather, and because of the high PCDD/F concentrations in this fraction (expected to originate from pentachlorophenol which is used as fungicide and is often contaminated by PCDD/Fs [30]), it contributed for about 91% to the total PCDD/F content of the RDF. As the amount of textile and leather (%) in the RDF incinerated during the co-incineration trial was not determined, it is difficult to evaluate whether also in this case textile and leather are the dominant PCDD/F contamination sources. The fingerprint of the ASR (Fig. 2) also corresponds well to the PCDD/F fingerprint of diesel exhaust reported by Chang et al. [31], indicating that these exhausts could be another important contamination source.

In contrast to the ASR and RDF, the PCDD/F fingerprint of sludge is dominated by PCDFs (representing approximately 70% of the total PCDD/F content), with hepta- and octa-CDF being the most important congeners, indicating that WWT

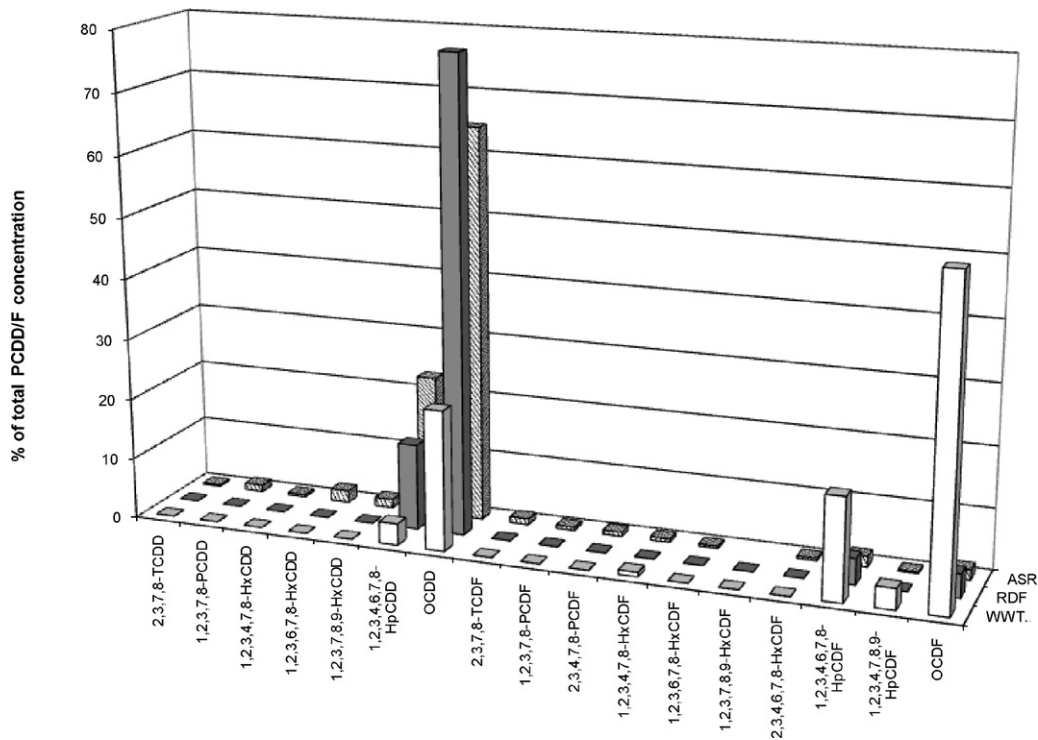


Fig. 2. Relative contribution of PCDD/F congeners to the total PCDD/F concentration in the different input wastes of the FBC.

sludge is contaminated by other PCDD/F sources than ASR and RDF.

### 3.2. PCDD/F fingerprints of the incinerator outputs

Figs. 3 and 4 give the PCDD/F fingerprints of the different output fractions generated in the FBC during the ASR co-incineration trial. The FGCR and fly and boiler ash contain the highest amounts of PCDD/F: approximately 30,000 and 2500 ng/kg<sub>DW</sub>, corresponding to approximately 1600 and 25 ng TEQ/kg<sub>DW</sub>, respectively. The PCDD/F fingerprints of these outputs are dominated by PCDFs, mainly hepta- (approximately 20%) and octa-CDF (approximately 45%), which makes them very similar to the PCDD/F-fingerprint of the sludge, but significantly different from PCDD/F fingerprints of the RDF and ASR (Figs. 1 and 2). The similarity between the PCDD/F-fingerprints of the fly and boiler ash and of the FGCR, and the PCDD/F-fingerprint of WWT sludge could indicate that the latter is contaminated by particulate emissions of incineration processes without flue gas cleaning, such as open fires. The total PCDD/F-concentration in the flue gas was approximately 0.1 ng/Nm<sup>3</sup>, corresponding to 0.007 ng TEQ/Nm<sup>3</sup>, which is well below the legal limit value of 0.1 ng TEQ/Nm<sup>3</sup>. The PCDDs and PCDFs each account for 50% of the total PCDD/F emission and again the higher chlorinated congeners are dominant. The bottom ash contained approximately 8 ng PCDD/Fs/kg<sub>DW</sub>. The PCDD/F-fingerprint of the bottom ash differs from the one of the other output streams: only octa-CDD (approximately 80%) and octa-CDF (approximately 20%) are present above the detection limit. As octa-CDD and octa-CDF are the most dominant dioxin and furan congeners in the waste mix, respectively, it seems reasonable to assume that they are not newly formed but remain from the PCDD/Fs in the incinerated waste. From the comparison of the input and bottom ash fingerprints with the fingerprints of the other output fractions, it can be concluded that the PCDD/Fs in the waste are destroyed. The PCDD/Fs in the fly and boiler ash, FGCR and flue gas are newly

formed in the post combustion process. In the flue gas, fly ash and FGCR, the PCDF/PCDD ratio was 1 or higher, indicating that de novo synthesis and not homogeneous or heterogeneous formation through precursors is the dominant formation mechanism [9–11,32–34].

### 3.3. Influence of the high PCDD/F and copper concentration in the ASR on the PCDD/F-fingerprint of the outputs

The average copper concentration in the ASR, RDF and WWT sludge samples taken during the trial was 5940, 310 and 190 mg/kg<sub>DW</sub>, respectively. Due to the relatively high copper concentration in the ASR, the waste mix incinerated during the co-incineration trial contained about 7.5 times more copper than the usual waste mix of 70% RDF and 30% WWT sludge. It was proven that copper is a catalyst of the de novo synthesis [35–38] and the question could be asked whether the increase of copper concentration of the waste mix would enhance PCDD/F formation during the post combustion stage.

Fig. 5 compares the PCDD/F fingerprints of the fly and boiler ash, the FGCR, the flue gas and the bottom ash generated during the trial co-incineration of ASR and during incineration of the usual waste feed. In the fly and boiler ash generated during ASR co-incineration, the PCDD/F concentrations were 3–10 times higher than in the fly and boiler ash generated during incineration of the usual waste mix (Fig. 5a). The highest increase was noted for HpCDD and OCDD, which are also the dominant congeners in the ASR. This could indicate that very fine ASR particles were elutriated from the fluidised bed and were collected together with the fly and boiler ash. The fact that the average copper concentration increased about two times more in the fly and boiler ash than in the bottom ash, sustains this elutriation theory.

In the FGCR, the PCDD/F congener concentrations increase approximately by a factor 2 (Fig. 5b). Fig. 5c shows that the PCDD/F congener concentrations in flue gas emitted during the



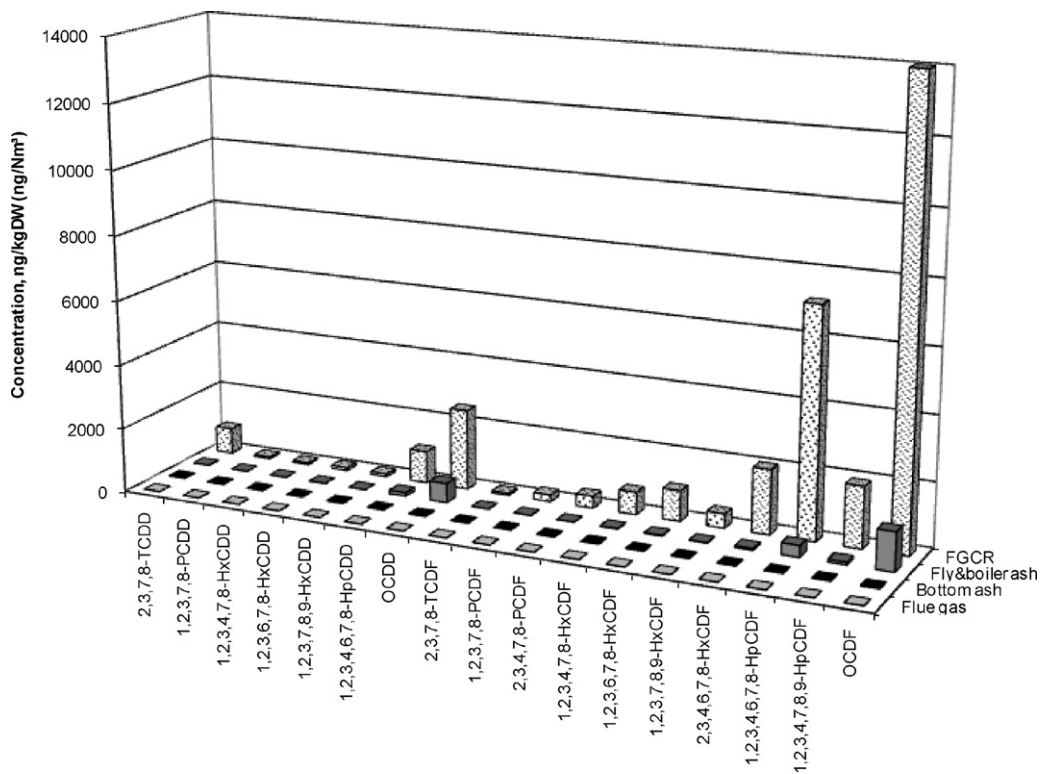


Fig. 3. PCDD/F congener concentrations in the different outputs of the FBC.

co-incineration trial are on average 25% higher than the PCDD/F congener concentrations in the flue gas emitted during incineration of the usual waste mix. In the bottom ash, only the concentration of OCDD and OCDF could be compared (Fig. 5d), and both concentrations were lower in the bottom ash gen-

erated during the co-incineration trial. This indicates that the PCDD/F destruction efficiency of the FBC did not depend on the PCDD/F concentrations in the input waste mix (which were approximately 3 times higher during the ASR co-incineration trial).

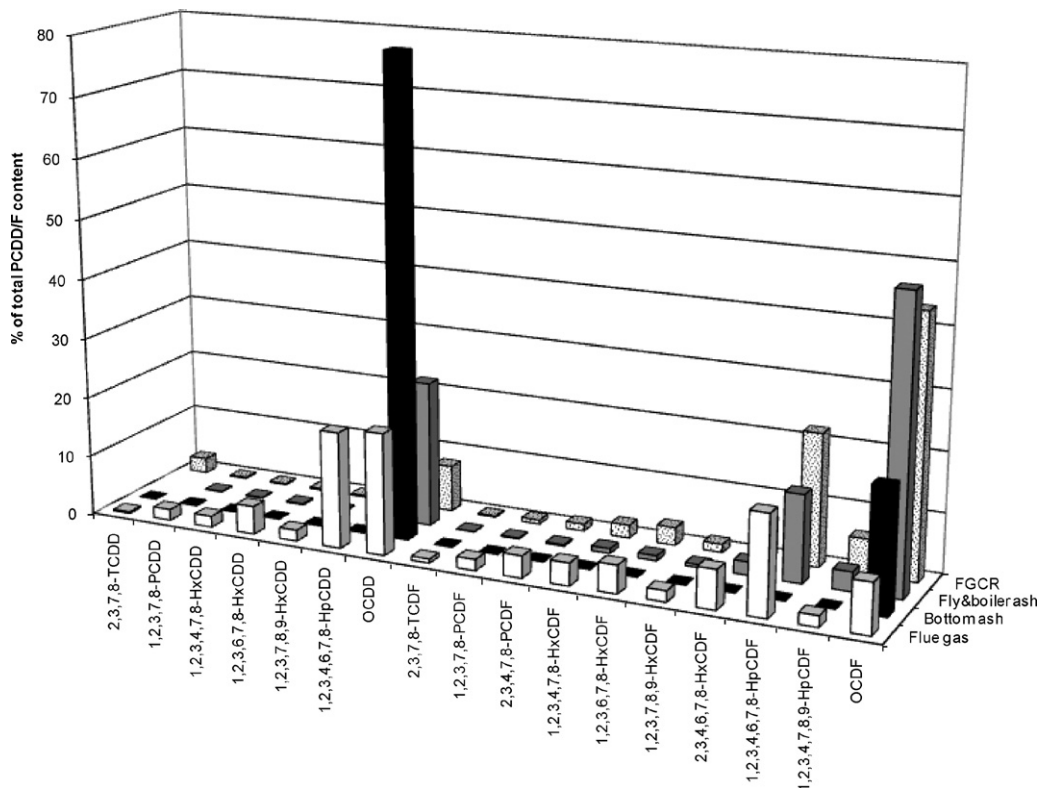
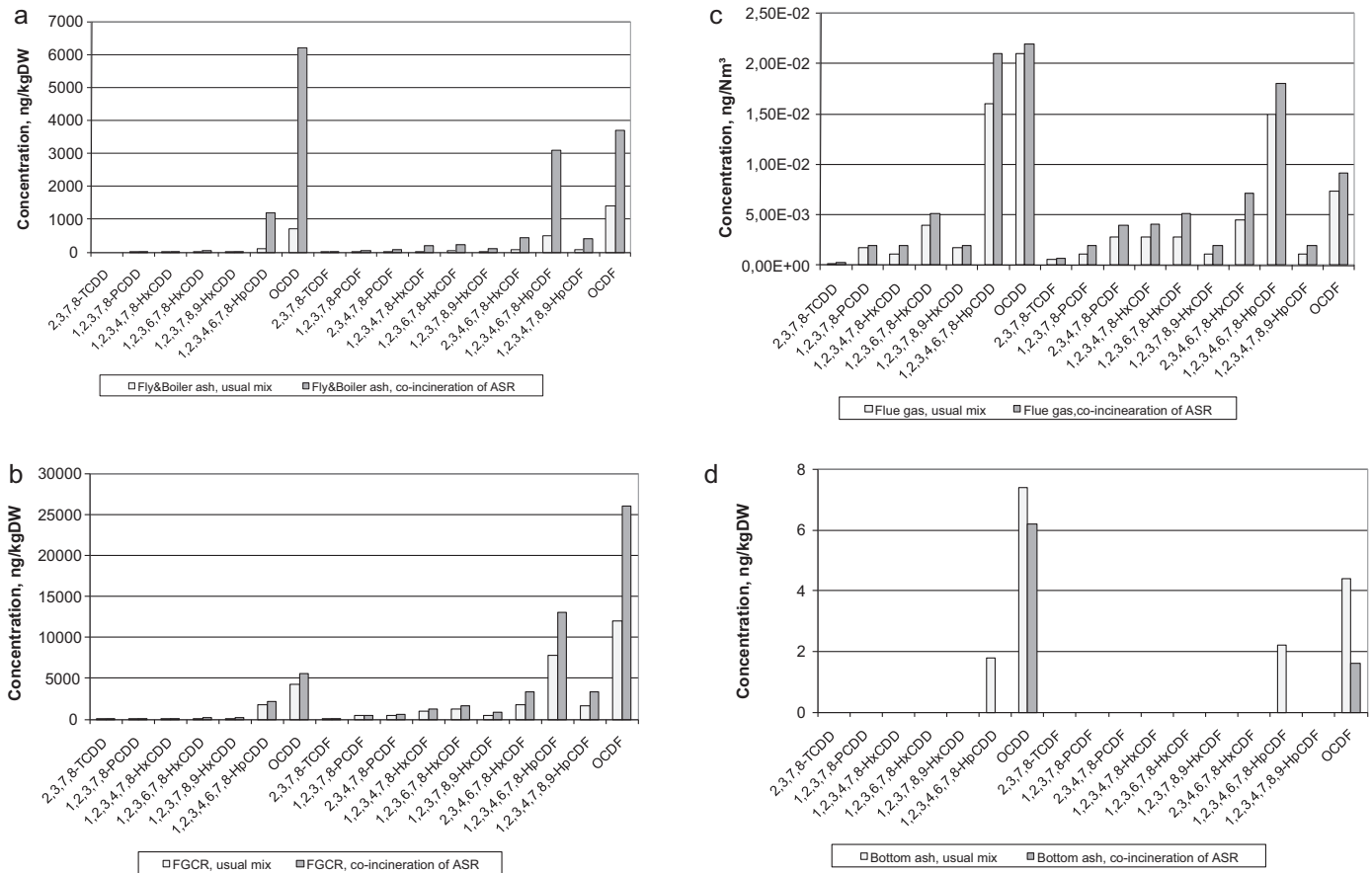


Fig. 4. Relative contribution of PCDD/F congeners to the total PCDD/F concentration in the different outputs of the FBC.



**Fig. 5.** Comparison of PCDD/F congener concentrations in the different outputs of the FBC generated during trial co-incineration of ASR and during incineration of the usual waste mix.

In the fly and boiler ash and the FGCR, the concentration of the higher chlorinated PCDD/Fs increased most. As these congeners have the lowest TEF-factors, the total PCDD/F output, expressed in kg TEQ/year, of the FBC did not increase significantly when ASR was co-incinerated [21].

#### 4. Conclusions

During an eight day trial ASR was added to the normal waste feed of a real scale FBC for waste-to-energy conversion. The normal waste feed consists of a mixture of RDF and WWT sludge. All inputs and outputs were sampled and the concentration of the 17 PCDD/Fs with TEF-factors was determined in order to obtain “PCDD/F fingerprints”.

From the comparison of the fingerprints of the input wastes it could be concluded that ASR contained the highest PCDD/F concentrations. The fingerprint of ASR and RDF was dominated by OCDD and HpCDD, whereas the WWT sludge contained relatively more HpCDFs and OCDF. Of the output fractions, the FGCR contained the highest PCDD/F concentrations. The fingerprints of the fly and boiler ash and the FGCR were dominated by HpCDFs and OCDF.

From the comparison of the input and bottom ash fingerprints with the fingerprints of the other output fractions, it could be concluded that the PCDD/Fs in the waste were destroyed. The PCDD/Fs in the fly and boiler ash, FGCR and flue gas were newly formed in the post combustion process. The PCDF/PCDD ratio of the fly and boiler ash, FGCR and flue gas is higher than 1, indicating that de novo synthesis is the dominant PCDD/F formation mechanism.

ASR contains relatively high concentrations of copper, which is a known catalyst in de novo synthesis. The PCDD/F congener concen-

trations were 1.25–10 times higher in the fly and boiler ash, FGCR and flue gas generated during the ASR-co-incineration compared to the same output fractions generated during incineration of the usual waste mix. The fact that ASR contains relatively high copper levels and that HpCDD and OCDD (the dominant congeners in the ASR) were the congeners with the highest concentration increase in the fly and boiler ash could indicate that very fine ASR particles were elutriated from the fluidised bed. In order to sustain this theory, further research including PCDD/F and copper analysis on different size fractions of the ASR will be carried out.

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#### References

- [1] L. Wilken, B. Cornelsen, B. Zeschmar-Lahl, J. Jäger, Distribution of PCDD/PCDF and other organochlorine compounds in different municipal solid waste fractions, *Chemosphere* 25 (1992) 1517–1523.
- [2] S. Sakai, T. Ukai, H. Takatsuki, K. Nakamura, S. Kinoshita, T. Takasuga, Substance flow analysis of coplanar PCBs released from waste incineration processes, *J. Mater. Cycles Waste* 1 (1999) 62–74.
- [3] E. Abad, A. Adrados, J. Caixach, J. Rivera, Dioxin abatement strategies and mass balance at a municipal waste management plant, *Environ. Sci. Technol.* 36 (2002) 92–99.
- [4] J. Moeller, U. Reeh, Degradation of DEPH, PAHs and LAS in source separated MSW and sewage sludge during composting, *Compost Sci. Util.* 11 (2003) 370–378.

- [5] L. Tange, D. Drohmann, Waste electrical and electronic equipment plastics with brominated flame retardants – from legislation to separate treatment – thermal processes, *Polym. Degrad. Stabil.* 88 (2005) 35–40.
- [6] Y. Ishikawa, Y. Noma, Y. Mori, S. Sakai, Congener profiles of PCB and a proposed new set of indicator congeners, *Chemosphere* 67 (2007) 1838–1851.
- [7] M. Schlummer, L. Gruber, A. Märer, G. Wolz, R. van Eldik, Characterisation of polymer fractions from electrical and electronic equipment (WEEE) and implications for waste management, *Chemosphere* 67 (2007) 1866–1876.
- [8] E. Abad, M. Adrados, J. Caixach, B. Fabrellas, J. Rivera, Dioxin mass balance in a municipal waste incinerator, *Chemosphere* 40 (2000) 1143–1147.
- [9] K. Everaert, J. Baeyens, The formation and emission of dioxins in large scale thermal processes, *Chemosphere* 46 (2002) 439–448.
- [10] G. McKay, Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review, *Chem. Eng. J.* 86 (2002) 343–368.
- [11] M. Altarawneh, Z. Dlugogorski, E. Kennedy, J. Mackie, Mechanisms for formation, chlorination, dechlorination and destruction of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), *Prog. Energy Combust. Sci.* 35 (2009) 245–274.
- [12] F. Mark, M. Fischer, K. Smith, Energy recovery from automotive shredder residue through co-combustion with municipal solid waste, *Plastics Europe Technical Report 8026*, 1998.
- [13] S. Sakai, H. Takatsuki, S. Urano, Leaching behaviour of persistent organic pollutants in shredder residues, *Chemosphere* 37 (1998) 2047–2054.
- [14] L. Börjesson, G. Löfvenius, M. Hjelt, S. Johansson, S. Marklund, Characterization of automotive shredder residues from two shredding facilities with different refining processes in Sweden, *Waste Manage. Res.* 18 (2000) 358–366.
- [15] L. Aae Redin, M. Hjelt, S. Marklund, Co-combustion of shredder residues and municipal solid waste in a Swedish municipal solid waste incinerator, *Waste Manage. Res.* 19 (2001) 518–525.
- [16] Eurostat, End-of-Life Vehicles, Data, 2006, Available from <http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/wastestreams/elvs> (accessed 02.11.08.).
- [17] P. Ferrão, P. Nazareth, J. Amaral, Strategies for meeting EU End-of-life vehicle reuse/recovery targets, *J. Ind. Ecol.* 10 (2006) 77–93.
- [18] C.A. Ambrose, R. Hooper, A.K. Potter, M.M. Singh, Diversion from landfill: quality products from valuable plastics, *Resour. Conserv. Recycl.* 36 (2002) 309–318.
- [19] M. Nourreddine, Recycling of auto shredder residue, *J. Hazard. Mater.* A139 (2007) 481–490.
- [20] L. Morselli, A. Santini, F. Passarini, I. Vassura, Automotive shredder residue (ASR) characterization for a valuable management, *Waste Manage.* 30 (2010) 2228–2234.
- [21] J. Van Caneghem, C. Block, A. Van Brecht, P. Van Royen, M. Jaspers, G. Wauters, C. Vandecasteele, Mass balance for POPs in a real scale fluidised bed combustor co-incinerating automotive shredder residue, *J. Hazard. Mater.* 181 (2010) 827–835.
- [22] C. Vandecasteele, C. Bock, Industrial processes for (domestic and industrial) waste incineration, in: *Waste Recovery – Strategies, Techniques and Applications in Europe*, FrancoAngeli, Italy, 2009.
- [23] OVAM, Sorting Analysis – Research Household Waste, Flemish Waste Agency, Mechelen, 2008 (in Dutch).
- [24] OVAM, Progress Reporting 2005–2006 Sludge Execution Plan, Flemish Waste Agency, Mechelen, 2008 (in Dutch).
- [25] J. Van Caneghem, C. Block, A. Van Brecht, G. Wauters, C. Vandecasteele, Mass balance for POPs in hazardous and municipal solid waste incinerators, *Chemosphere* 78 (2010) 701–708.
- [26] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Ordinance on Waste and Sewage Sludge (AbfklärV). Annex 1: Sampling, Sample Preparation and Analysis of Sludge and Soil, 2006.
- [27] B. Hedman, J. Burvall, C. Nilsson, S. Marklund, PCDD/F in source-sorted waste fractions and emissions from their co-combustion with reed canary-grass, *Waste Manage.* 27 (2007) 1580–1592.
- [28] I.H. Hwang, T. Matsuto, N. Tanaka, Y. Sasaki, K. Tanaami, Characterization of char derived from various types of solid wastes from the standpoint of fuel recovery and pretreatment before landfilling, *Waste Manage.* 27 (2007) 1155–1166.
- [29] H.T. Joung, S.J. Cho, Y.C. Seo, W.H. Kim, Status of recycling end-of-life vehicles and efforts to reduce automobile shredder residues in Korea, *J. Mater. Cycles Waste Manage.* 9 (2007) 159–166.
- [30] M. Horstmann, M.S. McLachlan, Results of an initial survey of polychlorinated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF) in textiles, *Chemosphere* 31 (1995) 2579–2589.
- [31] M. Chang, S. Chang, Y. Chen, H. Hsu, Dioxin emission factors for automobiles from tunnel air sampling in Northern Taiwan, *Sci. Total Environ.* 325 (2004) 129–138.
- [32] E. Grandesso, S. Ryan, B. Gullet, A. Touati, E. Collina, M. Lasagni, D. Pitea, Kinetic modelling of polychlorinated dibenzo-p-dioxin and dibenzofuran formation based on carbon degradation reactions, *Environ. Sci. Technol.* 42 (2008) 7218–7224.
- [33] H. Huang, A. Buekens, On the mechanisms of dioxin formation in combustion processes, *Chemosphere* 31 (1995) 4099–4117.
- [34] E. Wickström, S. Ryan, A. Touati, B.K. Gullet, Key parameters for de novo formation of polychlorinated dibenzo-p-dioxins and dibenzofurans, *Environ. Sci. Technol.* 37 (2003) 1962–1970.
- [35] T. Hatanaka, A. Kitajima, M. Takeuchi, Role of copper chloride in the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans during incineration, *Chemosphere* 57 (2004) 73–79.
- [36] J.Y. Ryu, J.A. Mulholland, M. Takeuchi, D.H. Kim, T. Hatanaka, CuCl<sub>2</sub>-catalyzed PCDD/F formation and congener patterns from phenols, *Chemosphere* 61 (2005) 1312–1326.
- [37] K.H. Karstensen, Formation, release and control of dioxins in cement kilns, *Chemosphere* 70 (2008) 543–560.
- [38] M. Lasagni, E. Collina, E. Grandesso, E. Piccinelli, D. Pitea, Kinetics of carbon degradation and PCDD/PCDF formation of MSWI fly ash, *Chemosphere* 74 (2009) 377–383.