

# A Study to Facilitate the Implementation of the Waste Related Provisions of Regulation (EC) No 850/2004 on Persistent Organic Pollutants

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# A Study to Facilitate the Implementation of the Waste Related Provisions of Regulation (EC) No 850/2004 on Persistent Organic Pollutants

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# Glossary

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Defra	Department for Environment, Food and Rural Affairs
EA	Environment Agency
ABS	Acrylonitrile Butadiene Styrene
ASR	Automotive Shredder Residue
BFR	Brominated Flame Retardant
Congeners	A group of chemicals which have different chemical formulas, but have related properties and structural features.
CRT	Cathode Ray Tube (a specific type of VDU)
HBCD	Hexabromocyclododecane
HIPS	High Impact Polystyrene
Isomers	A chemical compound with the same formula, but different molecular structure
PBDE	Polybrominated diphenyl ether
PCB	Printed Circuit Board
PFOS	Perfluorooctane Sulphonic Acid
POPs	Persistent Organic Pollutants
PS	Polystyrene
PUR	Polyurethane
TBBA	Tetrabromobisphenol-A
VDU	Visual Display Unit
Units	Conventional SI units and prefixes used throughout: {k, kilo, 1000} {M, mega, 1,000,000} {G, giga, 10 <sup>9</sup> } {kg, kilogramme, unit mass} {t, metric tonne, 1000 kg}

# Executive Summary

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## Aim and objective

The aim of this study was to assess the impact of the addition of the Annexes of EC Regulation 850/2004 on Persistent Organic Pollutants (POPs) on UK recycling and waste management, and to recommend suitable limits for waste. These changes are as a consequence of amendments Stockholm Convention, and this legislation will affect the following chemicals:

- perfluorooctane sulfonic acid and its derivatives, otherwise known as PFOS,

and the following polybrominated diphenyl ethers (PBDEs),

- tetrabromodiphenyl ether
- pentabromodiphenyl ether
- hexabromodiphenyl ether
- heptabromodiphenyl ether.

These PBDEs are used in the mixtures c-pentaBDE and c-octaBDE, which have historically been used as flame retardants in plastics.

Based on global and UK production and consumption data, waste statistics and life cycle analysis, the concentrations of these chemicals in waste and recycling streams in the UK were estimated. Only those products were taken into account in which waste BDE and PFOS are expected to appear.

In parallel justifiable threshold limits according to Annex IV of Regulation (EC) 850/2004 were derived for both families of substances. Finally, based on our findings, recommendations are given.

## Occurrence of PFOS and BDEs in the waste streams in the UK

PBDEs were historically primarily used as flame retardants in plastics. The use of these flame retardants has been banned in the EU since 2004 (Directive 76/769/EEC), though EU production was stopped prior to this date; therefore almost none is expected to be entering the UK in new products at present.

C-pentaBDE was used for a variety of purposes in the past, but only applications associated with polyurethane (PUR) foam were found to be relevant to the UK waste stream. The largest uses were in the automotive and furniture industries, which accounted for 68% and 31% of the UK consumption of c-pentaBDE. The concentration of c-pentaBDE in the waste streams for these products is estimated to be between 150 and 240 mg/kg in automotive shredder residue (ASR, composed of non-recycled scrapped vehicle waste), and between 42 to 70 mg/kg for PUR foam arising from furniture. From this data the concentration of the most common PBDE present from these commercial mixtures is estimated to fall between 98 and 156 mg/kg for ASR, and 27 and 51 mg/kg for furniture. These values are predicted to fall rapidly in the next two to five years.

The main use for c-octaBDE was as a flame retardant in plastic CRT housings for televisions and computer monitors. Other uses required much smaller quantities, and do not introduce significant quantities in the UK waste streams, if any at all. The range of estimated

concentration of c-octaBDE in current CRT VDU waste streams is estimated to be between 20,300 and 25,000 mg/kg, resulting in a concentration of 13,200 and 16,300 mg/kg for the most common individual PBDE. Though this concentration will reduce over time, it is expected to remain high, particularly when compared to concentrations found in c-pentaBDE containing products.

Perfluorooctane sulfonate (PFOS) and its derivatives were, and still are, used as inert surfactant chemicals in a wide range of applications, and may be found in stain-protected carpets and home textiles, water proofed clothing, and coated paper. PFOS is no longer applied within the UK, but may still be present in old products and imported products - especially from outside the EU and may well contain significant amounts of this POP. Our study has been able to estimate a concentration of up to 0.04 mg/kg of PFOS in the waste streams of these product groups.

### **Recycling of wastes containing PFOS and BDEs in the UK**

The wastes containing c-pentaBDE from furniture or automotive PUR foam are not recycled at present. Therefore no impact to the recycling industry is expected due to the inclusion of components c-pentaBDE in this new legislation. The estimated concentrations in this waste also should not affect the existing practices of sending this waste to landfill if the recommended levels are set.

The plastic from CRT housings typically enters WEEE recycling streams after the CRT glass has been separated. In existing practices, the housing plastic is mixed with general WEEE plastic and then sent abroad where plastics containing brominated flame retards are separated. The high concentrations of c-octaBDE in these housings plastics could impact the recycling of these materials as the levels estimated are well above those allowable by regulations covering hazardous waste for electronic equipment. The efficiency of separation process abroad is not well documented either, therefore it is possible that these BFR may re-enter the product streams, contrary to WEEE Regulations. As this plastic is initially part of a separate CRT waste stream, sorting these plastics could be achieved by modification of the current CRT disassembly process. Plastics containing any brominated flame retardant could be separated prior to mixing with other WEEE plastic. This is estimated to be 3,350 tonnes of plastic per year, which would then require destruction by hazardous waste incineration. The cost associated with this is estimated to be £2m per year not including additional costs associated with sorting, disruption to supply chains and additional equipment. In practice it is suggested that further analytical data be gathered to monitor the concentration of c-octaBDE, and any changes made if these high concentrations are confirmed.

Recycling of products containing PFOS is of little significance in the carpet and textile sector, as recycling rates are (unfortunately) still very low. In the paper industry recycling rates are much higher, with approx. 70% of all paper produced in the UK being based on paper waste.

This study shows that recycling of PFOS containing material is the environmental preferable option, as it avoids the manufacture of new products that contain more PFOS on average than end-of-life material.

### **Setting of a threshold limit for waste containing PFOS and BDEs**

A uniform threshold of 650 mg/kg for each individual PBDE is recommended. Existing EU legislation bans the import or manufacture of products with a concentration of c-pentaBDE or c-octaBDE higher than 1000 mg/kg. This value is for all PBDEs contained in the commercial

mixtures, therefore it has been scaled to reflect the highest estimated concentration seen for an individual PBDE. This is a conservative limit, but presents the most appropriate level for restrictions at present. Further reviews could be undertaken in the future to reduce this level should more data become available.

For PFOS the threshold limit according to Annex IV of EC 850/2004 was derived based on the already existing precautionary limit of 0.1 mg/kg for waste sewage sludge in several German Federal states. Based on this limit, and taking into account the share of PFOS-containing waste in UK's landfills, a threshold of 1 mg/kg for PFOS is recommended. Above this threshold, waste will need to be treated such that the contained PFOS is destroyed or irreversibly transformed.

## **Recommendations**

It is recommended that the threshold for each individual PBDE according to Annex IV EC 850/2004 may be set at 650 mg/kg. This is believed to be a conservative level, so should be reviewed over time as a greater body of evidence is gathered.

C-pentaBDE is found in automotive waste and furniture waste, which under existing practices is sent to landfill. The estimated concentrations of individual PBDEs are well below the threshold suggested above. It is recommended that the level of PBDEs could be assessed and monitored in these wastes to ensure that estimates are accurate, and to provide further information for future reductions in the concentration levels.

C-octaBDE is found in CRT housings at concentrations which are estimated to be well above any reasonable concentration limit. If alternative processing is required as a consequence of this legislation it is suggested that the lowest impact solution is to destroy all CRT housing with BFR content by high temperature hazardous waste incineration. Additionally it is recommended that an analytical study of this specific waste stream could be conducted. This will provide a better basis for implementing suggested changes in recycling practices.

To prevent additional PBDEs entering the waste streams in the future, the existing ban on importing products containing >0.1% c-pentaBDE and c-octaBDE could be strongly enforced and monitored. Related legislation, such as that related to BFRs in WEEE could also be considered at the same time to ensure coherency between how each is implemented.

It is recommended that the threshold for PFOS according to Annex IV EC 850/2004 is set at 1 mg/kg.

As the values used in this study were based on averages and global production numbers, a project to actually measure the PFOS content in samples of textile waste, carpet waste and paper waste could be analysed to verify the estimates of this study.

As most of PFOS emission in carpets and textiles happens during the use phase, the most efficient way to reduce PFOS levels in the environment seems not to be via restricting waste or recycling routes, but via enforcing the already existing limit of 0.001 mg/m<sup>2</sup> according to Regulation (EC) 552/2009.

In a similar fashion a project to actually measure the PFOS content in samples of carpets, workwear / home textiles and coated papers imported into the UK may be initiated. Even though it may be impossible to obtain a representative sample from these imports, more data needs to be generated to obtain an overview, and to gain the confidence that imported products generally conform to the existing limit of 0.001 mg/m<sup>2</sup> (Regulation (EC) 552/2009).



# 1 Introduction

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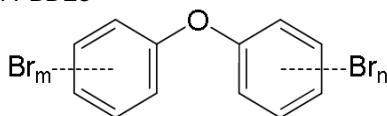
The aim of this study was to assess the impact of the addition of the Annexes of EC Regulation 850/2004 on Persistent Organic Pollutants (POPs) on UK recycling and waste management, and to recommend suitable concentration limits for waste. This is as a consequence of amendments to the Stockholm Convention. The new regulation means that, for new POPs, allowable concentration levels need to be set for waste containing these chemicals. Above these levels, the POPs in the waste are required to be destroyed or irreversibly transformed. This study will assess the levels in waste of the new POPs, PFOS (and its derivatives) and a range of brominated diphenyl ethers (BDEs) found in commercial penta-BDE and octa-BDE. It will also assess how much of this waste is recycled and the impact of the new Regulations on the industry. Finally concentration limits will be proposed, and the costs and benefits of implementing these concentration limits on the recycling industry will be calculated.

## 1.1 PBDEs

Polybrominated diphenyl ethers (PBDEs) are a class of organobromine compounds which have historically been used as additive-type flame retardants, primarily in plastic products. The terminology used to refer to PBDEs often depends on context, therefore it is important to provide clarification to avoid confusion within this study.

All PBDEs share a common basic structure of two aromatic phenyl moieties connected by an oxygen atom (Figure 1). This structure allows a variation of between 2 and 10 bromine atoms in PBDEs, equivalent to  $m+n$  in the figure below.

Figure 1: General structure of PBDEs



Scientifically, PBDEs are most commonly categorised by the number of bromine atoms they contain, (e.g. tribromodiphenyl ether contains three bromine atoms). The Stockholm Convention uses this terminology, and the particular PBDEs affected are shown in Table 1.

Table 1: PBDEs included in the Stockholm convention

No. of Bromine atoms (m+n)	Name of isomer
4	Tetra-bromodiphenyl ether (tetraBDE)
5	Penta-bromodiphenyl ether (pentaBDE)
6	Hexa-bromodiphenyl ether (hexaBDE)
7	Hepta-bromodiphenyl ether (heptaBDE)

Further distinction can be made between chemicals, as several different structural arrangements of bromine atoms exist for each PBDE; these are referred to as isomers. In total there are 209 different isomers of all PBDEs. As a group these are referred to as congeners, as they have a different chemical formula, but share similar structural and chemical properties. Each congener has a specific number assigned to it (1 to 209) which is

used when greater specificity is necessary. However such distinction is generally not required for this project, as the Stockholm Convention refers to the number of bromine atoms present in each PBDE rather than specific congeners.

When PBDEs are used as fire retardants, a related but slightly different nomenclature is used, as they are present in mixtures rather than as a single PBDE or congener. A mixture is used as limitations with the selectivity of industrial scale manufacture mean that the average overall bromine content can be controlled, but it is not selective to the production of a single PBDE. Three different mixtures of PBDEs have been commonly used as flame retardants. These are referred to as:

- commercial-pentaBDE (c-pentaBDE),
- commercial-octaBDE (c-octaBDE) and
- commercial-decaBDE (c-decaBDE),

with the name roughly indicating the dominant level of bromination of PBDEs in these mixtures. Table 2 below gives an indication of the PBDE content of each of these formulations.<sup>1</sup> The exact composition of each of the commercial mixtures varies with time, company and region as the manufacturing processes vary and are improved. Further breakdown of specific congeners is available in some cases; however this is not relevant to this project.

Table 2: Typical PBDE composition in commonly used flame retardants

<b>PBDE</b>	<b>C-pentaBDE</b>	<b>C-octaBDE</b>	<b>C-decaBDE</b>
TriBDE	0-1%		
TetraBDE	24-38%		
PentaBDE	50-62%	0.5%	
HexaBDE	4-12%	12%	
HeptaBDE		45%	
OctaBDE		33%	trace
NonaBDE		10%	0.3-3%
DecaBDE		0.7%	97-99%

Source: US EPA

The implementation of the Stockholm Convention will impact the use of c-pentaBDE and c-octaBDE, as these formulations contain the affected PBDEs. According to expert comment and to the literature surveyed for this work, no commercial applications for these PBDEs are known, other than being part of the commercial mixtures for these two products. Therefore the scope of the project will be restricted to the applications and products that relate to these specific flame retardants.

Earlier legislation has already affected the use of PBDEs in the UK as within Europe their import has been banned since 2004; this includes products with a concentration of c-pentaBDE or c-octaBDE above 0.1 % by weight, (Directive 76/769/EEC), and it is known production stopped in 1998.<sup>2</sup> Therefore within this study it is assumed that this ban has been enforced, and only small quantities of these flame retardants have entered the UK since this date. However, despite this overarching ban, the uses, consumption and end-of-life fate of c-pentaBDE and c-octaBDE are entirely distinct, and they are therefore treated separately within this study.

<sup>1</sup> "Polybrominatediphenyl Ether Project Plan", US EPA, 2006

## C-PentaBDE

Commonly used c-pentaBDE formulations contain a mixture of at least four PBDEs containing an average of approximately five bromine atoms. In the past, c-pentaBDE has been used in phenolic papers used in printed circuit boards (PCBs), drilling fluids, hydraulics, non-foamed polyurethane, and textiles as well as other minor uses.<sup>2</sup> However, it is apparent that either c-pentaBDE is no longer used for these purposes or the quantities used are very small, therefore no further study has been made of these applications.

Historically, by far the largest use has been in flexible polyurethane (PUR) foam, specifically in the furniture and automotive sectors.<sup>3</sup> The highest demand occurred in the USA where its white colouring was desirable<sup>4</sup>, and it is estimated that 95% of world demand arose in the early 2000s.<sup>5</sup> Typical concentrations found in these foams are between 10-18% c-pentaBDE. However other flame retardants have also been used for this application, so this concentration is not indicative of the average concentration arising in PUR foam waste.<sup>6</sup>

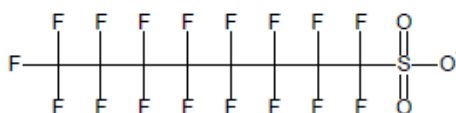
## C-OctaBDE

C-octaBDE was primarily used as a flame retardant in acrylonitrile butadiene styrene (ABS) plastics, and also to a smaller extent in high impact polystyrene (HIPS). Hence the greatest product application is in plastic electronic and electric casings, specifically TV and monitor housings where strict fire regulations were in force. Typical concentrations of c-octaBDE in these plastics are estimated to be between 12 and 15%. However, as with c-pentaBDE other flame retardants have been used for the same application so this concentration is not directly indicative of the concentration found in waste.<sup>7</sup>

## 1.2 PFOS

Perfluorooctane sulfonate (PFOS, see Figure 2) and its derivatives were used as inert surfactant chemicals in a wide range of applications, or as intermediates in the production of PFOS<sup>8</sup>. Recently, PFOS, its salts and perfluorooctane sulfonyl fluoride (POSF) were added to the appropriate annex to the Stockholm Convention due to their nature as persistent organic pollutants<sup>9</sup>.

Figure 2: Chemical structure of perfluorooctane sulfonate (PFOS)



Source: KEMI, 2006

<sup>2</sup> "Draft Risk Management Evaluation: Commercial Pentabromodiphenyl Ether", UNEP August 2007

<sup>3</sup> "Risk Reduction Strategy and Analysis of Advantages and Drawbacks for PentaBDE", RPA, 2000

<sup>4</sup> Willem Hoffland, ICL-IP Corporation, personal communication

<sup>5</sup> BSEF, 2003. Taken from Polybrominated diphenyl Ethers Project Plan, US EPA, 2006

<sup>6</sup> "An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release", M. Alaee et al. *Environmental International*, 2003

<sup>7</sup> "Risk Assessment Report: Diphenyl ether, Octabromo Derivative", EU Commission, 2003

<sup>8</sup> "Draft Guidance document on Alternatives to perfluorooctane sulfonic acid (PFOS) and its derivatives", Stockholm Convention on Persistent Organic Pollutants – POPs Review Committee, 2010

<sup>9</sup> "Stockholm Convention on Persistent Organic Pollutants Stockholm, 22 May 2001 – Adoption of Amendments to Annexes A, B and C"; C.N.524.2009.TREATIES-4, UN, 2009

Many of the applications use PFOS and its derivatives as a process aid (most notably in the chrome plating industry, semiconductor industry). It will not appear in the final products of these processes and use is considered as still acceptable by the Stockholm Convention.

Applications where PFOS may appear in the final product were mainly in the wider textile sector - carpet protection, apparel and leather protection, fabric and upholstery protection - where it was used as an anti-stain agent. Hence it will occur in the disposal routes of these products, including the textile recycling industry and the waste management of upholstery fabrics, carpets, leather and other apparel. Furthermore, PFOS and its derivatives were used to impregnate paper, especially in food packaging. Even though this practice is no longer allowed within the UK, imported packing may still use PFOS derivatives and thus PFOS may end up in recycling streams.

In all of these applications PFOS is mainly present as part of polymers of high molecular weight.<sup>10</sup> Due to impurities, or due to decomposition of the polymer, PFOS itself will be present only in small quantities.

Limited amounts are still held in stock for fire fighting foams, however, with no issues of recycling.

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<sup>10</sup> "Co-operation on Existing Chemicals – Hazard Assessment of Perfluorooctane Sulfonate and its Salts", OECD, 2002

## 2 Conclusions and interpretation

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### 2.1 PBDEs

The historic global production of c-pentaBDE and c-octaBDE were estimated based on available data, and used to derive the UK consumption of these substances. The products in which these flame retardants were present in the UK market were identified. This information was used to construct a model of the arisings of these substances in waste, allowing an estimation of the concentration occurring in current waste streams for automotive waste, furniture and CRT housings. The estimated concentrations are shown below.

Product	ASR* (Vehicles)	PUR Foam (Furniture)	CRT housings
Concentration Ranges for Individual PBDE [mg/kg]	98-156	27-51	13,200 – 16,300
Estimated Total Waste Arisings [tonnes]	430,000	108,500	10,800

\*Automotive Shredder Waste  
Source: Oakdene Hollins estimates

As PBDEs are used as mixtures, these figures represent the estimated concentration range for the most common individual PBDE (including all isomers) found in this waste.

It is concluded, based on concentration levels in existing legislation, that a concentration of 650 mg/kg is the most suitable threshold for each individual PBDE. This is believed to be a conservative level, and should be reviewed and reduced over time as further information becomes available. It should also be mentioned that these flame retardants were used in high concentrations (up to ~20%) but in a minority of products, and these products are now well dispersed within the UK. Therefore it is unavoidable that isolated situations of high concentrations of PBDEs will occur due to these products in the waste streams. However, it is most appropriate to monitor the average concentration in waste.

The concentration of c-pentaBDE in ASR and furniture waste was found to be at a relatively low level and, as this waste is sent to landfill, it will be diluted further at this point. The concentration levels in both these wastes are expected to drop off rapidly in the next two to five years. If a limit is adopted which requires that this waste is treated according to the procedures outlined in the Stockholm Convention, the additional quantity of waste which would require incineration is viewed as prohibitive for the resources currently available. Therefore it is not considered beneficial to attempt to disrupt these waste streams in this circumstance. No impact on the recycling industry is predicted from either of these scenarios, as little or none of this waste is recycled.

The concentration of c-octaBDE in plastic CRT housings was estimated to be much higher than is acceptable for any of the scenarios outlined. Once CRT glass is separated this plastic is then recombined with other WEEE plastic. Existing processing of WEEE demands that plastics containing BFRs are separated out to ensure they do not enter the product streams. In practice, mixed WEEE plastic is mainly sent abroad for sorting to countries such as China. The effectiveness of separation of these plastics in these countries is unclear. If a change is adopted, the most efficient mechanism would be to separate out all CRT housings containing BFRs, and send them for high temperature incineration. This would ensure that

BFRs are removed from recycling streams, and that all PBDEs present are destroyed. However, this would cause significant disruption for recyclers, and additional cost of at least £2m per year is anticipated just for the treatment of this waste. Further costs will be incurred due to extra manpower and supply chain changes. Additionally, this may become less critical over time as the concentration of c-octaBDE is expected to drop. Therefore such a change would be best justified using data analysis of this waste stream, and a study to measure the concentration of c-octaBDE in waste would provide a more robust evidence for this change. An exception for plastic CRT housings could be in place whilst this occurs.

## 2.2 PFOS

Based on the global production of PFOS it was possible to estimate the concentration of this POP in its main consumer products: carpets, workwear/home textiles and coated paper. Due to loss of PFOS during either the use (carpets, textiles) or the recycling phase, the concentration in the corresponding waste is further reduced.

Recycling was found to be an environmentally preferable option for carpets and textiles, as it reduces the average PFOS content due to avoiding imports of new products with a higher PFOS content.

Based on the precautionary principle, a threshold of 1 mg/kg for PFOS was derived at. Waste exceeding this threshold would need to be treated such that the contained PFOS is destroyed or irreversibly transformed.

Product group	PFOS concentration [mg/kg]
Waste from carpets	0.02 - 0.2
Waste from workwear /home textiles	0.04 – 0.1
Waste from coated paper	0.003 – 0.01
Recommended threshold	1

If the recent regulation (EC) 552/2009 limiting the PFOS content in coated materials to a maximum of 0.001 mg/m<sup>2</sup> is adhered to, a fast drop of PFOS concentration in paper and textiles is to be expected. Due to the long lifetime of carpets it may take considerably longer until the phase out is felt for this type of waste. However, due to the fact that both carpets and textiles, the two product groups with the largest potential concentration of PFOS, emit most of their PFOS during their use phase (75% - 95%), the most effective route to reducing PFOS levels in the environment is via enforcing low levels of PFOS in new products.

## 2.3 Recommendations

It is recommended that the threshold for each individual PBDE according to Annex IV EC 850/2004 may be set at 650 mg/kg. This is believed to be a conservative level, so should be reviewed over time as a greater body of evidence is gathered.

C-pentaBDE is found in automotive waste and furniture waste, which under existing practices is sent to landfill. The estimated concentrations of individual PBDEs are well below the threshold suggested above. It is recommended that the level of PBDEs could be assessed and monitored in these wastes to ensure that estimates are accurate, and to provide further information for future reductions in the concentration levels.

C-octaBDE is found in CRT housings at concentrations which are estimated to be well above any reasonable concentration limit. If alternative processing is required as a consequence of this legislation it is suggested that the lowest impact solution is to destroy all CRT housing with BFR content by high temperature hazardous waste incineration. Additionally it is recommended that an analytical study of this specific waste stream could be conducted. This will provide a better basis for implementing suggested changes in recycling practices.

To prevent additional PBDEs entering the waste streams in the future, the existing ban on importing products containing >0.1% c-pentaBDE and c-octaBDE could be strongly enforced and monitored. Related legislation, such as that related to BFRs in WEEE could also be considered at the same time to ensure coherency between how each is implemented.

It is recommended that the threshold for PFOS according to Annex IV EC 850/2004 is set at 1 mg/kg.

As the values used in this study were based on averages and global production numbers, a project to actually measure the PFOS content in samples of textile waste, carpet waste and paper waste could be analysed to verify the estimates of this study.

As most of PFOS emission in carpets and textiles happens during the use phase, the most efficient way to reduce PFOS levels in the environment seems not to be via restricting waste or recycling routes, but via enforcing the already existing limit of 0.001 mg/m<sup>2</sup> according to Regulation (EC) 552/2009.

In a similar fashion a project to actually measure the PFOS content in samples of carpets, workwear / home textiles and coated papers imported into the UK may be initiated. Even though it may be impossible to obtain a representative sample from these imports, more data needs to be generated to obtain an overview, and to gain the confidence that imported products generally conform to the existing limit of 0.001 mg/m<sup>2</sup> (Regulation (EC) 552/2009).

## 3 Methods and approach

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### 3.1 PBDEs

#### Estimation of PBDE concentration in waste

In order to assess the impact of potential legislation on the waste streams and recycling, models have been generated to estimate the levels of PBDEs in relevant UK waste streams. That limited data exist for the production, use and concentration of all BDEs has previously been acknowledged by those working within the relevant industries. Therefore models for world PBDE production were generated, and assumptions about UK consumption were made to estimate the concentrations in UK waste.

The different uses of c-pentaBDE and c-octaBDE, and variations in data available, resulted in the adoption of slightly different methodologies for modelling their concentrations in waste streams. However, both approaches used a similar technique based on estimating the production and consumption of each flame retardant in the UK, then applying these consumption figures to current waste streams for products which have been identified as contained the relevant PBDEs. For each product type the waste processing stage resulting in the highest concentrations of PBDEs was identified, based on current waste management practices. For example, c-octaBDE is present in plastic CRT monitor housings; this plastic is separated from the rest of the components of the monitor under standard practices, before it is mixed with other WEEE plastic. Therefore the highest concentration was associated with this separated plastic. Other scenarios were modelled where appropriate, for example to determine the effect of additional separation of materials.

Further information was gathered for weights, ages and other relevant data for the identified products, which allow an estimate of the average concentration of these flame retardants arising in specific waste streams. Upper and lower estimates are also included in this data to account for uncertainties. The highest concentration of PBDE in any mixture as found to be 65%<sup>11</sup>, therefore concentrations for individual PBDEs were calculated using this factor, as a worst case scenario.

Certain assumptions were made. For example, it has been assumed that PBDEs present in products do not alter or degrade over time. In this case, evidence does exist that this process does occur, but the data were not sufficiently robust to incorporate them. A complete description of the assumptions made for each model can be found in Annex A.

#### Impact on recycling and waste practices

The impact on recycling and waste practices was assessed by estimating the total weight of waste containing PBDEs arising from each scenario, and finding existing disposal options. This data was compared against alternative waste disposal options and UK capacity.

Existing recycling practices relevant to each of these scenarios was identified, and loss of revenue estimated where recycling was prevented through the need for other treatment. The additional cost of separation and disposal was estimated using figures gathered from

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<sup>11</sup> Isomers of pentaBDE in c-pentaBDE. For consistency this was applied across all PBDEs in c-pentaBDE and c-octaBDE which have been classified as POPs.



industry for alternative disposal options. These different scenarios were compared to existing practices to assess the additional cost to recyclers.

### **Definition of a concentration limit for PBDE**

To determine possible concentration limits for PBDE in waste other threshold values were investigated in related legislation, with those applicable to the UK and Europe deemed most relevant. Several limits were obtained, and used to define high, medium and low concentration limits for each of the individual PBDEs. A single consistent level was defined to apply to each individual PBDE, rather a range of values for each PBDE based on the compositions in commercial mixtures.

## **3.2 PFOS**

### **Estimation of PFOS concentration in waste**

Limited data exist for the production, use and concentration of PFOS, especially regarding the years since the phase-out of 3M's production in 2001. Therefore a model for world production and consumption was generated based on available literature. Based on the use of PFOS for different products, and their imports to the UK, an estimate for the average content of PFOS products used and disposed of in the UK can be made.

The focus of this study is on products containing PFOS that are still widely used in the UK and whose disposal is not yet restricted: carpets, textiles and paper. Other applications of PFOS such as fire extinguishers, process aids in the industry and hydraulic fluids in aviation are not within the scope of this study.

Effects of recycling of the investigated products have been included. Imports of waste material of these product groups in the UK are not relevant and have not been included. Further information was gathered for the age of these products, and for the decrease in PFOS concentration during their lifetime.

### **Definition of a concentration limit for PFOS**

The starting point for the definition of a possible concentration limit was the already existing threshold values within Europe, both for PFOS and for other POPs. Based on these, a low- and a high-threshold scenario were defined and discussed with regards to their justifications. As both scenarios were considered unsatisfactory a third scenario was developed which takes both the precautionary principle to protect the environment, and the actual circumstances in the UK, into account.

Details of the assumptions being used can be found in Annex A.

## 4 POPs in the waste stream

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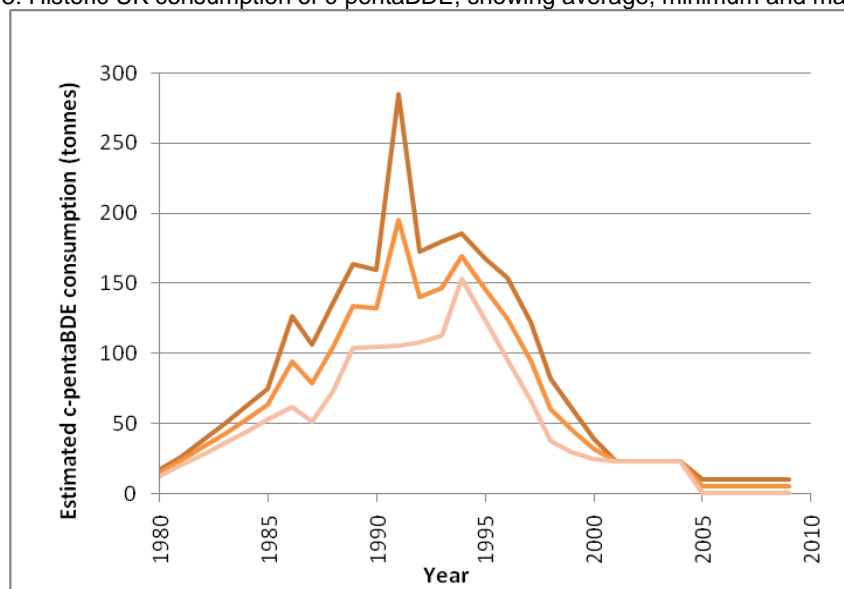
### 4.1 Occurrence of PBDEs in the waste

The calculated concentrations of c-pentaBDE and c-octaBDE are outlined below. The figures given are for a sum concentration of each constituent PBDEs found in these flame retardants. This was believed to be the most appropriate way to report these figures as this is the method typically used elsewhere (with exception to the Stockholm Convention). The concentrations of the most common individual PBDE are then derived from this value using known compositions of commercial mixtures.

#### C-PentaBDE

Accurate historic production data of c-pentaBDE are limited, with few sources available such as WHO.<sup>12</sup> The most complete estimate of pentaBDE consumption is presented by Jones<sup>13</sup> who estimates European consumption from 1970 to 2001. This work provided several scenarios for c-pentaBDE consumption, allowing upper and lower limits to be set for each year. As far as possible this was cross checked with data available elsewhere. To estimate the consumption value for the UK, these scenarios have been scaled according to the historic GDP values for Europe and the UK.<sup>14</sup> This provides maximum and minimum consumption (and average) values for the consumption of c-pentaBDE in the UK. After 2004 it is assumed that annual consumption dropped to 0 for the low estimate, and 10 and 5 tonnes for the high and average model respectively.

Figure 3: Historic UK consumption of c-pentaBDE, showing average, minimum and maximum scenarios



Source: Oakdene Hollins estimates, derived from reference (10)

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<sup>12</sup> WHO, <http://www.inchem.org/documents/ehc/ehc/ehc162.htm>, accessed 12/07/2010

<sup>13</sup> "Estimation of the Production, Consumption, and Atmospheric Emissions of Pentabrominated Diphenyl Ether in Europe between 1970 and 2000", K. Jones et al., *Environmental Science and Technology*, 2004

<sup>14</sup> World Development Indicators, World Bank, 2010, accessed 14/07/2010

## C-pentaBDE in Automotive Waste

Based on historical information, we estimate that 68% of c-pentaBDE consumption in PUR foams was in the automotive sector, and that this figure has remained constant.

An industry representative indicated that, assuming that no unknown manual dismantling occurs prior to processing, all PUR used in vehicles ends up as automotive shredder residue (ASR, which forms the portion of vehicles which it is not economically viable to reuse or recycle). ASR is sent to landfill as further separation or recycling is not economic. Therefore the concentration of c-pentaBDE was calculated for this wastes stream. A further scenario, where the foam was separated out as a separate stream was also modelled for comparative purposes. Figures obtained from industry indicate that approximately 45,000 tonnes of PUR from vehicles are shredded each year, and are incorporated with approximately 430,000 tones of general ASR.<sup>15</sup> In 2010 the mean life of a vehicle in the UK is 14 years, and it is expected that 2 million vehicles will be scrapped in the UK in 2010.<sup>16</sup> This is assumed to be equal to the number of new vehicles registered in 1996. To allow further predictions it has been assumed that this equivalence will continue.

Based on these figures, and the c-pentaBDE consumption scenarios above, the estimated concentrations of c-pentaBDE and individual PBDE in ASR in 2010 are shown in the table below. Figures for automotive PUR foam are also shown for comparative purposes, as it was indicated that further separation is under investigation for future implementation. However, industry representatives stated that PUR foam would be incinerated for energy recovery if this occurs.

Table 3: Estimated concentrations of PBDEs in general ASR and separated PUR foam for 2010

		Mean	Minimum	Maximum
ASR [430,000 tonnes]	Total Concentration of PBDEs [mg/kg]	200	150	240
	% by weight	0.020%	0.015%	0.024%
	Max individual PBDE [mg/kg]	130	98	156
	Max individual % by weight	0.013%	0.001%	0.016%
Separated automotive foam [45,500 tonnes]	Total Concentration of PBDEs [mg/kg]	1,900	1,400	2,300
	% by weight	0.19%	0.14%	0.23%
	Max individual PBDE [mg/kg]	1,240	910	1,500
	Max individual % by weight	0.12%	0.09%	0.15%

Source: Oakdene Hollins estimates

<sup>15</sup> Personal communications with Richard Hooper (Simms Recycling), source data commercially sensitive

<sup>16</sup> SMMT data

The estimates indicate that these values will drop rapidly in the next five years, as the level of c-pentaBDE entering the waste stream falls away (this data are shown in the annex). Within five years the levels are predicted to fall by a factor of ten. However it is also likely that small quantities of c-pentaBDE will enter the automotive waste streams for a long time to come due a small proportion of vehicles which have a much longer lifespan.

It should also be stated that the highest existing concentrations of PBDEs will be found in pure ASR; however in many cases vehicle waste is mixed with other sources of materials prior to shredding, which will reduce this concentration further.

### **C-pentaBDE in Furniture Waste**

Information gathered from various industry sources was used to estimate the quantity of PUR foam used by the furniture industry. From these data the waste PUR foam arisings for furniture were derived. Historically the main uses of PUR foam in furniture have been in seating and bedding, and these applications were focused on. Typically these items are sent to landfill and mixed with other waste. However the waste stream modelled was just for PUR foam containing furniture to provide a worst case scenario. Other, smaller uses of c-pentaBDE may also occur within the furniture sector; however the volumes involved are not expected to significantly influence the final concentration found.

Table 4: Estimated concentrations of PBDEs in waste PUR foam from furniture and total waste for PUR foam containing furniture for 2010.

		Mean	Minimum	Maximum
PUR Foam [108,503 tonnes]	Total Concentration of PBDEs [mg/kg]	60	42	79
	% by weight	0.006%	0.004%	0.008%
	Max individual PBDE [mg/kg]	39	27	51
	Max individual % by weight	0.004%	0.003%	0.005%
Total Furniture Waste* [968,907 tonnes]	Total Concentration of PBDEs [mg/kg]	6.8	4.8	8.9
	% by weight	0.0007%	0.0005%	0.0009%
	Max individual PBDE [mg/kg]	4.4	3.1	5.8
	Max individual % by weight	0.0005%	0.0003%	0.0006%

Source: Oakdene Hollins estimates

\*This does not account for *all* furniture waste, only those products which were included in the model

To provide an accurate model, distinction was made between contract and office furniture, and domestic furniture; this information was gathered from industry sources.<sup>17</sup> Contract and office furniture supplies the commercially focussed area of the furniture market, and was estimated to account for almost 50% of the sales and 40% of the PUR foam usage. There is

<sup>17</sup> Personal communication with Alastair Bromhead (independent consultant) and Craig Anderson (Furniture Reuse Network)

a high usage rate for this furniture and therefore a correspondingly high turnover for these products; the average lifespan is expected to be five years before disposal. Domestic furniture accounted for the remaining 50% of the furniture studied, but accounts for 60% of PUR foam usage, based on industry figures. Domestic furniture was found to have a longer lifespan of 10 years on average. Figures for waste for each of these sectors and uses were obtained, and concentrations of c-pentaBDE and individual PBDE in waste furniture PUR foam were calculated (Table 4). As the materials from furniture are rarely separated, the concentration in the overall waste from the products being modelled was calculated. The average concentration of PBDEs in the foam was also calculated to model a scenario where materials separation does occur. These two scenarios provide an indication of the highest average concentrations likely to be found. In reality this waste is mixed with general landfill material, therefore the concentrations in general furniture and all land filled waste will be much lower.

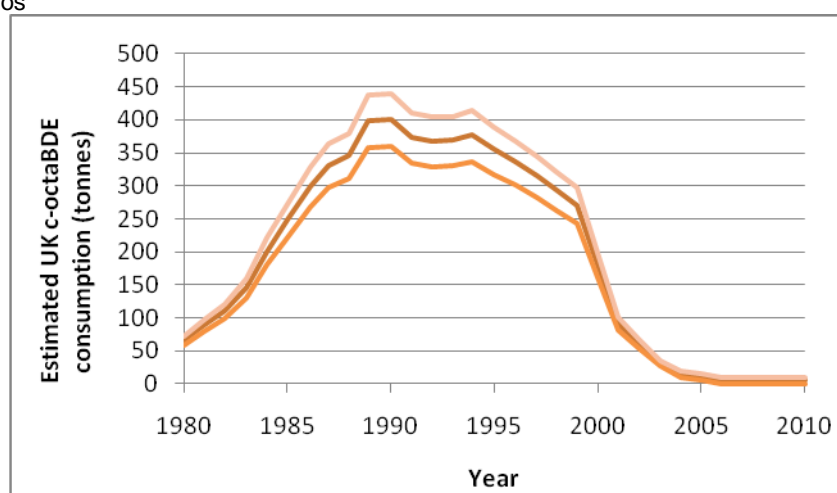
These levels are expected to remain relatively constant for the next five years, due to the lifespan of domestic furniture, and then drop away rapidly (these data are shown in detail in the Annex).

Reuse of furniture does prolong the life of furniture, and this was not fully accounted for as reliable data could not be found. Therefore reuse will increase the time span in which c-pentaBDE enters the waste streams, and will also lower the concentrations seen in the short term.

### **C-OctaBDE**

Due to the limited nature of the data available for c-octaBDE production, use and consumption, alternative sources have been sought to estimate the historic production and UK consumption of c-octaBDE using figures such as world bromine production, total PBDE production, comparisons with other BFR production levels and total fire retardant usage. Estimates for c-octaBDE consumption in the UK are shown in Figure 4.

Figure 4: Estimated UK consumption of C-OctaBDE, showing average, minimum and maximum scenarios



Source: Oakdene Hollins estimates

This defines the quantity of c-octaBDE present in products in the UK over time, including local product manufacturing and imports. As described above, the main use for c-octaBDE has historically been in VDU casings, due to fire regulations.

Figures were obtained to estimate the quantity of televisions, monitors and other display units entering the waste streams. CRT-type VDUs were assessed as these were historically produced when c-octaBDE was commonly used, and are therefore assumed to contain the vast majority of the flame retardant. Under existing UK waste legislation the complete CRT VDU is treated as hazardous waste until the CRT glass is removed; after this has occurred the plastic and other components can be reintroduced into the normal waste or recycling streams, typically after separation into materials. Therefore, due to this initial separation, the plastic arising from waste CRT VDU can be seen as forming a distinct waste stream from other plastics, and this waste stream has been modelled below.

Displays were divided into two categories to reflect different usage patterns – TVs and other, which were assumed to have a lifetime of 12 years, and computer monitors which were assumed to have a lifetime of 5 years. Historically it was assumed that just over 8 million new display units are sold each year, the same quantity is disposed of and that approximately one quarter of these are computer monitors. This was estimated to result in 10,800 tonnes of waste plastic arising from CRT type in 2010.<sup>18</sup> By factoring in the different lifespans of each product type, the expected concentration in all waste housings was calculated (Table 5). A further estimate of the concentration in only the housings which contain BFRs (not only c-octaBDE) has been made as a further scenario; existing data suggests that about 31% of housings contain BFRs.<sup>19</sup> This is to model a scenario where plastics containing brominated flame retardants may be separated out further in the processing.

Table 5: Estimated concentration of c-octaBDE in waste VDU housings in 2010

		Mean	Minimum	Maximum
C-octaBDE in waste housings [10,800 tonnes]	Total Concentration of PBDEs [mg/kg]	22,800	20,300	25,000
	% by weight	2.3%	2.0%	2.5%
	Max individual PBDE [mg/kg]	14,800	13,200	16,300
	Max individual % by weight	1.5%	1.3%	1.6%
C-octaBDE in waste housings containing BFR [3,350 tonnes]	Total Concentration of PBDEs [mg/kg]	73,500	65,600	80,700
	% by weight	7.4%	6.6%	8.1%
	Max individual PBDE [mg/kg]	47,800	42,600	52,500
	Max individual % by weight	4.8%	4.3%	5.3%

Source: Oakdene Hollins estimates

These concentrations are much higher than those seen in the c-pentaBDE and exceed the limits set for c-octaBDE in new products (0.1%) and levels for WEEE to be considered

<sup>18</sup> "New Approach to Cathode Ray Tube Recycling", ICER 2003, and ONS data

<sup>19</sup> "Develop a process to separate brominated flame retardants from WEEE polymers", WRAP, 2006

hazardous waste (0.25%). However, a practical study found comparable concentrations in shredded CRT housings from German waste tested in 2004.<sup>20</sup>

## 4.2 Occurrence of PFOS in the waste

### Production and use of PFOS

In the past, global production of PFOS was dominated by the company 3M until it announced in May 2000 that it would phase out the product from the beginning of 2001 due to environmental concerns. Since then production is estimated to have dropped dramatically, and PFOS derivatives have been substituted with other, less persistent substances. However, as a processing aid it is still used in many applications, as no suitable substitutes could be found.

The data used in this analysis are mainly based on the paper by Paul *et al.* in 2009<sup>21</sup>, which gives an estimate of worldwide production of PFOS from 1985, since the phase-out of 3M's production the data are less reliable. In this work we have defined a "high production" scenario which is based on the estimate by Paul *et al.* of approximately 1,000 tonnes per annum after 2003.

This figure differs significantly from a 2006 OECD survey<sup>22</sup> which reports a production of less than 200 tpa. However, as major producing countries such as China did not take part in this survey, the figure is believed to underestimate global production. Based on the OECD survey and reports on Chinese production<sup>23</sup> a "low production" scenario, which assumes 500 tpa annual production since 2003, was defined.

A graph of the historic development of the production of PFOS including both scenarios for the production since 3M's phase-out is given in Figure 5.

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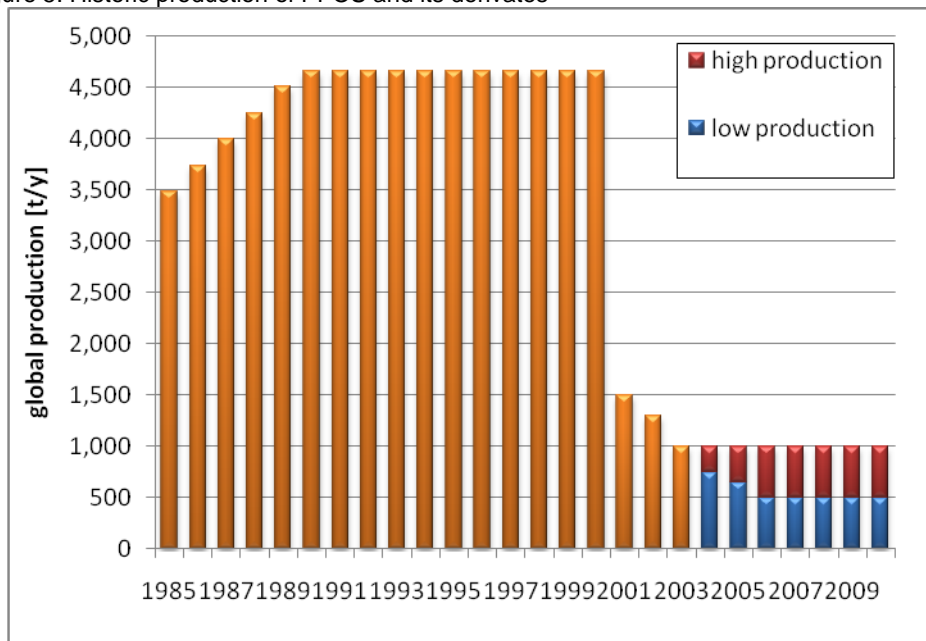
<sup>20</sup> "Analysis of flame retardant additives in polymer fractions of waste of electric and electronic equipment (WEEE) by means of HPLC–UV/MS and GPC–HPLC–UV", Schlummer *et al.*, 2004, *Journal of Chromatography A*

<sup>21</sup> "A First Global Production, Emission and Environmental Inventory For Perfluorooctane Sulfonate", Paul A.G., Jones K.C.J., Sweetman A.J., 2009, *Environ. Sci. Technol.* 43, 386-392

<sup>22</sup> "Results of the 2006 Survey on Production and Use of PFOS, PFAS, PFOA, PFCA, Their Related Substances and Products/Mixtures Containing These Substances", ENV/JM/MONO(2006)36, OECD, 2006

<sup>23</sup> "Obstacles In Risk Management On PFOS in China, Ministry of Environmental Protection China", presentation at "Informal Workshop on Stakeholders' Information Needs on Chemicals in Articles/Products" UNEP, Yao Wei 2009, available at [http://www.chem.unep.ch/unepsaicm/cheminprod\\_dec08/Presentations/YWei%20-%20Obstacles%20In%20Risk%20Management%20On%20PFOS%20In%20China-Yao%20Wei.pdf](http://www.chem.unep.ch/unepsaicm/cheminprod_dec08/Presentations/YWei%20-%20Obstacles%20In%20Risk%20Management%20On%20PFOS%20In%20China-Yao%20Wei.pdf) (accessed 13.08.2010)

Figure 5: Historic production of PFOS and its derivatives



Source: Based on data from Paul et al. 2009, adapted to take the results from OECD 2006 into account

The UK itself has never been a producer of PFOS; however, manufacturers have imported PFOS both as a protection agent for textiles<sup>24</sup>, carpets, leather or paper, and as a processing aid. With the phasing-out of PFOS by 3M, producers in the UK have switched to alternative products, a process which is believed to have been completed at the end of 2003. Since 2009 an EC regulation (552/2009) limits the maximum content of PFOS in imports of coated product is to 0.001 mg/m<sup>2</sup>. To provide a conservative estimate the effect of this regulation is not taken into account in this study.

Robust data for the split of uses for PFOS in different applications are available for the period before 2002.<sup>25,26</sup> These data together with the current use within the OECD led to the “low production” and “high production” scenarios shown in Table 6:

Table 6: PFOS production scenarios

Application	Low production		High production <sup>27</sup>	
	before 2002	after 2003	before 2002	after 2003
Total production	4,650 tpa	500 tpa	4,650 tpa	1,000 tpa
Carpet	23%	14%	48%	38%
Textiles	25%	15%	25%	20%
Paper & Packaging	24%	15%	33%	26%

<sup>24</sup> In this report “textiles” includes clothing and home textiles (e.g. upholstery) but not carpets, as these are such a very significant application segment of PFOS that they are discussed on their own.

<sup>25</sup> “A First Global Production, Emission and Environmental Inventory For Perfluorooctane Sulfonate”, Paul A.G., Jones K.C.J., Sweetman A.J., 2009, *Environ. Sci. Technol.* 43, 386-392

<sup>26</sup> “Perfluorooctane Sulphonate – Risk Reduction Strategy and Analysis of Advantages and Drawbacks”, RPA/DEFRA, 2004

<sup>27</sup> It is recognised that the sum of shares for the high production scenario exceeds 100%, which is due to the fact that the highest reported share for each segment has been used.



## Carpets

Fluorinated compounds are widely used during manufacturing of carpets to provide stain-protection. Especially carpets based on synthetic fibres are being impregnated, whereas the small segment (approx. 1%) of carpets made of natural fibres are usually not treated with fluorinated proofing agents.<sup>28</sup>

PFOS itself is not directly applied to the fibre, but is first chemically bound in a polymer, which is then applied to the carpet. Products containing PFOS exclusively in the form of polymers are in theory not subject to any regulatory restrictions, as the regulatory frameworks (e.g. Stockholm Convention, EC Directive 850/2004, EC Regulation 552/2009) only apply to 'free' PFOS.

However, due to the complex chemical process, part of the PFOS remains as impurity in the polymer and the so-called residual organic fluorochemicals (ROF) content - i.e. the content of fluorinated chemicals not immobilized as polymers - is typically in a range of 2-5%.<sup>29,30</sup> It is this residual amount of free PFOS, together with any PFOS from a decomposition of the polymer during the lifetime of the carpet, which is emitted from the carpet. A life cycle analysis by the company 3M states that approx. 95% of this free PFOS is removed during the lifetime of the carpet due to steam and vacuum cleaning.<sup>31</sup>

An estimate for the content of PFOS in carpets is derived as follows:

- Based on the estimated global use of PFOS for carpets and the global production of carpets, the average content of PFOS-polymer and the average content of residual PFOS are calculated.
- Based on the production and import figures the average concentration of free PFOS is calculated for carpets used in the UK. To calculate the concentration of PFOS in carpet waste, the age distribution is combined with the rate of loss of free PFOS due to wear. Any treatment of carpets with stain-proofing agents after their installation has not been taken into account, as PFOS is no longer used in such agents within the UK since 2004.

An overview of the average concentrations of free PFOS in carpets is given in Table 7.

The expected concentration of PFOS in the waste is currently in the range of 0.06-0.2 mg/kg (0.1 – 0.4 mg/m<sup>2</sup>). Due to the average long lifetime of carpets of about 12 years there is still a high share of carpets treated with PFOS before the phase-out in the waste. Overall the level is slowly decreasing at a annual rate of about 0.005-0.01 mg/kg per year.

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<sup>28</sup> "PFOA in Norway", Statens Forurensningstilsyn, 2007, Norwegian Pollution Control Authority

<sup>29</sup> "A First Global Production, Emission and Environmental Inventory For Perfluorooctane Sulfonate", Paul A.G., Jones K.C.J., Sweetman A.J., 2009, *Environ. Sci. Technol.* 43, 386-392

<sup>30</sup> "Perfluorooctane Sulphonate – Risk Reduction Strategy and Analysis of Advantages and Drawbacks", RPA/DEFRA, 2004

<sup>31</sup> "Sulfonated Perfluorochemicals: U.S. Release Estimation – 1997; Part 1: Life-Cycle Waste Stream Estimate", Battelle Memorial Institute, 2000, for 3M Speciality Materials; company sanitizes version AR 226-0681 available from the EPA (US) on request

Table 7: Summary PFOS in carpets

Material	PFOS content [mg/kg]	
	Low production	High production
New carpet before 2002	1	3
New carpet 2010	0.07	0.3
Carpet waste 2010	0.06	0.2

Source: Oakdene Hollins

Detailed data including graphs of the time trend can be found in the Annex.

## Textiles

Fluorinated compounds are used to render textiles stain- and water-proof. They are mainly applied for home textiles like upholstery and for outdoor wear, especially workwear including uniforms.<sup>32</sup>

Similar to carpets, the PFOS itself is not directly applied but is part of a polymer. Again, some PFOS remains, as impurity in the polymer gives rise to the residual PFOS content which is typically in the range of 1-2%.<sup>33,34</sup> A life cycle analysis by the company 3M states that approx. 75% of this free PFOS is removed during the lifetime of the textile due to wear and cleaning.<sup>35</sup>

An estimate for the content of PFOS in textiles is derived as follows:

- Based on the estimated global use of PFOS for textiles and an estimate of the global production of workwear and home textiles, the average content of PFOS-polymer and the average content of residual PFOS are calculated.
- Based on the production and import figures the average concentration of free PFOS is calculated for textiles used in the UK.
- To calculate the concentration of PFOS in waste the age distribution is combined with the rate of loss of free PFOS due to wear. Any treatment of carpets with stain proofing agents after their installation has not been taken into account, as PFOS is no longer used in such agents within the UK since 2004.

An overview of the average concentrations of free PFOS in this group of textiles is given in Table 8.

<sup>32</sup> "Perfluorinated substances and their uses in Sweden", Report 7/06, Swedish Chemicals Agency, KEMI, 2006

<sup>33</sup> "A First Global Production, Emission and Environmental Inventory For Perfluorooctane Sulfonate", Paul A.G., Jones K.C.J., Sweetman A.J., 2009, *Environ. Sci. Technol.* 43, 386-392

<sup>34</sup> "Perfluorooctane Sulphonate – Risk Reduction Strategy and Analysis of Advantages and Drawbacks", RPA/DEFRA, 2004

<sup>35</sup> "Sulfonated Perfluorochemicals: U.S. Release Estimation – 1997; Part 1: Life-Cycle Waste Stream Estimate", Battelle Memorial Institute, 2000, for 3M Speciality Materials; company sanitizes version AR 226-0681 available from the EPA (US) on request

Table 8: Summary PFOS in workwear and home textiles

Material	PFOS content [mg/kg]	
	Low production	High production
New workwear/home textiles 2010	0.1	0.25
Workwear/home textiles waste 2010	0.04	0.1
Combined textiles waste 2010	0.01	0.02

Source: Oakdene Hollins

The values shown in the table are expected to remain stable for the next few years as the effect of phasing out PFOS in the USA and in Europe has already been absorbed. However, it may be expected that PFOS production will continue, especially in Asian countries, referring to a specific exemption for use in textiles and upholstery in the Stockholm Convention.

## Paper and Packaging

Fluorinated compounds are used to render paper and cardboard grease- and water-proof and are thus applied only in a small part of the market. Such types of coated papers are of special importance in the food industry. As with carpets and textiles, PFOS itself is not directly applied but is part of a polymer. Again, some PFOS remaining as impurity in the polymer gives rise to the residual PFOS content which is typically in a range of 1%.<sup>36,37</sup>

An estimate for the content of PFOS in coated paper is derived as follows:

- Based on the estimated global use of PFOS for paper and packaging and an estimate of the global production of coated paper, the average content of PFOS-polymer and the average content of residual PFOS are calculated.
- Based on the production and import figures, the average concentration of free PFOS is calculated for coated paper used in the UK.
- To calculate the concentration of PFOS in waste, recycling is taken into account.

An overview of the average concentrations of free PFOS in coated paper is given in Table 9.

Table 9: Summary PFOS in coated paper

Material	PFOS content [mg/kg]	
	Low production	High production
New coated paper 2010	0.002	0.01
Coated paper waste 2010	0.002	0.01
Combined paper waste 2010	0.001	0.004

Source: Oakdene Hollins

As with textiles, no major change in concentration is expected within the next few years.

<sup>36</sup> "A First Global Production, Emission and Environmental Inventory For Perfluorooctane Sulfonate", Paul A.G., Jones K.C.J., Sweetman A.J., 2009, *Environ. Sci. Technol.* 43, 386-392

<sup>37</sup> "Perfluorooctane Sulphonate – Risk Reduction Strategy and Analysis of Advantages and Drawbacks", RPA/DEFRA, 2004

## Summary

### PBDEs

Analysis of PBDE production and use has provided the concentrations of these substances in existing wastes streams to be determined, summarised in Table 10.

Table 10: Summary of PBDE concentrations in waste.

Product	ASR (Vehicles)	PUR Foam (Furniture)	VDU housings
Concentration Range for Individual PBDE [mg/kg]	98-156	27-51	13,200 – 16,300
Estimated Total Waste Arisings (tonnes)	430,000	108,500	10,800

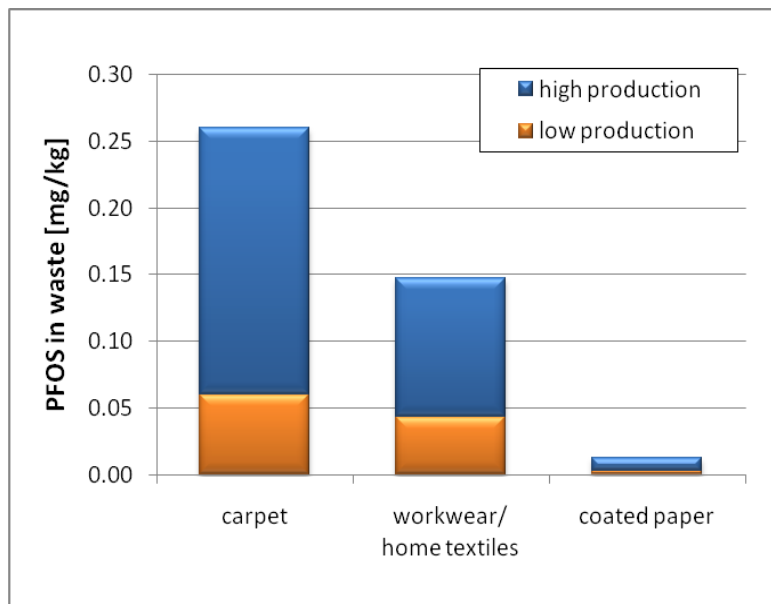
Source: Oakdene Hollins estimates

The impacts of these levels are discussed in the next section.

### PFOS

By analysis of current PFOS production, its use for different applications and the lifetime of the related products an estimate of PFOS concentration both in new products and in the corresponding waste was obtained. An overview is given in Figure 6:

Figure 6: Overview of PFOS in waste



Source: Oakdene Hollins

## 5 Impact on recycling and waste processing

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### 5.1 PBDEs

#### C-pentaBDE

In the course of this study the end of life fate for the two primary uses of PUR foam containing c-pentaBDE was determined. The origin, volume and existing management practices for this waste were considered when assessing the impacts on the recycling and waste processing industry.

All PUR foam in vehicles, and therefore all the c-pentaBDE (assuming little is lost during the shredding process), is known to end up in ASR. ASR forms the portion of vehicles which is not recycled, and is used as lining for landfills. Therefore, no impact on the recycling streams due to PBDE content is predicted. The concentrations of PBDE found for ASR is estimated to be between 98-156 mg/kg; this will be further diluted with other shredder residue when sent to landfill. If these levels set for c-pentaBDE concentration meant other disposal options were required, an extra 430,000 tonnes of ASR or 45,500 tonnes of PUR foam from vehicles, would have to be treated, most likely by hazardous waste incineration.<sup>38</sup> The volume of this disposal is considered to be prohibitive, as the total capacity of suitable hazardous waste incineration in the UK is approximated 100,000 tpa, and spare capacity much less than this.<sup>39</sup> Separation of PUR foam on the necessary scale is also considered prohibitive at this stage.

The life of furniture is highly variable, depending on the specific type and usage. However, almost all waste furniture in the UK is sent to landfill, with little recycling or energy recovery occurring. Therefore any concentration of c-pentaBDE is unlikely to strongly influence the recycling industry. More generally, the estimated concentrations are low enough that this waste can be treated normally, as it is not considered hazardous. The concentration for the most common individual PBDEs in PUR foam is estimated to be between 27 to 51 mg/kg; this will be reduced further if the entire furniture waste stream is considered. As with ASR, the volume of furniture or PUR foam from furniture which would require additional disposal is greater than alternative disposal options are able to handle at this time. The scale of operations required for separation is also considered prohibitive. However, due to the low concentrations of c-pentaBDE present, this is not believed to be an issue.

#### C-octaBDE

As described above, all the waste plastic arising from CRT housings is assumed to form a separate waste stream, as these VDUs are treated as hazardous waste until separation of materials occurs (though this plastic may eventually be mixed with other WEEE plastics).

The concentrations estimated for c-octaBDE in plastic CRT housings exceeded all safe recommended levels found. It also constitutes hazardous waste electrical products as the levels are above 0.25%, therefore it should be treated as such. Separation should already occur due to the WEEE Directive which requires that plastics containing bromine are

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<sup>38</sup> A temperature of above 850°C is required to completely destroy these substances other hazardous chemicals such as dioxins which are generated during low temperature combustion.

<sup>39</sup> Personal communication, Jacob Hayler, Environmental Services Association

separated out and that they do not re-enter the product stream.<sup>40</sup> However, the presence of POPs poses additional issues as - unless an exemption is present - these substances are required to be destroyed or irreversibly transformed.

Several possible methods were identified to remove c-octaBDE from the waste stream. These rely on the fact that VDUs containing CRTs are treated separately as hazardous waste until the CRT glass is removed. Therefore separation of the plastic at this stage, prior to mixing with other waste, would be the most effective isolation route. The two options believed to be most suitable are described below; other discarded options can be found in the Annex. The majority of these data were obtained from a WRAP report investigating the possible processing options for WEEE plastics containing BFRs.<sup>41</sup>

Both of these routes rely on specialist incinerators to destroy the waste. The nearest alternative, use of fuels in cement kilns was also considered. However, industry sources stated this is not possible as kilns based in the UK are unable to handle the level of bromine present in this waste. There are also additional complications of calorific value and capacity – therefore this disposal route was discounted as implementation is likely to be difficult on a short timescale.

### ***Separation of all BFR containing housings from CRT waste***

A simple scanner (costing around £3,500) has been shown to be effective at distinguishing between plastics that contain BFR and those that do not. Though each casing would have to be tested, this could be done in a matter of seconds prior to disassembly of the CRT. This would cause some disruption to reclamation processes, and increase the time and expense of processing, as separation of BFR containing plastics currently occurs abroad. This would reduce the quantity of recycled plastics arising from CRT housings by an estimated 3,350 tpa, with a market value of £335,000 at £100 per tonne.<sup>41</sup> Additionally, incineration is required which is estimated to cost £450 per tonne for this waste when baled (this baling is assumed to occur anyway).<sup>42,43</sup> Therefore, the overall increased cost - omitting additional labour, equipment and transport costs - is estimated to be just over £2m per year.

### ***Incineration of all waste plastic arising from waste plastics***

Rather than separating out the BFR- and non BFR-containing plastics, all casings could be sent to incineration. Based on the costs above, this would reduce the value of CRT waste by £1m per year and incur incinerations costs of £5.5m per year, based on the figures used above.

The difference in cost between the above scenarios is approximately £3.5m. This is higher than the likely additional costs associated with sorting during CRT disassembly and other costs required in the first scenario. In addition to this, spare capacity in the UK for this type of incineration is estimated to be 5,200 tpa, and the quantity of plastic requiring processing in

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<sup>40</sup> The WEEE directive requires that all plastic containing BFRs arising from WEEE is removed prior to recycling or further processing and ensure that BFRs do not re-enter the product stream.

<sup>41</sup> Develop a process to separate brominated flame retardants from WEEE polymers, WRAP, 2006

<sup>42</sup> A temperature of above 850°C is required to completely destroy these substances and other hazardous chemicals such as dioxins which are generated during low temperature combustion. In addition to this, hydrogen bromide may be formed which is corrosive and requires special treatment.

<sup>43</sup> Figures for hazardous waste incineration obtained from the Environmental Services Association

the second option is 11,800 tonnes. Therefore, this precludes the second scenario unless more expensive export options are adopted.

Introducing one of these measures is likely to provide additional environmental benefits. This processing would ensure the destruction of not just c-octaBDE in this plastic, but also all BFRs. Though separation should occur, the efficiency of this separation is not clear as this processing occurs abroad after export. Therefore ensuring this process occurs in the UK would provide a greater degree of control over the fate of this plastic, though it only represents a small portion of WEEE plastics.

It should be noted that the model predicts that the CRT waste is likely to reduce rapidly over the next few years (see Annex), and therefore the quantity of c-octaBDE-containing plastics will reduce. This change would impact existing recyclers of CRT and may lower existing levels of processing. A full scale analysis of this waste could be conducted to provide material evidence of high levels of c-octaBDE in present in this waste. This would provide better justification for the implementation of different processing strategies.

## 5.2 PFOS

### Relevance and effect of recycling

The effect of recycling was not included in the mass balances except for paper, as recycling rates for carpets and textiles are still very low (1%-5%).

To determine the effect of recycling of carpets and textiles on the issue of PFOS three scenarios were compared:

- no recycling
- recycling at the current rate (1% for carpets<sup>44</sup>, 5% for textiles<sup>45</sup>)
- recycling at an increased rate (10% for carpets, 10% for textiles)

For all scenarios the concentration of PFOS in freshly installed carpets and manufactured workwear is compared. The results of these scenarios are shown in Table 11.

Table 11: Effect of recycling on PFOS concentrations

Product group	Recycling rate	Change in PFOS concentration [mg/kg]	
		Low production	High production
Carpets	1% recycling	-0.0001	-0.001
	5% recycling	-0.001	-0.012
Workwear / home textiles	5% recycling	-0.003	-0.008
	10% recycling	-0.006	-0.016

Source: Oakdene Hollins

As can be seen from the data, the effect of current and significantly higher recycling rates on PFOS content is in general small. For carpets and textiles, recycling is lowering the PFOS content in products. This is due to the fact that recycled products containing less PFOS are crowding out freshly made imports with a higher concentration of PFOS.

<sup>44</sup> "Flooring: Towards a Resource Efficiency Plan", Contract Flooring Association, P. Thomas, 2009

<sup>45</sup> "Maximising Reuse and Recycling of UK Clothing and Textiles EV0421", Defra, Oakdene Hollins, 2009

For coated paper recycling leads to a distribution of PFOS into other types of paper due to the high overall recycling rate of approx. 70% for paper<sup>46</sup>. This can lead to a PFOS concentration of max. 0.001-0.004 mg/kg in general paper.

### Impact of different threshold limits on recycling

As discussed above, a threshold limit on PFOS in waste preventing certain products from being recycled is not expected to lead to a significant reduction of PFOS in the UK, provided imports containing PFOS still occur. Such a threshold limit does not only prevent waste from being recycled but also requires a method of disposal fit to destroy all contained POPs. As there are currently not commercially available techniques to separate waste containing PFOS from waste containing other organoflourine chemicals, all waste from the corresponding category could no longer be recycled but would require disposal in suitable high temperature incinerators<sup>47</sup>.

A rough estimate of the economic burdens from disposing carpets, workwear/home textiles and coated paper can be made based on the extra costs of incineration. This calculation, which does neither include any investments in new capacities, nor in the infrastructure of collection and storage, results in additional cost in the range of £15-65 m per year.

### Conclusions

Except for old carpets, the original sources of PFOS in waste are imports from outside Europe. Consequently, recycling of waste is, in principle, a preferable environmental option as it reduces the need to acquire new products, which will – at least partially – be imported from countries not yet curtailing the use of PFOS.

Additionally, all involved products lose a considerable amount of their PFOS content during their lifetime or during recycling.

Recycling of waste from carpets and textiles decreases the presence of PFOS in the UK. However, this effect is small as recycling rates for carpets and textiles are currently low. Coated paper is an exception; recycling of waste from coated paper leads to contamination of other paper qualities by PFOS. If recycled paper is used for production of coated paper within the UK, then, similar to carpets and textiles, a reduction of PFOS content due to crowding out of imports is achievable. However, if recycled paper is only used for non-coated paper qualities, then imports of coated paper will remain the same and a low PFOS concentration (max. 0.001 - 0.004 mg/kg) will establish itself in general paper waste.

Table 12: Overview of effect of recycling on PFOS concentration

Selected product group	Carpets	Workwear Home textiles
Loss of PFOS during use or recycling stage	95%	75%
Current recycling rate of sector	1%	5%
Decrease of PFOS content due to current recycling	0.5%	3%

Source: Oakdene Hollins

<sup>46</sup> “Recovery and Recycling of Paper and Board”, confederation of paper industries, CPI, 2009, available at [http://www.paper.org.uk/information/factsheets/recovery\\_and\\_recycling.pdf](http://www.paper.org.uk/information/factsheets/recovery_and_recycling.pdf) (accessed 05.08.2010)

<sup>47</sup> “Perfluorooctane Sulfonate (PFOS)”, Swedish Chemical Inspectorate (KemI), 2004



A threshold limit banning the recycling of these materials, and simultaneously requiring incineration of all waste from these products, would lead - in a first, crude approximation - to additional cost in the range of £ 15-65m per year. Even more importantly, the additional amount of up to 1.8m tpa of waste for incineration may well exceed current disposal capacities.

## 6 Proposed concentration levels

### 6.1 PBDEs

#### General comments

Within the Stockholm Convention and corresponding legislation, individual PBDEs, rather than the commercially used mixtures are described. However, within products and other legislation the total concentration of either c-pentaBDE or c-octaBDE are referred to, therefore most commonly limits are based on the total concentration of PBDEs. To propose concentrations for the individual PBDEs, existing limits have been taken and, where necessary, scaled using the maximum identified percentage composition of each PBDE found in c-pentaBDE and c-octaBDE mixtures. Table 13 shows this information for the medium scenario, based on a limit on the commercial mixture concentration of 1000mg/kg.

Table 13: Example of concentration limit scaling, using medium scenario of 1000mg/kg

PBDE	Maximum percentage identified in c-pentaBDE or c-octaBDE*	Threshold based on individual proportion percentage	Single threshold for all, based on highest proportion
Tetra-BDE (all isomers)	42%	420 mg/kg	650 mg/kg
Penta-BDE (all isomers)	65%	650 mg/kg	
Hexa-BDE (all isomers)	12%	120 mg/kg	
Hepta-BDE (all isomers)	45%	450 mg/kg	

However, for consistency rather than setting individual levels based on different concentrations in c-pentaBDE and c-octaBDE, a single level has been set for all PBDEs with highest concentration identified used as the threshold for all PBDEs. Table 14 shows the low, medium and high threshold scenarios for PBDEs calculated using this method.

Table 14: Proposed concentration limits for PBDEs

Scenario	Description	Base	Base limit	Proposed Threshold
L	Low threshold scenario	Common limit for POPs in Annex 4 of the Stockholm convention.	50 mg/kg (0.005%)	50 mg/kg (0.005%)
M	Medium threshold scenario	Current limit set for new products in the EU.	1,000 mg/kg (0.1%)	650 mg/kg (0.065%)
H	High threshold scenario	Current limit set for hazardous wastes.	2,500 mg/kg (0.25%)	1,625 mg/kg (0.16%)

#### **Low threshold scenario**

The low threshold scenario is based on the existing EC legislation for POPs (EC Regulation 1195/2006) which sets a limit 50 mg/kg (0.005%) for the majority of POPs. No scaling was implemented as this is a common level used for many POPs. Whilst this value fits with legislation for existing POPs, it is not necessarily directly applicable to PBDEs from a scientific standpoint. In addition to this, existing POPs have experienced longer bans and

therefore a low concentration limit can be assigned without impacting waste, recycling or other forms of processing.

None of the waste streams can confidently be predicted to fall below this level, and adoption of this limit may cause issues due to the additional disposal burden of these wastes, which would most likely need to be incinerated due to the need to destroy the PBDEs. However, for the average scenarios described above for PBDE, it is predicted that the concentration in ASR will fall below this level in around five years, and furniture within two years. Therefore this could be a realistic longer term target level.

The concentration found for VDU housings is around 300 times this value at present, and is unlikely to fall below this level in the near future.

### ***Medium threshold scenario***

The medium threshold scenario of 650 mg/kg is based on a value of 1000 mg/kg (0.1%) from legislation. 1000 mg/kg is the value defined in EC Directive (2003/11/EC) as the maximum level at which both c-pentaBDE and c-octaBDE can be present in products being placed on the market. At this concentration both substances will be ineffective as flame retardants, but a small residual amount is likely to be present either through recycling or the presence and possible degradation of c-decaBDE.

The concentrations of individual PBDEs found in PUR foam from vehicle and furniture waste are both well below 650 mg/kg, therefore no impact would be seen. Again the concentration of PBDEs found in VDU casings is well above this level.

As this concentration limit already exists in legislation in a slightly different form, it is probably the simplest to adopt, and will also have minimal effect on the waste streams. However, it is still significantly higher than allowed for other POPs.

### ***High threshold scenario***

The high threshold scenario is set at 1,625 mg/kg (0.16%), and is based on the EU definition that any electronic waste containing over 0.25% c-pentaBDE should be treated as hazardous waste.<sup>48</sup>

This represents an extreme scenario and should only be considered if absolutely necessary due to the high concentration of PBDEs allowable. Little difference in impact between this level and the medium threshold is evident as the CRT housing waste is estimated to have a higher concentration.

## **6.2 PFOS**

### **General**

The aim of setting a concentration level for PFOS according to Annex IV of EC Regulation 850/2004 is to prevent emissions of PFOS from the waste and to contribute to a stabilisation or even reduction of PFOS concentrations in the environment.

As this study reflects, the main share of emissions of PFOS takes place during the use phase of the products. In the recycling and disposal phase PFOS is likely to enter into the environment either via leachates from landfills, process water from recycling (paper) and

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<sup>48</sup> Draft risk management evaluation: commercial pentabromodiphenyl ether, UNEP, 2007

from the off-gas of incinerates operating at temperatures below 760°C. An overview of all expected pathways is given in the Annex.

In order to arrive at a suitable threshold limit of PFOS in waste in the UK, three scenarios were derived based on already existing concentration levels for either PFOS or for other persistent organic chemicals, Table 15.

Table 15: Proposed concentration limits for PFOs

Scenario	Description	Base	Threshold
L	Low threshold scenario	limit for sewage sludge / German federal states	0.1 mg/kg
M	Medium threshold scenario	Low threshold scenario and waste composition	1 mg/kg
H	High threshold scenario	current limit values for most POPs in Annex IV	50 mg/kg

### **Low threshold scenario**

The only type of solid waste that limits values for PFOS that could be found was sewage sludge. The low threshold scenario is based on the “precautionary” threshold of 0.1 mg/kg for the total of PFOS and PFOA in sewage sludge enforced in a number of federal states in Germany (e.g. Nordrhein-Westfalen, Baden Württemberg, Bayern) and which is expected to be included into the next revision of Germany’s Federal Regulation on sewage sludge.<sup>49</sup> Sewage sludge exceeding these values is no longer allowed to be used as fertilizer in agriculture. Additionally, this threshold has already been included into a recent revision of Germany’s regulation of fertilizers.

This threshold is based, among others, on a study on the use of potable water contaminated with PFOS and similar perfluorinated compounds.<sup>50</sup> Based on the toxicological properties of PFOS, these studies derived an acceptable lifelong concentration of 0.3 µg/l of PFOS in potable water and supported - in accordance with the precautionary principle - a concentration limit of 0.1 µg/l PFOS. In the UK similar levels have been set. Action is required to be taken by water providers as soon as a level of 0.3 µg/l of PFOS is exceeded.<sup>51</sup>

By limiting the concentration of sewage sludge to 0.1 mg/kg it is believed that the concentration of PFOS in the ground water will remain below 0.1 µg/l.

<sup>49</sup> "PFC in Abfällen und im Klärschlamm", MUNLV NRW, U. Sauerland, 2009, available at [http://www.umweltbundesamt.de/wasser-und-gewaesserschutz/publikationen/fqpf/pfc\\_in\\_abfaellen\\_und\\_klaerschlamm-sauerland.pdf](http://www.umweltbundesamt.de/wasser-und-gewaesserschutz/publikationen/fqpf/pfc_in_abfaellen_und_klaerschlamm-sauerland.pdf) (accessed 13.08.2010)

<sup>50</sup> “Vorläufige Bewertung von Perfluorierten Tensiden (PFT) im Trinkwasser am Beispiel ihrer Leitsubstanzen Perfluorooctansäure (PFOA) und Perfluorooctansulfonsäure (PFOS)“, Trinkwasserkommission BMG UBA, 2006, available at <http://umweltbundesamt.de/uba-info-presse/hintergrund/pft-im-trinkwasser.pdf> (accessed 13.08.2010)

<sup>51</sup> “Guidance on the Water Supply (Water Quality) Regulations 2001 specific to PFOS (perfluorooctane sulphonate) and PFOA (perfluorooctanoic acid) concentrations in drinking water”, Drinking Water Inspectorate, 2009, [http://www.dwi.gov.uk/stakeholders/information-letters/2009/10\\_2009Appendix.pdf](http://www.dwi.gov.uk/stakeholders/information-letters/2009/10_2009Appendix.pdf) (accessed 13.08.2010)

A concentration limit of 0.1 mg /l may seem justified from the precautionary principle for a product directly exposed to rainfall with an uninhibited pathway into the groundwater.

However, the affected product groups (paper, carpet and workwear/home textiles) are mixed with other waste when landfilled, while the emission of PFOS via leaching of a landfill is expected to be considerably less than “leaching” of fertilizer on a field. Consequently, this threshold is considered to be too low to be defensible, based on the current state of knowledge.

### **Medium threshold scenario**

The medium threshold scenario is based on the threshold of 1 mg/kg. This value is derived from the low threshold scenario (0.1 mg/kg) taking into account the average composition of waste in landfills in the UK.

The only sources of PFOS in landfills to be expected are spent carpets, textiles and paper. Other PFOS sources, like chemicals or process aids, need to be disposed of as hazardous waste in any case. Consequently, it is possible to derive at the maximum concentration of PFOS acceptable in this waste to ensure that the overall concentration of 0.1 mg/kg in the landfill is not exceeded:

Table 16: Determination of the medium threshold value

<b>Lower threshold</b>	<b>0.1 mg/kg</b>
PFOS containing waste	1 mln tpa
Total waste to landfill	65 mln tpa
Share of PFOS waste in landfill	2%
Max. concentration in PFOS waste	5 mg/kg
Medium threshold value	1 mg/kg

However, the effective concentration of PFOS in the landfill may vary due to local industry. Additionally, the uncertainty of the data used to derive at this threshold is rather high. To account for this, and in line with the precautionary principle, it is proposed to set the limit value at 1 mg/kg.

This threshold value is above the concentrations estimated for carpets, workwear/home textiles and paper by a factor of 5–1,000. It is therefore not expected that this concentration limit will impede recycling of this materials, while at the same time sufficiently protecting the environment.

### **High threshold scenario**

The high threshold scenario is based on the threshold of 50 mg/kg for waste from most POPs set by EC Regulation 1195/2006 amending Annex IV to Regulation (EC) No 850/2004. The same limit is adopted by the EC for new products (EC Regulation 552/2009).

Even though it would be conceptually straightforward to prescribe for PFOS the same threshold as for the other POPs, this position is not scientifically defensible. It may however, be an acceptable temporary solution within a Member State until a threshold value for the whole of the EU is defined.

## Annex A:

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Please see attached document (Appendix).