

## INCINERATION AND ENERGY RECOVERY OF EXTRUDED POLYSTYRENE FOAM (XPS) WASTE (SCRAPS) IN A MUNICIPAL WASTE INCINERATOR SIMULATION PLANT (TAMARA)

### Test of the Destruction of Chloro-Fluoro-Carbons and of the Formation Potential of Polyhalogenated Dibenzodioxins and -Furans.

#### Part II; Analytical Methods and Results

**K.S. Brenner<sup>1</sup>, G. Alicke<sup>2</sup>**

<sup>1</sup> ZAX/OO, SpL; Bldg. D 216; <sup>2</sup> HSB/P; Bldg. D 219; BASF AG, D 67056 Ludwigshafen, P.O. Box, FRG

**J. Vehlou, C. Rittmeyer**

Forschungszentrum Karlsruhe G.m.b.H (FZK), JTC-TAB  
D 76021 Karlsruhe, P.O. Box 3640 FRG

**W.Ch. Graf<sup>†</sup>**

DOW Europe S.A., CH 8810 Horgen, Bachtobelstr. 3

#### ABSTRACT

Incineration tests have been performed with XPS, (extruded polystyrene foam) blended with the bromo-flame retardant (BFR) HBCD, mixed with municipal waste (MSW) to simulate the behaviour of such a mixture in MSWIs during everyday incineration conditions. Two incineration temperatures have been set, namely 950 °C and 850 - 900 °C and different materials have been incinerated, namely XPS blown with CFC 12, with a HCFC 22/142b-mixture and the XPS-granulate without CFCs. The main aim of these tests was the determination of the extent of destruction of the blowing agents and to test the hypothesis that PCDD/PCDF- and PHDD/PHDF-formation (de-novo-synthesis) remains in the normal range during XPS-incineration. The CFC/HCFC-destruction exceeded 99.9 % (see J. Vehlou et al., Part I [1]). Hi-Vol-sampling (ca. 7 - 8 m<sup>3</sup>/h sampling rate) of the raw gas allowed the determination of polyhalogenated (Cl, Br) dibenzodioxins and -furans (PHDDs, PHDFs) down to a range of  $\approx 10$  pg (10<sup>-12</sup>)/m<sup>3</sup>. PCDDs/PCDFs were detected in the range of 0.005 to 30 ng/m<sup>3</sup>; PBDDs/PBDFs were detected in the range of 0.002 to 10 ng/m<sup>3</sup>, and PHDDs/PHDFs in the range of 0.001 to 20 ng/m<sup>3</sup>. Parallel measurements with a different sampling train combination (FZK, plane filter plus cooler/scrubber-bottle, sampling rate ca. 1 - 2 m<sup>3</sup> raw gas/h) gave comparable results.

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The measured concentrations of PHDDs/PHDFs are in the normal range for raw gases of MSWIs. Modern emission control units therefore can handle raw gases from co-incineration of XPS and normal MSW effectively.

## INTRODUCTION

Extruded polystyrene foam (XPS, e. g. STYRODUR<sup>®</sup>, a Trademark of BASF AG or STYROFOAM<sup>®</sup>, a Trademark of DOW CHEMICAL COMPANY) is used mainly for insulation of buildings. During application of the foam boards some scrap material must be discarded and cannot be reused. Demolition (eventually dismanteling) of building constructions can also lead to broken material, which must be disposed of. One pragmatic way is the disposal via incineration combined with energy recovery. Incineration reduces the volume practically to zero and regains the energy contained via heat. For material or chemical recycling the technique is still under development.

The main interest in the behaviour of XPS and the contained (hydro-) chloro-fluoro-carbons (CFCs and HCFCs) and brominated flame retardant (BFR) hexabromocyclododecane (HBCD) during incineration, was the degree of destruction of the CFCs/HCFCs and the possible formation of poly-chloro-bromo-dibenzodioxins and -furans (PCDDs/Fs, PBDDs/Fs and PHDDs/Fs). As test-incinerator the TAMARA-incinerator at the FZK in Karlsruhe was used. It had been revised and equipped with the most recent oven technology, in order to simulate full scale incinerators to the nearest possible [2].

During the tests described below several different materials were burnt, i. e. XPS foamed with different types of CFCs/HCFCs and with the normally used concentration of BFR, HBCD, as well as the original XPS solid raw material (granulate without blowing agent). They were added to a standardized municipal solid waste (MSW, "blank waste") in amounts of 3 % (see Part I). The measurements covered all parameters normally used to describe the performance and conditions of an incinerator [1] plus the analytical determinations of undestroyed residual CFCs/-HCFCs, the content of fly ash and the concentrations of PHDDs/Fs in the raw gas. These measurements will be described, together with the methods used for stack gas sampling and the chromatographic/mass-spectrometric methods, including clean up and calibration. For the PHDD/F-measurements two different sampling and determination procedures were used and will be described.

## EXPERIMENTAL

All experimental details will be published elsewhere, see also FZK-report, part I [1].

## RESULTS

### Incineration Conditions

The comparability of the TAMARA-technique with full scale MWIs, like waste feeding conditions, fire conditions, influence of XPS-granulate (solid raw material) and XPS-foam feed, is explained in Part I of the report [1]. The differences of XPS-addition compared to blank waste ("normal test waste") incineration with respect to CFC/HCFC-destruction are discussed there, too.

### CFC/HCFC-Determinations

The results of the CFC/HCFC-determinations show, that a very high destruction rate was observed. HCFC 22 and HCFC 142b were below the detection limit of 3  $\mu\text{g}/\text{m}^3$  (see p. 37 and Table 12; Part I [1]).

CFC 12 can be destroyed at 950 °C down to limits of about 10 - 20  $\mu\text{g}/\text{m}^3$ .

At 850 °C residual CFC 12-concentrations up to 1000  $\mu\text{g}/\text{m}^3$  were measured

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(p. 35, 36; Part I [1]).

## PHDD/PHDF-DETERMINATIONS

### Results, BASF-Impg./PUF-ST

Technique of sampling trains (STs): The technique used [4] [5] allowed the best approach to isokinetic sampling in conjunction with the possibility to remove and exchange the glass-probe during the tests. This was one of the demands in order to fit the sampling conditions as close as possible in a dust loaded (ca. 580 to 710 mg fly ash/m<sup>3</sup> [1]) humid raw gas stream. The horizontal positioning of the probe was essential in order to prevent back flow and losses of the wet fly ash slurry forming in the probe during cooling. The 4 h-term sampling, together with the high sampling rate gave two advantages:

- a) the fluctuations, inevitable in an incinerator could be smoothed out and a representative incineration behaviour could be simulated;
- b) the analytical determinations could be performed sufficiently above the detection level, which allowed the determination of the poly-chloro/bromo-DDs and DFs with satisfying accuracy.

The approach to isokinetic conditions was satisfactorily, considering the difficult test and sampling conditions .

### Measured PHDD/PHDF-Values

The measured values in the bar graphs are given in the order: Blank (Test) Waste, XPS-Granules (solid raw material), XPS foamed with CFC 12 and XPS foamed with HCFC 22/142b (in the figures CFC 12 and HCFCs are referred to as R 12 and R22/142b respectively). The incineration conditions were 950 °C (1. series, this set of figures could not be included, it will be published elsewhere) and 850 - 900 °C (2. series, Fig. 1, 3, 7, 8, 9, 10, 11, 12; because of the limited printing space measured values are given only, no.2, 4, 5, 6, "Tab. f. Fig..."). The figures and tables contain the measured values for the sums of isomers, rounded up, and for the 2,3,7,8-substituted chloro-compounds, too (different concentration scales). No TEQ-values (toxic equivalents) were calculated because of the variety of TEQ-tables still used, their still discussed real toxicological meaning and because no TEQs can be calculated yet for the detected bromo- and chloro/bromo-congeners. Our main interests were the chemical reaction kinetics and the absolute amounts of PHDDs/PHDFs formed during incineration of the XPS. The highest contributions for the PHDD/F-content in the raw gas come from the hepta- and octachloro- and bromo-congeners. The test with XPS CFC 12 at 950 °C produced PCDD/F-results, which were unexpectedly high, due to irregular feeding and combustion conditions for longer periods (see Part I). The influence is significant for the hepta- and octa-dibenzodioxins and -furans [1].

In some graphs the tetra- to octa-congeners are summed up for better comparison (see also Part I [1]).

The di- to octa-halogen "distribution shape" shows an "exponential curve" shape towards the octa-dioxins and a "hill type" form for the furans, with a slight maximum at the hepta-substituted congeners.

The concentrations of the bromo-dioxins and -furans are very low. The bromo/chloro-compounds (PHDDs/Fs) are approximately one order in magnitude below the chloro-congeners, if we ignore the irregular test with XPS CFC 12 at 950 °C. The similarity of the different dioxin of furan patterns is remarkable (Fig. 1 - 10).

In this context it is also remarkable, that some polybromo-diphenylether (PBDPEs) residuals got through the full analytical clean-up procedure and interfered with the MS-measurements. This means that higher concentrations of PBDPEs must have been present in the raw gas, which indicates that the blank (standardized) waste itself could have contained substantial amounts of PBDPEs, which are well-known precursors of PBDFs [6]. It would not be surprising, that a very

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potential BFR like e. g. DecaBDPE resists incineration to some degree at levels of % or ppm, or is only partially debrominated. This points to a possible source of PBDPEs in the environment, especially in the North Sea, Japan and other marine zones [9 - 14]. The de-novo formation of merely brominated PBDPEs in the chlorine-containing oven atmosphere seems less likely. The used BFR HBCD (hexabromo-cyclododecane) has a very low tendency of forming PBDFs/Ds during thermolysis [15] [7], (di- to hexa-BDFs), which could be the reason for the very small di- to tetra-bromo-DF-contribution at 950 °C. The PBDF-formation sensitively indicates irregular combustion conditions (test XPS CFC 12). These formations during pyrolysis are "worst case" considerations, because no confirmed assignment to toxic 2,3,7,8-congeners could be made [7]. The measured values for the 2,3,7,8-substituted PCDDs/Fs fall in the region of about 0.1 and 25 ng/m<sup>3</sup> (Nm<sup>3</sup>). The results for the XPS granulate (containing no CFC/HCFs) and for the XPS HCFC 22/142b-product are similar to the results with the blank waste at 950 °C. The irregular combustion conditions (CO-content, temp.) for the XPS CFC 12-test (series no.1) are reflected in all the analysis data [1].

At 850 °C small differences between the combustion of blank waste and the three products can be seen, especially with the bromo-substituted congeners, but at a very low level (Fig. 7 - 10). For the PCDDs and PCDFs (Fig. 1 and 3) the homologues are summarized (ST4 - O8, sum of tetra- to octa CDDs/CFs), showing a slightly higher difference between blank waste and XPS for the PCDDs.

## Results, FZK-ST and FZK Analytical Laboratory

The analytical results of the PCDD/PCDF-measurements (no PHDDs/PHDFs were measured) performed by FZK are presented in Fig. 11 and 12.

## DISCUSSION

### CFC/HCFC-destruction

The destruction of CFCs showed satisfactory results with respect to environmental considerations. Part I of the report gives the slight differences in the behaviour of the former used CFC 12 and its substitute, the HCFC 22/142b-mixture [1].

### PHDD/PHDF-formation

It must be stressed again, that the given results were determined in the **raw gas** (see remarks above). The values measured are low and comparable to normal MSWIs (see [1]).

Fig. 40, 41 in Part I [1] give the average normal raw gas levels of PCDDs/Fs measured during many incineration tests at the TAMARA test site (gray background area in Fig.). The determined values of PCDDs/PCDFs are shown by the overlaying bar graphs. These comparisons show, that the incineration of XPS does not generate higher values in the raw gas, than those measured during normal MSW-incineration.

Some significant differences can be seen in the PCDD/F-formation during incineration of the 4 different materials and at the two temperatures (950 ° and 850 - 900 °C). The results for the PCDDs/Fs are also reflected by the results for the bromo-/chloro compounds. As has been already discussed in Part I, some technical irregularities during waste feeding have generated higher CO-levels in the raw gas at one single test at 950 °C with XPS CFC 12 material. The enhanced formation of PHDDs/Fs seems to be a response to these irregular technical conditions via another reaction (-mechanism), because only distinct groups of compounds are influenced.

The higher concentration of Cu-, Fe- and other heavy metal-halides in the gas phase might be an additional reason for this (see Part I, volatility curves [1] and Brenner [3]). At 850 - 900 °C the XPS-granules produced higher PCDF-values. The XPS-CFC 12 showed the highest formation tendency for dioxins. How far the de-novo-synthesis is influenced by the higher reactivity of the

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bromo compounds and by a limited "depot-build up" of  $[\text{Cu/Fe}]\text{Cl}_x\text{Br}_y$ -complexes in the fly ash is still not clear [8]. The higher reactivity of bromine might influence the reaction with Cu and Fe in the fly ash, up to a certain plateau with regard to the bromine concentration and the formation of  $[\text{Cu/Fe}]^{(x-y)}\text{Cl}_x\text{Br}_y$  Friedel-Crafts complexes. Any further increase of the Br-concentration [8] does not influence this process, because enough complex is formed and the chlorination/bromination of the precursors via these Friedel-Crafts complexes takes time (residence time of raw gas only about 2 to 4 sec!). The re-halogenation of the Cu/Fe-complexes in the fly ash no more influences the reaction because the stack gases are cooled meanwhile and filtered. It might be a similar situation like the PCDD/PCDF-formation and the chlorine input in an incinerator (no influence of e.g. PVC, if chlorine is present anyway).

The formation of PHDDs/PHDFs during heating of fly ash in a quartz tube might be explained in the same way. The formed  $[\text{Cu/Fe}]^{(x-y)}\text{Cl}_x\text{Br}_y$  complex reacts with the precursors in the fly ash, until the complex or the precursors are consumed. In the absence of HCl,  $\text{Cl}_2$ , CO,  $\text{CO}_2$  (also  $\text{CO}_2$  can undergo Friedel-Crafts reactions [3]) no rehalogenation and formation of PHDDs/Fs can take place.

It seems that the higher CO-level has more influence than the CFC 12-content at higher temperatures (higher concentration of catalytically acting Cu/Fe-halides, "depot" and influence on Boudouard-equilibrium). The type of product burnt (solid granules without CFC/HCFC or XPS) seems to have more influence at lower temperatures.

The new type of XPS-HCFC 22/142b shows in most cases (except OCDD) the lowest tendency towards PHDD/PHDF-formation.

The PCDD/PCDF-analyses performed by FZK resulted in values comparable to the ones obtained with the BASF-methods in the expected range of precision and therefore validated the results. It must be considered that FZK worked with a different ST-combination, at a different sampling spot with a different analysis method. This confirmation of the BASF-data is supported by the similarity of the congener bar graph shapes ("exponential" and "hill-typs" shape) of the BASF- and FZK-data sets and the comparable congener distribution pattern.

It should be emphasized again, that the discussed facts are significant, but at a very low concentration level, characteristic for normal MSWI-fly ashes and raw gas.

## The results can be interpreted as follows:

The destruction of the CFCs or HCFCs contained in the scrap XPS-material is almost quantitative. Therefore no adverse influence on the ozone layer can be expected from the emissions during incineration of XPS (see [1]).

Because the measured values for the chloro-, bromo- and chloro-/bromo-dibenzofurans and dioxins in the raw gas are comparable to those from normal, modern municipal solid waste incinerators, demonstrated with the general TAMARA-levels, **no additional** output of PHDDs/PHDFs is to be expected. PBDPEs contained in municipal waste can be a more potent source for PHDFs/PHDDs, therefore XPS/HBCD-blends can be classified as very minor sources. The evaluation of TEQs for the bromo-derivatives is not possible, because no TEQ-list exists yet, and because the determination of exact figures for the 2,3,7,8-substituted derivatives is not satisfactorily possible at the moment. Comparing the data of the sums of homologues shows, that a TEQ contribution, about one order of magnitude lower can be expected in the raw gas under normal technical conditions. Given the fact, that nowadays the air pollution control units of modern MSWIs, equipped with modern electrostatic precipitators, combined with DENOX/DIOXIN-catalysts or active carbon/ $\text{CaO}$ -baghouse cleaning systems can deal with raw gases of any kind, emissions can be kept in ranges below the set limits.

The presented results show some of the expected influences by the involved chemistry on catalytic surfaces, especially when the incineration temperature and the CO-level were irregular during one burning period. During regular conditions, the combustion of XPS-foam or granules scrap can be performed satisfactorily in modern MWIs in parallel to the intended energy recovery. The differences in PCDD/PCDF-formation during incineration of normal waste plus XPS or waste alone are very small. Formation of PHDDs/PHDFs could be detected, but at very low levels in

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the range of about 0.001 to 3 ng/m<sup>3</sup> during the 850°C series (XPS-HCFC 22/142b, Fig. 7 - 10). Therefore the raw gas formed can be cleaned in normal modern MSWIs in the same way as during incineration of conventional MSW.

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## REFERENCES

- [1] Vehlow J, Rittmeyer C, Stieglitz L, Vogg H, Wanke Th, Brenner KS, Mark FE (1995) Co-Combustion of XPS Foams and Municipal Solid Waste in the Karlsruhe Test Incinerator TAMARA, Part I; submitted for publication in Environ Sci Technol; see APME-Technical Paper (Brochure): Vehlow J, Mark FE (Oct. 1995) Co-combustion of BUILDING INSULATION Foams with municipal solid waste. APME, Association of Plastics Manufacturers in Europe; Avenue E. van Nieuwenhuysse 4, box 3; B-1160 Brussels
- [2] Rittmeyer C, Kaese P, Vehlow J, Vilöhr W (1994) Decomposition of Organohalogen Compounds in Municipal Solid Waste Incineration Plants, Part II: Co-combustion of CFC Containing Polyurethane Foams. Chemosphere; **28**: 1455
- [3] Brenner KS (1995) Waste Incineration and PCDD/F-Formation - Problems, Solutions. Tox Environ Chem; **47**: 7 - 14 (many lit. citations)  
see also:
  - a) Hagenmaier HP, Brunner H, Haag R, Kraft M (1987) Die Bedeutung katalytischer Effekte bei der Bildung und Zerstörung von polychlorierten Dibenzodioxinen und polychlorierten Dibenzofuranen. VDI Berichte; **634**: 557 - 584; VDI Verlag, Düsseldorf  
ISBN 3-18-090634-0
  - b) Cains PW, Dyke P (1994) Chlorinated Dibenzodioxin and Dibenzofuran Emissions from Waste Combustion Plants in the UK. Chemosphere; **28**: 2101 - 2119
  - c) Stieglitz L, Vogg H, Zwick G, Beck J, Bautz H (1991) On Formation Conditions of Organohalogen Compounds from Particulate Carbon of Fly Ash. Chemosphere; **23**: 1255
- [4] Brenner KS, Dorn IH, Menz G (1994) Polyurethane (PU)-Foam-Plug/Impinger Sampling Train for Monitoring of PCDD/F-Emissions from Incinerators and other Emission Sources. Tox Environ Chem; **41**: 187 - 208
- [5] VDI-Richtlinie 3499, Blatt 4, Cooled Probe/PU-Impinger-ST; DRAFT; CEN TC 264 WG 1, Cooled Probe/PU-Impinger-ST; pr EN 000-1 (European Norm) Sampling, to be published, and Brenner KS (1991) in "Verfahren zur Bestimmung von 2,3,7,8-Tetrachlordibenzo-p-dioxin und anderen in 2,3,7,8-Stellung chlorierten PCDDs und PCDFs". Hauptverband der gewerblichen Berufsgenossenschaften, Fachausschuss Chemie; ZH1/120.47, Carl Heymanns Verlag KG, Luxemburger Str. 449, 5000 Köln
- [6] Brenner KS, Knies H (1993) Workplace Monitoring of Polybrominated Dibenzofurans (PBDFs) and -Dioxins (PBDDs) during Extrusion Production and Injection Molding of a Polybutylene-Terephthalate (PBTP)/Glass Fibre Resin Blended with Tetrabromobisphenol-A Carbonate Oligomer (BC52)/Sb<sub>2</sub>O<sub>3</sub>; Air Sampling Train and Product Analysis. Tox Environ Chem; **38**: 81 - 94
- [7] Brenner KS (1993) Polystyrene- and Extruded Polystyrene Foam (XPS)-Hexabromo-Cyclododecane-Blends under Thermolytic Stress; PBDF & PBDD-Determination. Organohalogen Compounds Vol. 11, Analytical Methods - Formation and Sources; Fed. Environ. Agency, Spittelauer Lände 5, A-1090 Vienna, Austria: p. 381 - 386, ISBN 3-85457-129-1
- [8] Luijk R, Dorland C, Smit P, Jansen J, Govers HAJ (1994) The Role of Bromine in the de-novo-Synthesis in a Model Fly Ash System. Chemosphere; **28**: 1299 - 1309
- [9] Watanabe I, Kashimoto T, Tatsukawa R (1987) Polybrominated Biphenyl Ethers in Marine Fish, Shellfish and River and Marine Sediments in Japan. Chemosphere; **16**: 2389 - 2396
- [10] Jansson B, Asplund L, Olsson M (1987) Brominated Flame Retardants - Ubiquitous Environmental Pollutants? Chemosphere; **16**: 2343 - 2349
- [11] de Boer J (1989) Organochlorine Compounds and Bromodiphenylethers in Livers of Atlantic Cod (Gadus Morhua) from the North Sea, 1977 - 87. Chemosphere; **18**: 2131 - 2140
- [12] Sellström U, Jansson B, Kierkegaard A, de Wit C, Odsjö T, Olsson M (1993) Polybrominated Diphenyl Ethers (PBDE) in Biological Samples from the Swedish Environment. Chemosphere; **26**: 1703 - 1718
- [13] Gribble G (1995) Organochlorine Compounds.

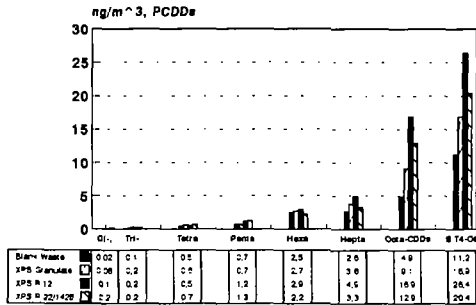
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C & EN; Feb. 13: 4 - 5 [see also Environ Sci Technol (1994); **28**: 310A]

- [14] Zelinski V, Lorenz W, Bahadir M (1993) Brominated Flame Retardants and Resulting PBDD/PBDF in Accidental Fire Residues from Private Residences. Chemosphere; **27**: 1519 - 1528
- [15] Dumler R, Thoma H, Lenoir D, Hutzinger O (1989) PBDF and PBDD from the Combustion of Bromine Containing Flame Retarded Polymers: A Survey. Chemosphere; **19**: 2023 - 2031

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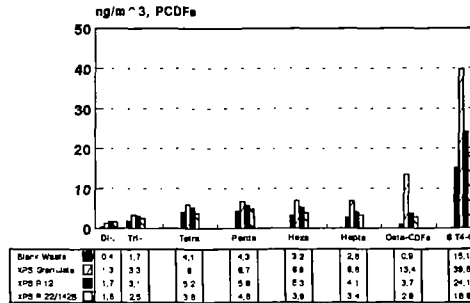
XPS\* Test Combustion, TAMARA; 850°C  
Sum of PCDDs In Raw Gas



PU/Impg.-Sampling Train  
\* XPS: Extruded Polystyrene Foam

Fig.1

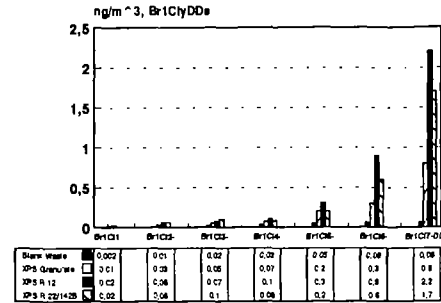
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Sum of PCDFs In Raw Gas



PU/Impg.-Sampling Train  
\* XPS: Extruded Polystyrene Foam

Fig.3

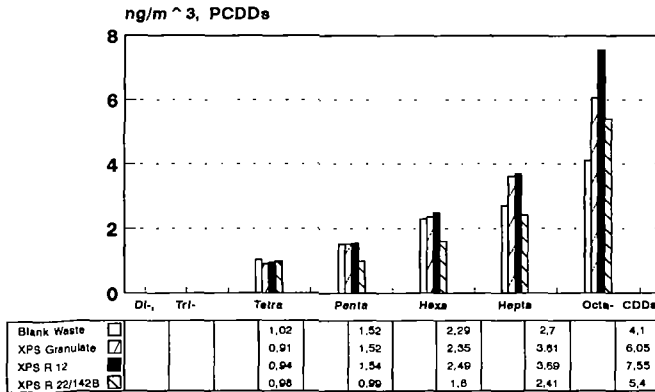
XPS\* Test Combustion, TAMARA; 850°C  
Sum of Br1ClyDDs In Raw Gas



PU/Impg.-Sampling Train  
\* XPS: Extruded Polystyrene Foam

Fig.7

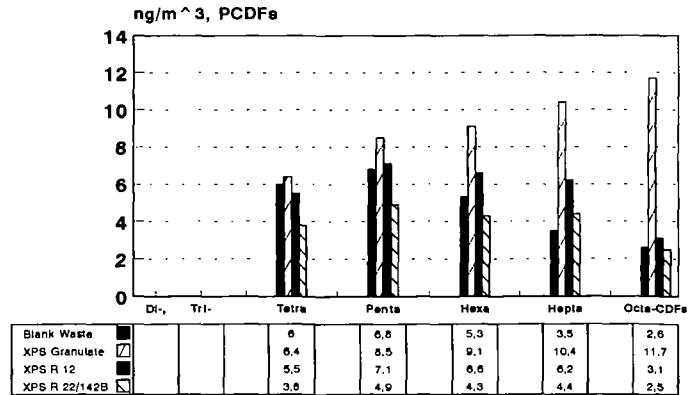
XPS\* Test Combustion, TAMARA; 850°C  
Sum of PCDDs In Raw Gas; FZK-Results



PU/Impg.-Sampling Train  
\* XPS: Extruded Polystyrene Foam

Fig.11

XPS\* Test Combustion, TAMARA; 850°C  
Sum of PCDFs In Raw Gas; FZK-Results



PU/Impg.-Sampling Train  
\* XPS: Extruded Polystyrene Foam

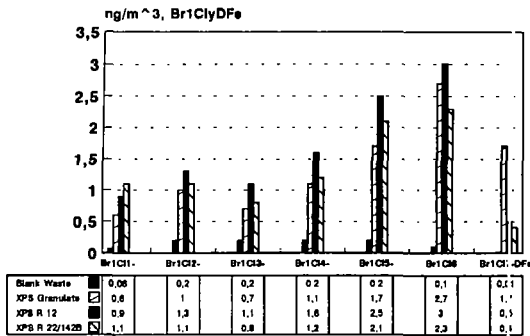
Fig.12

STYRFIG1,RO28



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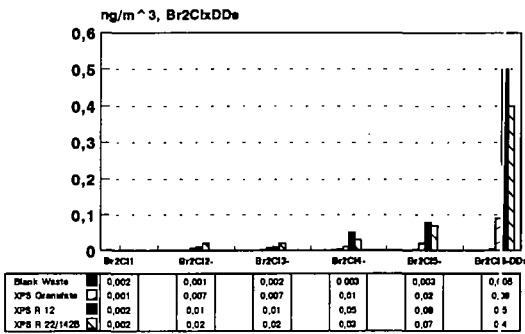
## XPS\* Test Combustion, TAMARA; 850°C Sum of Br1ClyDFs in Raw Gas



PU/tepp.-Sampling Traps  
\* XPS: Extruded Polystyrene Foam

Fig.8

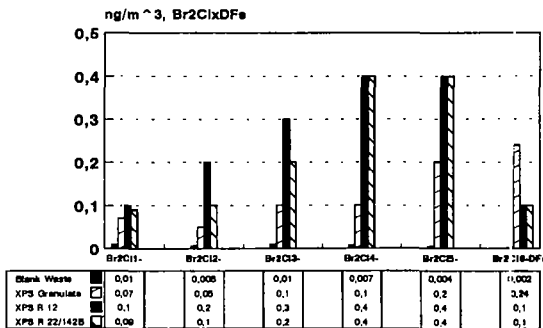
## XPS\* Test Combustion, TAMARA; 850°C Sum of Br2ClyDDs in Raw Gas



PU/tepp.-Sampling Traps  
\* XPS: Extruded Polystyrene Foam

Fig.9

## XPS\* Test Combustion, TAMARA; 850°C Sum of Br2ClyDFs in Raw Gas



PU/tepp.-Sampling Traps  
\* XPS: Extruded Polystyrene Foam

Fig.10

XPS\* Test Combustion, TAMARA; 850°C  
2,3,7,8-subst. PCDDs in Raw Gas; ng/m<sup>3</sup>

	Blank Waste	XPS Granulate	XPS R 12	XPS R 22/142B
Tetra	0,006	0,07	0,006	0,004
Penta	0,04	0,05	0,05	0,03
Hexa	0,05	0,06	0,07	0,04
Hexa	0,1	0,1	0,2	0,1
Hexa	0,08	0,09	0,1	0,06
Hepta	1,6	2,4	2,7	1,8
Octa-CDDs	4,9	10,5	12,7	5,4

PU/mppg-ST; HRMS-Measurements  
\* XPS: Extruded Polystyrene Foam

Tab. f. Fig.2

XPS\* Test Combustion, TAMARA; 850°C  
2,3,7,8-subst. PCDFs in Raw Gas; ng/m<sup>3</sup>

	Blank Waste	XPS Granulate	XPS R 12	XPS R 22/142B
Tetra-	0,1	0,3	0,2	0,1
Penta	0,5	0,7	0,6	0,4
Penta-	0,4	0,6	0,5	0,3
Hexa	0,5	0,9	0,8	0,5
Hexa	0,6	0,9	0,8	0,5
Hexa	0,1	0,4	0,2	0,2
Hexa-	0,7	1,9	1,2	0,9
Hepta	2,5	7,9	6,4	4,5
Hepta-	0,2	1,9	0,5	0,3
Octa-CDFs	0,9	13,4	3,7	2,9

PU/mppg-ST; HRMS-Measurements  
\* XPS: Extruded Polystyrene Foam

Tab. f. Fig.4

XPS\* Test Combustion, TAMARA; 850°C  
Sum of PBDDs in Raw Gas; ng/m<sup>3</sup>

	Blank Waste	XPS Granulate	XPS R 12	XPS R 22/142B
Di-, Tri-		0,001	0,001	0,004
Tetra	0,002	0,003		
Penta				
Hexa				
Hepta				
Octa-BDDs	0			

PU/mppg-Sampling Train  
\* XPS: Extruded Polystyrene Foam

Tab. f. Fig.5

XPS\* Test Combustion, TAMARA; 850°C  
Sum of PBDFs in Raw Gas; ng/m<sup>3</sup>

	Blank Waste	XPS Granulate	XPS R 12	XPS R 22/142B
Di-, Tri-	0,02	0,2	0,3	0,3
Tri-	0,007	0,02	0,03	0,01
Tetra	0,001			
Penta		0,001		
Hexa		0,006		
Hepta	0,04	0,02	0,03	0,02
Octa-BDFs				0

PU/mppg-Sampling Train  
\* XPS: Extruded Polystyrene Foam

Tab. f. Fig.6