**Management of WEEE Containing Polybrominated Diphenyl Ethers – A material flow analysis case study from Vienna**

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Polybrominated diphenyl ethers (PBDEs) were routinely applied as flame retardants in plastic materials in electrical and electronic equipment (EEE) for several decades. Commercial mixtures of *pentabromodiphenyl ether (cPentaBDE)* and commercial *octabromodiphenyl ether (cOctaBDE)* are classified because of their toxicity and persistence as persistent organic pollutants (POPs) under the Stockholm Convention [1]. Stockholm Convention is an international treaty that aims at controlling and phasing out major POPs. Another commercial mixture, *decabromodiphenyl ether* (cDecaBDE) is not regulated by the Stockholm Convention, but may be in the future, as it is currently under review [2]. On the European level, all three PBDEs are administered by two key directives [3, 4]. The European framework established removal of pollutants as a basic treatment rule, and restricted recycling of waste electrical and electronic equipment (WEEE) containing cPentaBDE, cOctaBDE and cDecaBDE above a threshold value of 0.1 wt% (1 g/kg). This limitation is also called a maximum concentration value (MCV).

PBDEs were found in high concentrations in cathode ray tube (CRT) computer monitors and televisions. Because people tend to store old EEE in their homes (cellars, attics), large amounts of PBDEs are still present in European cities.

Various problems are associated with PBDEs. First, despite directives restricting them, cOctaBDE concentrations above the allowed value were found in plastics in European WEEE [5-8]. Second, the presence of PBDEs was reported in house dust, soils, sediments, sewage sludge and elsewhere in the environment [9]. Third, the knowledge about the fate of PBDEs in the city of Vienna, as in every other city, is limited. In other words, it is merely known in which amounts and where they are present.

In Europe, recycling of plastic materials is a preferred option but pollutants such as PBDEs must be strictly excluded from recycling streams. Various recycling technologies for PBDE-containing plastics have been continuously developed during the past decade, using either mechanical or chemical processes. The technologiesthat allow for production of recycled plastics from mixed plastic streams, with PBDEs’ levels below the limit value, are in development or pilot-scale. There is no information about a full-scale operation, approximately ten years after recycling industry announced this as an aim [10].

The main objective of the management of PBDEs is to dispose of them in environmentally sound final sinks [11]. PBDEs are organic semi-volatile compounds, which can be effectively transformed into harmless substances by incineration. Possible formation of emissions from incineration, such as dioxins and furans, can be controlled by existing technologies (air pollution control) which in use in today’s municipal solid waste (MSW) incinerators [10, 12]. For PBDE-containing plastics, incineration with air pollution control is thus a preferred treatment option, as long as no automated full-scale operation capable of their removal is in place. Incineration is an appropriate final sink for PBDEs.

Cities are major sources of PBDEs emissions and PBDE concentrations on sites close to emission sources, such as road soils in urban areas, are much higher than at remote sites [13, 14]. The knowledge of their fate from the source to the final sink is crucial for the development of waste management strategies at an urban level. The municipality has means to manage PBDEs by designing and optimizing waste management systems.

Vyzinkarova and Brunner (2013) published a case study of two commercial PBDE-mixtures in the city of Vienna with a reference year 2010, in all applications including in EEE [15]. This study used methodology of substance flow analysis (SFA) as defined in Brunner and Rechberger (2003) [16]. SFA has been widely applied to trace pollutants, heavy metals, and nutrients through cities [12, 17-18]. Results from SFA can be compared with experimental results, such as concentrations of substances in specific flows of goods. For instance, a case study from Switzerland showed that SFA-based results match field results in a small WEEE recycling plant quite well [6].

A large share of PBDE-containing materials have already entered waste management, therefore the focus should be on waste management options [10]. The key process in Waste Management is the incineration, where PBDEs are effectively destroyed [19]. The import to waste management are WEEE plastics, which are then divided between reuse, export for treatment abroad, incineration, and recycling. Substance flows from Consumption to Waste Management are much bigger than the flows from Consumption to the Environment in Vienna, therefore Waste Management is the key process within and outside of Vienna. Consumer emissions to the environment are very small and will no longer play a significant role, neither for cPentaBDE nor cOctaBDE, and they will still decrease with time as the amounts of PBDE-containing plastics in cities decrease.

Amount of cOctaBDE in the EEE in use in Vienna (consumer stock) was estimated to be around 3600 kg in 2010, with high uncertainties [15]. The cOctaBDE flow into waste management was 1300 kg/a. According to STAN modeling, 70% of cOctaBDE entering waste management ends up in MSW incineration, also with a high uncertainty. Through reuse and recycling, some cOctaBDE returned into Consumption. The reuse was very small compared to the recycling. Based on input values, the amount of cOctaBDE returning into Consumption via recycled plastics amounts to 290 kg/a (or 22% of cOctaBDE entering waste management as WEEE).

The stock was declining with approximately -1000 kg/a, but assumed that the return into consumption via recycling continues, there are still cOctaBDE present in the consumption stock in Vienna in 2016. Its main part is likely in stored devices no longer in use. The stock of DecaBDE can still be high in 2016.

Figure 1. Waste Management of cOctaBDE in WEEE in Vienna, 2010, in kg/a.

Flows of cOctaBDE, including WEEE recycling flow, could only be estimated with a great uncertainty. Part of the uncertainty is caused by the fact that there is no information about the amount of old appliances stockpiled in households, per capita statistics from Switzerland had to be used for the purpose of determining stocks in CRT-PCs and CRT-TVs in Vienna. The high dStock uncertainty is influencing the recycling flow estimate. The flows of substances are calculated as flow of goods, multiplied by plastic fractions, and further multiplied by substance concentrations in the plastic. Thus, the uncertainties originate from three parameters, and they are additive. From the three parameters, the main origin of the uncertainty is the wide cOctaBDE concentration range in European WEEE plastics. At the current state of knowledge, the difference between minimum and maximum value is sometimes as high as a factor of 100 (0.14 to 10.6 g/kg in CRT monitors, or 0.05 to 3.54 g/kg in CRT-TVs). In order to narrow down this uncertainty, Vyzinkarova and Brunner (2013) recommended to provide more and improved data. To support the hypothesis that the current knowledge is insufficient, the available cOctaBDE concentration data sets were reviewed in Vyzinkarova and Brunner (2013) [15]. They include European WEEE streams [20], European housing and mixed WEEE shredder residues [8], and CRT-PCs and TVs imported to Nigeria [21].

SFA methodology and scenario modeling are, in general, appropriate tools for estimating the amount of cOctaBDE in recycling streams. The case study of Vyzinkarova and Brunner (2013) shows that the current data on cOctaBDE concentrations are insufficient for assessing cOctaBDE recycling flow of WEEE plastics within reasonable uncertainty levels. A larger scale cOctaBDE concentration measuring campaign in CRT monitors (PCs and TVs) is recommended. This is needed for better understanding of flows and stocks, and hence for avoiding risks arising from cOctaBDE for human health and the environment. Results indicate a possible return of cOctaBDE to the consumption stock via recycled WEEE in the city of Vienna. In Switzerland, a robust experimental analysis at a recycling plant of small WEEE plastics, representing the relevant appliances in WEEE, followed a nation-wide SFA analysis for PentaBDE, OctaBDE and other contaminants [6, 12]. The average cOctaBDE concentration in this WEEE stream amounted to 0.53 g/kg ± 0.03 g/kg and agreed fairly well with the SFA-calculated concentration of 0.39 g/kg. Furthermore, cOctaBDE concentrations corresponding to PC-screen housings and TV housing at the output of the plant were determined at 11 g/kg cOctaBDE in both cases. In a Swiss experience more than a decade ago, plastics from PC-screen and TV housings posed a problem equivalent to exceeding allowed concentrations by factor 10 and thus should not have been recycled.

In Austria, such analysis has not yet been published. The Austrian law obliges the relevant institution on federal state level to undertake control of plants that treat hazardous waste at a minimum of every 5 years [22]. Information about substance flows is also needed for plastic recycling plants in order to follow PBDEs from sources to final sinks, and to ensure that clean cycles and appropriate final sinks can be reached by waste management strategies in place.

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**Tags 1:**

* **Environmental Health / sinks for hazardous substances**
* **Secondary resources / hazardous fraction, plastics**
* **E-waste characteristics / screens, small ICT, sWEEE**
* **Stakeholders / recyclers**
* **Legal frameworks / European Union, global**

**Tags 2: Recovery of material, disposal**

**Summary**

PBDEs were used as flame retardants in various plastic applications, also in electrical and electronic equipment (EEE). Because of their toxicity, they are currently being phased out. We describe the presence of PBDEs in cities (in use and in the environment where they landed via emissions) on the example of the city of Vienna. Afterwards we focus on the appropriate treatment of PBDE-containing plastics as a waste management strategy.