# Guidance on best available techniques and best environmental practices relevant to the polybrominated diphenyl ethers (PBDEs) listed under the Stockholm Convention on Persistent Organic Pollutants

March 2021

STOCKHOLM CONVENTION

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# Acknowledgements

The work to review and update the guidelines and guidance on best available techniques and best environmental practices is conducted by the experts on best available techniques and best environmental practices in accordance with the terms of reference set out in annex to decision SC-8/6, thanks to the generous financial support provided by European Union through the European Commission Global Public Goods and Challenges (GPGC) programme and through the in-kind contributions of the nominated experts. The valuable input of the experts nominated by Parties and others to be consulted in the process for review and update of the guidelines and guidance is highly acknowledged. The experts' names are listed in the joint Toolkit and BAT and BEP expert roster, accessible on the Stockholm Convention's website.

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# Preface

This document has been initially developed in 2012 by the United Nations Industrial Development Organization (UNIDO) and the United Nations Institute for Training and Research (UNITAR), working in collaboration with the Secretariat of the Stockholm Convention and with financial support of the Global Environment Facility (GEF). In 2013, further to the request of the Conference of the Parties (COP) to the Stockholm Convention, the document has been revised in the frame of the Stockholm Convention best available techniques (BAT) and best Environmental Practices (BEP) expert process, based on comments received from parties and others, and submitted for consideration by the COP in 2015. The present document supersedes the guidance on BAT/BEP issued in January 2017 (re-issued for technical reasons in March 2017) (http://chm.pops.int/Implementation/NIPs/Guidance/GuidanceonBATBEPfortherecyclingofPBDEs/tabid/3172/Default.aspx), contains most up-to-date information and knowledge as evaluated and integrated in the guidance by the BAT and BEP experts, and supersedes the previous versions. The initial contribution of contributory organizations and the expert input provided by the BAT and BEP group of experts is highly acknowledged. Before finalization, the draft document was circulated for comments to Parties and others in September 2020.

# Abbreviations and acronyms

| | |
|---|---|
| ABS | Acrylonitrile-butadiene-styrene |
| ASR | Automotive shredder residue |
| BAT | Best available techniques |
| BDP | Bisphenol A-bis (diphenylphosphate) |
| BEP | Best environmental practices |
| BFR | Brominated flame retardant |
| BSEF | Bromine Science and Environmental Forum |
| c-decaBDE | Commercial decabromodiphenyl ether |
| c-octaBDE | Commercial octabromodiphenyl ether |
| c-pentaBDE | Commercial pentabromodiphenyl ether |
| CFC | Chlorofluorocarbon |
| CKD | Cement kiln dust |
| COP | Conference of the Parties |
| CRT | Cathode ray tube |
| DecaBDE | Decabromodiphenyl ether |
| DOPO | 9,10-Dihydro-9-oxa-10-phosphaphenanthrene oxide |
| EAF | Electric arc furnace |
| EEE | Electrical and electronic equipment |
| ELV | End-of-life vehicle |
| EMS | Environmental management system |
| ESM | Environmentally sound management |
| FPF | Flexible polyurethane foam |
| FR | Flame retardant |
| GHG | Greenhouse gas |
| HeptaBDE | Heptabromodiphenyl ether |
| HexaBDE | Hexabromodiphenyl ether |
| HBCD | Hexabromocyclododecane |
| HFC | Hydrofluorocarbon |
| HIPS | High impact polystyrene |
| HxBB | Hexabromobiphenyl |
| ISWA | International Solid Waste Association |
| MSW | Municipal solid waste |
| NIR | Near-infrared |
| ODS | Ozone depleting substances |
| PBB | Polybrominated biphenyl |
| PBDE | Polybrominated diphenyl ether |
| PBDD/PBDF | Polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans |
| PBT | Polybutylene terephthalate |
| PC | Polycarbonate |
| PCB | Polychlorinated biphenyl(s) |
| PCDD/PCDF | Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans |
| PentaBDE | Pentabromodiphenyl ether |
| PET | Polyethylene terephthalate |
| PFR | Phosphorous based flame retardant |
| POPs | Persistent organic pollutants |
| POPRC | Persistent Organic Pollutants Review Committee |
| PP | Polypropylene |
| PPE | Polyphenyl ether |
| PPO | Polyphenylene oxide |
| PS | Polystyrene |

| | |
|---|---|
| PUR | Polyurethane |
| PVC | Polyvinylchloride |
| PWB | Printed wiring board |
| PXDD/PXDF | Polyhalogenated dibenzo-p-dioxins and polyhalogenated dibenzofurans |
| RDP | Resorcinol-bis(diphenylphosphate) |
| RoHS | Restriction of the use of certain hazardous substances in electrical and electronic equipment |
| S/F | Sink and float |
| SVOC | Semi-volatile organic compound |
| TetraBDE | Tetrabromodiphenyl ether |
| VOC | Volatile organic compound |
| WEEE | Waste electrical and electronic equipment |
| WtE | Waste to energy |
| XRF | X-ray fluorescence |
| XRT | X-ray transmission |

# Executive Summary

PBDEs have been produced and used in different sectors, including electrical and electronics, transport (automotive and aviation), construction, furniture, textiles and carpets, and recycled, until the progressive ban under the Stockholm Convention. The production and use of PBDEs is restricted with specific exemptions for a limited number of applications. Exemptions for hexa- and heptaBDE and for tetra- and pentaBDE are respectively included in Parts IV and V of Annex A to the Stockholm Convention. Exemptions for decaBDE are defined under Part IX of Annex A.

Despite the ban, large volumes of PBDE-containing stockpiles and articles will continue to be used in consumer articles (in the aforementioned sectors) before entering the global recycling flow, since these are durable consumer and industrial products whose lifetime is relatively long (up to several decades).

The listing of decaBDE in Annex A under the Stockholm Convention in 2017 marked an important milestone. The estimated total global production of decaBDE has been over 1 million tonnes over the period 1970 to 2005, which counts for approximately ten times that of tetra-, penta-, hexa- and heptaBDE, significantly increasing the quantity of PBDEs banned globally. As a result, several alternatives have been made available for the use of these chemicals in different applications.

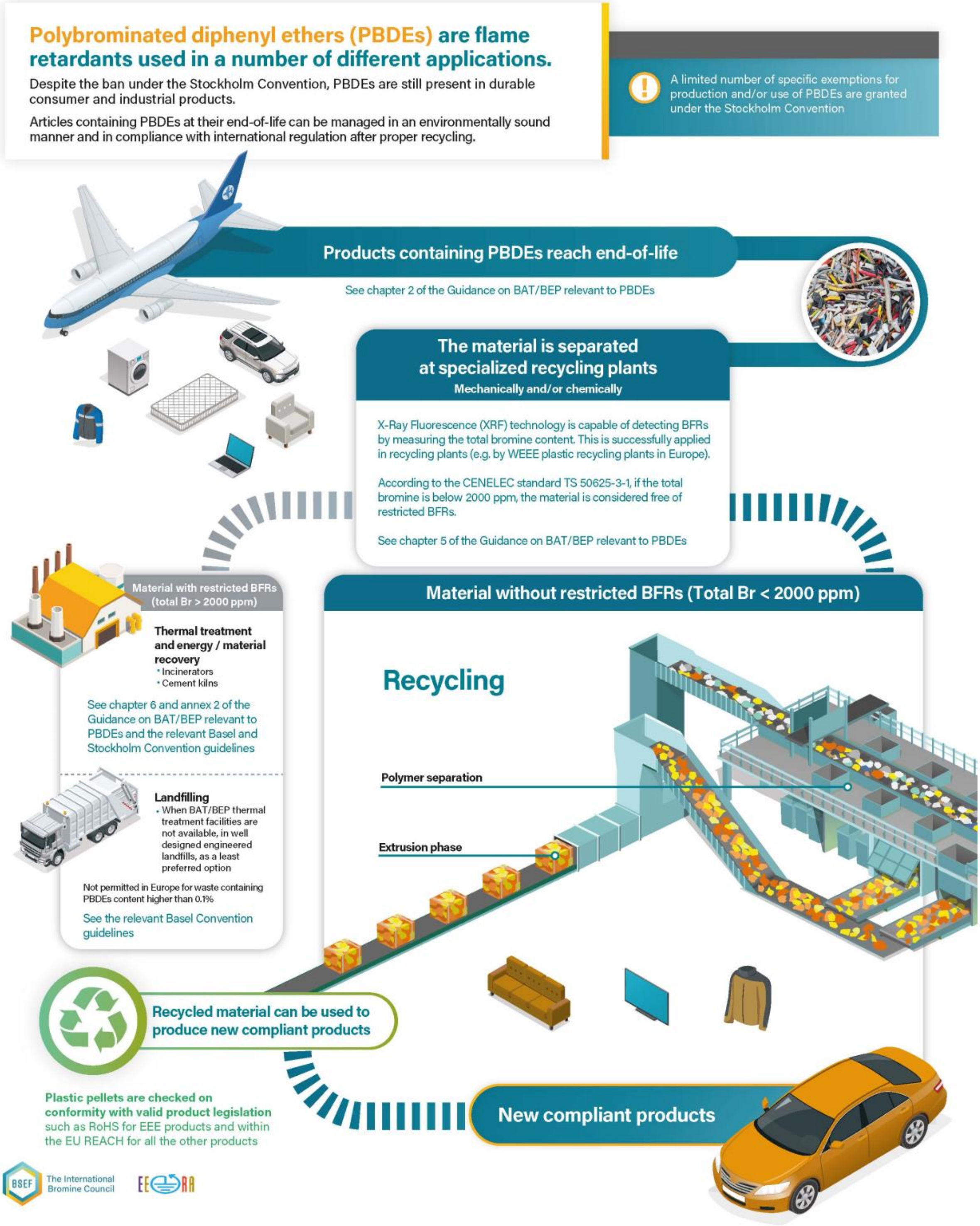
The application of best available techniques (BAT) and best environmental practices (BEP) is necessary to minimize releases from production and use. Depending on the application, a wide range of different substitutes of decaBDE are available for both plastics and in textile applications. BAT and BEP for the use of decaBDE and for the recycling of PBDE-containing articles (excluding decaBDE) have also been documented. These include analytical methods for screening and separation aimed at the recycling of PBDE-containing articles (excluding decaBDE).

Considering that avoidance of waste generation is not always possible, it is key to put in place a system to trace materials and wastes. It has been demonstrated through life-cycle assessments that recycling is a preferable option when compared with alternative scenarios such as the use of virgin raw material combined with waste incineration. According to the waste management hierarchy, the last resort option to deal with end-of-life PBDEs is responsible disposal in permanent safe landfills, following recommendations included in the text. Controlled landfilling could be considered as an option to avoid open air incineration where recycling and incineration plants are not available.

Recycling processes for both waste electrical and electronic equipment (WEEE) and end-of-life vehicles (ELV) follow a precise logic: either parts (potentially) containing brominated flame retardants are separated manually at the beginning of the treatment process or, as in most cases where mechanical recycling takes place, the separation process of brominated flame retardant-containing plastics occurs at the end of the recycling process but before the extrusion of the recyclable content, based on different methods. The separated plastics that contain brominated flame retardants are subsequently treated in appropriate BAT/BEP incinerators or thermal facilities, resulting in energy recovery.

Several stakeholders are involved in processes of end-of-life management. The Voluntary Emissions Control Action Programme is a significant example of a voluntary industry commitment by producers and the value chain at global level to handle chemicals and their emissions, including PBDEs.

Energy / material recovery can take place for PBDE-containing fractions after sorting from the PBDE-free fractions that are fed into the recycling process. There are a number of considerations for incineration processes, recovery in cement kilns and for the metal industry, favourably including energy and material recovery (e.g. recovery of metals from the shredder fractions of Automotive Shredder Residue (ASR) and WEEE), and conversely including generation of toxic releases like brominated dioxins and furans (PBDD/PBDF) and corrosion caused by bromine/HBr, which need to be monitored. BAT and BEP are documented for the relevant processes, including municipal waste incinerators, cement kilns, copper smelters and integrated smelters-refineries, electric arc furnaces, secondary aluminium industries and primary steel industry.



**Polybrominated diphenyl ethers (PBDEs) are flame retardants used in a number of different applications.**

Despite the ban under the Stockholm Convention, PBDEs are still present in durable consumer and industrial products.

Articles containing PBDEs at their end-of-life can be managed in an environmentally sound manner and in compliance with international regulation after proper recycling.

! A limited number of specific exemptions for production and/or use of PBDEs are granted under the Stockholm Convention

**Products containing PBDEs reach end-of-life**

See chapter 2 of the Guidance on BAT/BEP relevant to PBDEs

**The material is separated at specialized recycling plants**
**Mechanically and/or chemically**

X-Ray Fluorescence (XRF) technology is capable of detecting BFRs by measuring the total bromine content. This is successfully applied in recycling plants (e.g. by WEEE plastic recycling plants in Europe).

According to the CENELEC standard TS 50625-3-1, if the total bromine is below 2000 ppm, the material is considered free of restricted BFRs.

See chapter 5 of the Guidance on BAT/BEP relevant to PBDEs

**Material with restricted BFRs (total Br > 2000 ppm)**

**Thermal treatment and energy / material recovery**
- Incinerators
- Cement kilns

See chapter 6 and annex 2 of the Guidance on BAT/BEP relevant to PBDEs and the relevant Basel and Stockholm Convention guidelines

**Landfilling**
- When BAT/BEP thermal treatment facilities are not available, in well designed engineered landfills, as a least preferred option

Not permitted in Europe for waste containing PBDEs content higher than 0.1%

See the relevant Basel Convention guidelines

**Material without restricted BFRs (Total Br < 2000 ppm)**

**Recycling**

**Recycled material can be used to produce new compliant products**

**Plastic pellets are checked on conformity with valid product legislation** such as RoHS for EEE products and within the EU REACH for all the other products

**New compliant products**

# 1. Introduction

This document supersedes the “Guidance on best available techniques and best environmental practices for the recycling and waste disposal of articles containing polybrominated diphenyl ethers (PBDEs) listed under the Stockholm Convention on POPs” as of January 2017 (http://chm.pops.int/Implementation/NIPs/Guidance/GuidanceonBATBEPfortherecyclingofPBDEs/tabid/3172/Default.aspx) to reflect decision SC-8/10, listing of decabromodiphenyl ether, and to include updated information pursuant to decision SC-9/7 on best available techniques (BAT) and best environmental practices (BEP).

## 1.1. Purpose

The concept of BAT is not aimed at the prescription of any specific technique or technology. BAT means the most effective and advanced activities, methods of operation, and techniques for providing the basis for release limitations designed to prevent and, generally to reduce releases of chemicals and their impact on the environment. BEP describes the application of the most appropriate combination of environmental control measures and strategies (Article 5, f (i) and (v) of the Stockholm Convention on Persistent Organic Pollutants (POPs)).

Article 3, paragraph 6 of the Stockholm Convention, requests Parties that have a specific exemption and/or acceptable purpose for a chemical listed in Annex A or Annex B to the Convention to take measures to ensure that any production or use under such exemption or purpose is carried out in a manner that prevents or minimizes human exposure and releases to the environment. For the three groups of POPs mentioned below, there are no specific requirements on BAT/BEP in the Convention.

For the purpose of this document, the following groups of PBDEs are defined:

- tetrabromodiphenyl ether and pentabromodiphenyl ether (SC-4/18), abbreviated as c-pentaBDE
- hexabromodiphenyl ether and heptabromodiphenyl ether (SC-4/14) abbreviated as c-octaBDE
- decabromodiphenyl ether (SC-8/14) abbreviated as c-decaBDE

**Chapter 1** outlines the purpose and structure of this document.

**Chapter 2** provides information on the substances in the scope of this document, including the relevant provisions under the Stockholm Convention and the Basel Convention.

**Chapter 3** addresses general BAT and BEP principles for general chemical management and general guidance for the management of PBDEs. Further relevant details are included in **Annex 1**.

**Chapter 4** addresses BAT and BEP for the use of decaBDE in polymer/plastic and textile applications listed as specific exemptions under the Convention. Each section provides a general description of the process/application in which decaBDE is exempted for use, and specific BAT and BEP guidance for management of decaBDE, including information on available alternatives for that use.

**Chapter 5** addresses BAT and BEP for the recycling of PBDE-containing articles (excluding decaBDE), focusing on the key material recycling flows – namely electrical and electronic equipment (EEE) / Waste EEE (WEEE), vehicles in the transport sector, and polyurethane foam.

**Chapter 6** summarizes BAT and BEP considerations for energy and/or material recovery from PBDE-containing materials and provides links to relevant detailed guidance. Further relevant details are included in **Annex 2**.

# 2. Substances covered under this document

## 2.1. Specific substances

### 2.1.1. Hexabromodiphenyl ether and heptabromodiphenyl ether

In May 2009, by decision SC-4/14, the Conference of the Parties to the Stockholm Convention listed hexabromodiphenyl ether (hexaBDE) and heptabromodiphenyl ether (heptaBDE) into Annex A of the Convention. The listing includes a specific exemption for articles containing hexaBDE and heptaBDE in accordance with the provisions of part IV of the Annex, as follows:

| Chemical | Activity | Specific exemption |
|---|---|---|
| Hexabromodiphenyl ether and heptabromodiphenyl ether | Production | None |
| | Use | Articles in accordance with provisions of part IV of this Annex |

According to Part III of Annex A, “Hexabromodiphenyl ether and heptabromodiphenyl ether” means 2,2',4,4',5,5'-hexabromodiphenyl ether (BDE-153, CAS No: 68631-49-2), 2,2',4,4',5,6'-hexabromodiphenyl ether (BDE-154, CAS No: 207122-15-4), 2,2',3,3',4,5',6-heptabromodiphenyl ether (BDE-175, CAS No: 446255-22-7), 2,2',3,4,4',5',6-heptabromodiphenyl ether (BDE-183, CAS No: 207122-16-5) and other hexa- and heptabromodiphenyl ethers present in commercial octabromodiphenyl ether.

According to Part IV of Annex A:

> 1. A Party may allow recycling of articles that contain or may contain hexabromodiphenyl ether and heptabromodiphenyl ether, and the use and final disposal of articles manufactured from recycled materials that contain or may contain hexabromodiphenyl ether and heptabromodiphenyl ether, provided that:
>
> (a) The recycling and final disposal is carried out in an environmentally sound manner and does not lead to recovery of hexabromodiphenyl ether and heptabromodiphenyl ether for the purpose of their reuse;
>
> (b) The Party takes steps to prevent exports of such articles that contain levels/concentrations of hexabromodiphenyl ether and heptabromodiphenyl ether exceeding those permitted for the sale, use, import or manufacture of those articles within the territory of the Party; and
>
> (c) The Party has notified the Secretariat of its intention to make use of this exemption.
>
> 2. At its sixth ordinary meeting and at every second ordinary meeting thereafter the Conference of the Parties shall evaluate the progress that Parties have made towards achieving their ultimate objective of elimination of hexabromodiphenyl ether and heptabromodiphenyl ether contained in articles and review the continued need for this specific exemption. This specific exemption shall in any case expire at the latest in 2030.

### 2.1.2. Tetrabromodiphenyl ether and pentabromodiphenyl ether

By decision SC-4/18, the Conference of the Parties to the Stockholm Convention listed tetrabromodiphenyl ether (tetraBDE) and pentabromodiphenyl ether (pentaBDE) into Annex A of the Convention. The listing includes a specific exemption for articles containing tetraBDE and pentaBDE in accordance with the provisions of part V of the Annex, as follows:

| Chemical | Activity | Specific exemption |
|---|---|---|
| | Production | None |

| | | |
|---|---|---|
| Tetrabromodiphenyl ether and pentabromodiphenyl ether | Use | Articles in accordance with the provisions of Part V of this Annex |

According to Part III of Annex A, "Tetrabromodiphenyl ether and pentabromodiphenyl ether" means 2,2',4,4'-tetrabromodiphenyl ether (BDE-47, CAS No: 5436-43-1) and 2,2',4,4',5-pentabromodiphenyl ether (BDE-99, CAS No: 60348-60-9) and other tetra- and pentabromodiphenyl ethers present in commercial pentabromodiphenyl ether.

According to Part V to Annex A as follows:

> 1. A Party may allow recycling of articles that contain or may contain tetrabromodiphenyl ether and pentabromodiphenyl ether, and the use and final disposal of articles manufactured from recycled materials that contain or may contain tetrabromodiphenyl ether and pentabromodiphenyl ether, provided that:
>
> (a) The recycling and final disposal is carried out in an environmentally sound manner and does not lead to recovery of tetrabromodiphenyl ether and pentabromodiphenyl ether for the purpose of their reuse;
>
> (b) The Party does not allow this exemption to lead to the export of articles containing levels/concentrations of tetrabromodiphenyl ether and pentabromodiphenyl ether that exceed those permitted to be sold within the territory of the Party; and
>
> (c) The Party has notified the Secretariat of its intention to make use of this exemption.
>
> 2. At its sixth ordinary meeting and at every second ordinary meeting thereafter the Conference of the Parties shall evaluate the progress that Parties have made towards achieving their ultimate objective of elimination of tetrabromodiphenyl ether and pentabromodiphenyl ether contained in articles and review the continued need for this specific exemption. This specific exemption shall in any case expire at the latest in 2030.

### 2.1.3. Decabromodiphenyl ether

In May 2017, by decision SC-8/10, the Conference of the Parties listed decabromodiphenyl ether (decaBDE), along known as BDE-209 into Annex A of the Convention. The listing includes specific exemptions for the production and use of commercial decabromodiphenyl ether, as follows:

| **Chemical** | **Activity** | **Specific exemption** |
|---|---|---|
| Decabromodiphenyl ether (BDE-209) present in commercial decabromodiphenyl ether (CAS No: 1163-19-5) | Production | As allowed for the Parties listed in the Register |
| | Use | In accordance with Part IX of Annex A:<br>• Parts for use in vehicles specified in paragraph 2 of Part IX Annex A<br>• Aircraft for which type approval has been applied for before December 2018 and has been received before December 2022 and spare parts for those aircraft<br>• Textile products that require anti-flammable characteristics, excluding clothing and toys<br>• Additives in plastic housings and parts used for heating home appliances, irons, fans, immersion heaters that contain or are in direct contact with electrical parts or are required to comply with fire retardancy standards, at concentrations lower than 10 per cent by weight of the part<br>• Polyurethane foam for building insulation |

According to Part IX in Annex A:

> 1. The production and use of decabromodiphenyl ether shall be eliminated except for Parties that have notified the Secretariat of their intention to produce and/or use it in accordance with Article 4.
>
> 2. Specific exemptions for parts for use in vehicles may be available for the production and use of commercial decabromodiphenyl ether limited to the following:
>
> (a) Parts for use in legacy vehicles, defined as vehicles that have ceased mass production, and with such parts falling into one or more of the following categories:
>
> (i) Powertrain and under-hood applications such as battery mass wires, battery interconnection wires, mobile air-conditioning (MAC) pipes, powertrains, exhaust manifold bushings, under-hood insulation, wiring and harness under hood (engine wiring, etc.), speed sensors, hoses, fan modules and knock sensors;
>
> (ii) Fuel system applications such as fuel hoses, fuel tanks and fuel tanks under body;
>
> (iii) Pyrotechnical devices and applications affected by pyrotechnical devices such as air bag ignition cables, seat covers/fabrics (only if airbag relevant) and airbags (front and side);
>
> (iv) Suspension and interior applications such as trim components, acoustic material and seat belts.
>
> (b) Parts in vehicles specified in paragraphs 2 (a) (i)–(iv) above and those falling into one or more of the following categories:
>
> (i) Reinforced plastics (instrument panels and interior trim);
>
> (ii) Under the hood or dash (terminal/fuse blocks, higher-amperage wires and cable jacketing (spark plug wires));
>
> (iii) Electric and electronic equipment (battery cases and battery trays, engine control electrical connectors, components of radio disks, navigation satellite systems, global positioning systems and computer systems);
>
> (iv) Fabric such as rear decks, upholstery, headliners, automobile seats, head rests, sun visors, trim panels, carpets.
>
> 3. The specific exemptions for parts specified in paragraph 2 (a) above shall expire at the end of the service life of legacy vehicles or in 2036, whichever comes earlier.
>
> 4. The specific exemptions for parts specified in paragraph 2 (b) above shall expire at the end of the service life of vehicles or in 2036, whichever comes earlier.
>
> 5. The specific exemptions for spare parts for aircraft for which type approval has been applied for before December 2018 and has been received before December 2022 shall expire at the end of the service life of those aircraft.

Information regarding the Parties that have registered for any of the specific exemptions mentioned above can be found on the Convention’s website at http://chm.pops.int/Implementation/Exemptions/SpecificExemptions/DecabromodiphenyletherRoSE/tabid/7593/Default.aspx. The register of specific exemptions is updated regularly by the Secretariat. Expired exemptions can be viewed as well.

## 2.2. Production and use

### 2.2.1. Production

Under the provisions of the Stockholm Convention, production of decaBDE is permitted for Parties listed in the Register and for the uses in accordance with Part IX of the Annex A. The total production of decaBDE from 1970 to 2005 has been estimated at between 1.1 and 1.25 million tonnes. The overall scale of current decaBDE production is unknown, as data on production, trade and stockpiles are only available for some countries (UNEP 2020a).

The production of tetra- and pentaBDE (c-pentaBDE) and hexa- and heptaBDE (c-octaBDE) is not permitted under the Stockholm Convention (see sections 2.1.1 and 2.1.2).

### 2.2.2. Use

#### *Tetra- and pentaBDE*

The estimated total production of tetra- and pentaBDE (c-pentaBDE) from 1970 to 2005 is between 91,000 and 105,000 tons. It is considered that between 90% and 95% of the use of c-pentaBDE was for the treatment of polyurethane (PUR) foam. These foams were mainly used in automotive (seating; head rests; car ceilings; acoustic systems; back-coating of textiles) and upholstery applications. Minor uses included textiles, printed circuit boards, insulation foam, cable sheets, conveyer belts, lacquers and possibly drilling oils (UNEP 2017a). The total amount of c-pentaBDE used for these minor uses is estimated to account for 5% or less of the total usage (SFT 2009; UNEP 2020b, 2010b).

An approximate distribution of c-pentaBDE use of 36% in transport, 60% in furniture and 4% residual in other articles is considered to be reasonable and is generally consistent with the analytical data for different waste streams (UNEP 2020b, 2010b).

#### *Hexa- and heptaBDE*

The estimated total production from 1970 to 2005 is between 102,700 and 118,500 tons for hexa-and heptaBDE (c-octaBDE). The largest use of c-octaBDE has been for the treatment of acrylonitrile-butadiene-styrene (ABS) plastics which were typically used in electrical and electronic equipment (EEE), (particularly for cathode ray tube (CRT) housings of televisions and computer monitors and office equipment such as copying machines and business printers), accounting, for instance, for about 95% of c-octaBDE supplied in the EU. Other minor uses were high impact polystyrene (HIPS), polybutylene terephthalate (PBT), and polyamide polymers (UNEP 2020b, 2017a, 2010a, b).

#### *DecaBDE*

The total production of decaBDE from 1970 to 2005 has been estimated at between 1.1 and 1.25 million tonnes. The overall scale of current decaBDE production is unknown, as data on production, trade and stockpiles are only available for some countries (UNEP 2020a). The Risk Management Evaluation for decaBDE (UNEP 2015) notes: The plastics industry is by far the major user of fire retardants. The amount of decaBDE used in plastics and textiles in various countries varies, but up to 90% of decaBDE ends up in plastic and electronics, while the remaining ends up in coated textiles, upholstered furniture and mattresses.

EEE applications of decaBDE include equipment casing, wires and cables, and small electrical components. The type of polymers in electronics that have been treated with decaBDE are principally HIPS, ABS co-polymers and polymer blends such as polyphenylene oxide /polystyrene (PPO/PS) blends. These polymers were used mainly as casing materials for EEE.

In vehicles, decaBDE is/was used in fabrics, plastics, under the hood or dashboard polymers or in cables. The aviation industry still uses decaBDE in electrical wiring and cables, interior components, and EEE of older airplanes and spacecraft (UNEP 2015).

In EEE, decaBDE is typically used in concentrations ranging from 10 to 15% (up to 20%). Levels of decaBDE in vehicle components is variable, with levels above 2% particularly found in seat cover materials from old cars. Information on the use of decaBDE in the construction sector is scarce. Typical decaBDE/BDE-209 would be used in concentrations between 10 and 30% in electrical insulation and is below 30% in epoxy adhesives (UNEP 2020a).

In the textile sector, decaBDE has been used to treat a wide range of synthetic, blended and natural fibres that require anti-flammable characteristics, such as automotive textiles, upholstery textiles including sofas, offices chairs, mattresses, filters for cookers, blinds, draperies, blackout curtains, geotextiles, wall coverings, households/furniture appliances, carpets etc. (UNEP 2014, 2015, 2019a). Concentrations of up to 12% decaBDE have been used in coated textiles, upholstery, window blinds, curtains, mattresses and carpets for public and domestic buildings, as well as tents and textiles used in the transportation sector (UNEP 2020a).

In the building and construction sector, decaBDE has been used in PUR, cladding panels, Polyethylene/Polypropylene (PE/PP) films, cables and electrical ducts and fittings or piping insulation (UNEP 2014, 2015, 2019a).

In the conveyance of goods sector, decaBDE has been used in plastic shipping pallet fleets servicing the pallet rental market in the United States (US Maine Department of Environmental Protection 2011). The pallets are flame retarded to meet the United States National Fire Protection Association (NFPA) Standard for the Installation of Sprinkler Systems (NFPA 13[1]).

## 2.3. Summary of Best Available Techniques (BAT) and Best Environmental Practices (BEP)

### 2.3.1. BAT and BEP for the use of decaBDE

The production and use of decaBDE are allowed for specific exemptions in accordance with Part IX of Annex A (see section 2.1.3.). Depending on the application, a wide range of different substitutes are available in plastics and in textile applications. An overview of the alternatives reported to be available for decaBDE has been compiled in UNEP (2019b) and is summarized in Chapter 4 (see Tables 4-2, 4-4, and 4-5 in Chapter 4).

It should be noted that a case-by-case assessment is necessary to find the best alternative suitable for a specific use. It is important to consider all the available health and environmental data to obtain a comprehensive and robust understanding of the toxicological and ecotoxicological effects and recycling performance of the alternatives (USEPA 2014; ECHA 2014).

Furthermore, some alternatives may be subject to controls in specific jurisdictions, such as Canada's New Substances Notification Regulations (Chemicals and Polymers) and the European Union's Candidate List of substances of very high concern for Authorisation[2].

BAT and BEP for the use of decaBDE in the applications listed as specific exemptions under the Convention are summarized in the table below. Further details are available in Chapter 4; general principles on BAT and BEP are laid out in Chapter 3 and Annex 1.

Table 2-1: Summary of BAT and BEP for the "Specific Exemption" applications (**Polymers**: Plastics (parts for use in vehicles and in aircraft, additives in plastic housings and parts used for heating home appliances, irons, fans, immersion heaters), Polyurethane foam for

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[1] https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=13

[2] For example, ethane-1,2-bis(pentabromophenyl) (CAS 84852-53-9) is subject to Canada's New Substances Notification Regulations (https://laws-lois.justice.gc.ca/eng/Regulations/SOR-2005-247/index.html) and subject to an United States EPA TSCA 5(a) Significant New Use Rule (https://iaspub.epa.gov/sor_internet/registry/substreg/searchandretrieve/substancesearch/search.do?synId=1454707&displaySynonym=). These regulations restrict the use of this substance for new uses until it has been assessed. Additionally, dodecachlorododecahydro-dimethanodibenzocyclooctane (CAS 13560-89-9) is listed on the EU Candidate List of SVHC for Authorization (https://echa.europa.eu/candidate-list-table/-/dislist/details/0b0236e181f392bf). Once a substance is identified as an SVHC, it is included in the Candidate List. The inclusion in the Candidate List brings immediate obligations for suppliers of the substance (https://echa.europa.eu/substances-of-very-high-concern-identification-explained)

building insulation; **Textiles**: Textile products that require anti-flammable characteristics excluding clothing and toys).

| Application | Measure | Release source to be addressed | BAT / BEP* |
|---|---|---|---|
| Polymers, textiles | Improving raw material handling | When handling raw materials for plastic processing, significant amounts of decaBDE could be lost in dust (which mainly ends up in solid waste or the atmosphere). | Losses can be minimised by a combination of options:<br>The packaging material should be durable to avoid leakages during transportation and handling<br>Where possible the material should be traded as coarse powder instead of fine powder that is prone to handling losses<br>The material must be stored in an enclosed area with extraction system that has appropriate dust capturing system<br>Careful handling of decaBDE packaging should avoid dust emissions from wear and tear, while scraping instead of rinsing will avoid further emissions to wastewater.<br>DecaBDE powder should be handled under local exhaust ventilation with filter, and any loose dust should be vacuumed up before washing the working area. |
| Polymers, textiles | Improving compounding process | Plastic processing:<br>The compounding process (blending of the base polymer with additives including flame retardants) may lead to dust formation (mainly in the first stages of the mixing cycle) and volatilisation (due to elevated processing temperatures).<br>Textile applications:<br>Main potential sources of decaBDE emissions during compounding are the dust formation when emptying decaBDE powder into the pre-mixer and the wastewater from washing mixing vessels. | Plastic processing:<br>DecaBDE should be added gently, close to the mixing vessel level to avoid dust formation<br>The mixing vessel should be connected to an extraction system that has an appropriate dust capturing system<br>Options such as localised containment may be implemented to collect and recycle the decaBDE-containing dust material. Dust emissions can also be reduced with an air aspiration system which sucks the air stream into the mixer when dosing.<br>Textile applications:<br>To minimise dust emissions, decaBDE powder should be handled under local exhaust ventilation with filter, and any loose dust should be vacuumed up before washing the working area. |
| Polymers, textiles | Improving conversion / backcoating | Plastic processing (conversion):<br>The conversion process (production of final products) may lead to volatilisation (due to elevated processing temperatures).<br>Textile applications (backcoating):<br>Main potential sources of decaBDE emissions during backcoating are the washing of equipment between batches. | Plastic processing (conversion):<br>Possible measures to avoid atmospheric emissions include operating in a closed system with collecting and treating waste gas containing decaBDE.<br>Textile applications (backcoating):<br>Possible measures include cleaning of the coating rolls with rubber knives and paper and safe disposal of waste instead of washing; the reduction at the minimum of the frequency of washing; and the wastewater collection after washing by an industrial wastewater treatment plant followed by suitable waste disposal. |

| Application | Measure | Release source to be addressed | BAT / BEP* |
|---|---|---|---|
| Textiles | Controlling or avoiding washing | Potential emissions can occur during the washing of the fabric. | In order to prevent emissions from washing, textile products should be designed to be more wash-resistant (withstand at least ten wash cycles without losing its flame-retardant properties).<br>If washing is needed (e.g. work wear and protective clothing), substitution of the flame retardant by molecules regarded as being wash-resistant should be required and washing conducted in designated facilities with appropriate wastewater treatment and disposal protocol. |
| Polymers, textiles | Chemical substitution | Replacing decaBDE with another flame retardant | Depending on the application, a wide range of different substitutes are available which are widely used in polymers and in textiles (see Table 1-7). |
| Polymers, textiles | Changing the product material | This option involves replacing the base polymer containing decaBDE by a less flammable material, for example by<br>- Changing the base polymer for another type of plastics;<br>- Changing the base polymer for a non-plastic material. | For polymer applications:<br>Changing the base polymer for another type of plastic:<br>The use of plastics that are inherently more resistant to ignition and do not need flame retardants, such as high performance thermoplastics, is particularly well adapted for applications where high temperature resistance or low smoke densities are required (e.g. aircraft, ships, tunnels).<br>Changing the base polymer for a non-plastic material:<br>In some cases, it is possible to change plastics for other types of materials which are less flammable, e.g. wood and metals. An example are laptop computers where the entire case would be made out of metal (magnesium alloys).<br>For textile applications:<br>Development of surface-active fibre systems having low flammability.<br>Flame-resistant materials also include modified polymers such as modified polyester which can be used in a wide range of textile applications (clothing, technical applications and interiors).<br>See Table 1-8. |
| Polymers | Redesigning the products | Redesigning products or fulfilling the product function in a different way to avoid the use of decaBDE as a flame retardant. | For plastic in electrical and electronic equipment, options such as:<br>Separating the high-voltage components that need greater ignition protection from the low-voltage components;<br>Reducing the operating voltage requirements, therefore reducing the need for fire-resistant enclosure materials;<br>Separating the power supply from the product, which reduces the fire-retardancy requirements of the electronic enclosure;<br>Shielding power supplies with metal to eliminate the need for additive flame retardants. |

| Application | Measure | Release source to be addressed | BAT / BEP* |
|---|---|---|---|
| | | | See Table 1-8. |

*(Vecap 2019, SOCOPSE 2008, European Commission 2019, 2007, 2003)*

*General BEP guidance is provided in Chapter 3.

### 2.3.2. BAT and BEP for environmentally sound recycling of PBDE-containing articles (excluding decaBDE)

Options for separating and treating plastics that contain PBDEs on an industrial scale are (Finnish Ministry of Environment 2016):

1. Manually disassembling and removing plastics that contain brominated flame retardants from EEE or vehicles and treating the separate fraction as POP waste.
2. Separating plastics that contain brominated flame retardants from shredded material and treating the separate fraction as POP waste.
3. Further treatment of the whole fraction created during shredding as POP waste without separating the plastic that contains brominated flame retardants.

Out of these treatment options, the most appropriate one should be selected, taking account of the functionality of the whole producer responsibility chain. In practice, the only usable method for separating plastics that contain POPs is to identify and isolate all plastics containing brominated flame retardants and treat them as POP waste, regardless of which bromine compounds have been used as flame retardants in the plastic (see Chapter 5).

In practice, the separation of materials containing PBDEs from those containing other brominated flame retardants not listed under the Convention is currently difficult due to technological limitations. Therefore, in practice, in order to achieve the separation of materials containing PBDEs, the separation of all materials containing BFRs/bromine from non-BFRs/bromine materials is required. Separation can also be done on the basis of knowledge of past uses of PBDEs.

If separation techniques or processes are not readily available or achievable and concentrations are assumed to be above the low POP level, recycling should be avoided.

Recycling processes for both WEEE and ELV (e.g. vehicles and PUR foam) follow a precise logic: either parts are separated manually at the beginning of the treatment process or, as in most cases where mechanical recycling takes place, the separation process of brominated flame retardants-containing plastics occurs at the end of the recycling process before the extrusion of the recyclable content, based on different methods (see Chapter 5). The separated plastics that contain brominated flame retardants are subsequently treated in appropriate BAT/BEP incinerators or thermal facilities, resulting in energy recovery (see Chapter 6).

Energy and/or material recovery from PBDE-containing materials can take place in the following sectors, for which BAT/BEP guidance is available according to the source materials cited in Table 1-2 below.

Table 2-2: List of guidance to address energy/material recovery from PBDE-containing material.

| Sector | BAT BEP guidance |
|---|---|
| Incinerators | • Basel Convention Technical Guidelines on Incineration on Land (D10) (currently being updated, UNEP/CHW/OEWG.12/INF/11) [http://www.basel.int/TheConvention/OpenendedWorkingGroup(OEWG)/Meetings/OEWG12/Meetingdocuments/tabid/8403/Default.aspx]<br>• Stockholm Convention BAT/BEP guidelines: V.A Waste incinerators [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx] |

| | |
|---|---|
| | • EU WI BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118637_WI_Bref_2019_published_0.pdf] |
| Cement kilns | • Basel Convention technical guidelines on the environmentally sound co-processing of hazardous wastes in cement kilns [http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx]<br>• Stockholm Convention BAT/BEP guidelines: V.B Cement kilns firing hazardous waste [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]<br>• EU CLM BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf] |
| Metal industries | • Basel Convention Technical guidelines on the environmentally sound recycling/reclamation of metals and metal compounds (R4) http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx]<br>• Stockholm Convention BAT/BEP guidelines: V.D Thermal processes in the metallurgical industry [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]<br>• Stockholm Convention BAT/BEP guidelines: V.D Thermal processes in the metallurgical industry not mentioned in Annex C, Part II [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]<br>• EU NFM BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC107041_NFM_bref2017.pdf]<br>• EU IS BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/IS_Adopted_03_2012.pdf] |

## 2.4. Relationship to the Basel Convention

In addition to the provisions of the Stockholm Convention, those of the Basel Convention are directly relevant to the application of best available techniques and best environmental practices to address PBDE releases from waste. Considering that several waste streams, including WEEE, automobile parts and others are major potential PBDEs-containing material flows, synergies between the Stockholm Convention and Basel Convention are of high importance. The Basel Convention places obligations on countries that are Parties to, *inter alia*: minimize generation of hazardous waste; ensure that adequate disposal facilities are available; and ensure environmentally sound management of wastes.

Under the Stockholm Convention, POP-containing wastes are, in accordance with Article 6, paragraph 1 (d) (ii), to be disposed of in such a way that the POP content is destroyed or irreversibly transformed so that they do not exhibit the characteristics of POPs or otherwise, they may be disposed of in an environmentally sound manner when destruction or irreversible transformation does not represent the environmentally preferable option, or the POP content is low, taking into account international rules, standards, and guidelines, including those that may be developed pursuant to paragraph 2, as well as relevant global and regional regimes governing the management of hazardous wastes.

Paragraph 2 of Article 6 of the Stockholm Convention, which addresses measures to reduce or eliminate releases from stockpiles and wastes, contains the following provisions:

"The Conference of the Parties shall cooperate closely with the appropriate bodies of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal to, inter alia:

(a) Establish levels of destruction and irreversible transformation necessary to ensure that the characteristics of persistent organic pollutants are not exhibited;

(b) Determine what they consider to be the methods that constitute environmentally sound disposal referred to above; and

(c) Work to establish, as appropriate, the concentration levels of the chemicals listed in Annexes A, B and C in order to define the low persistent organic pollutant content referred to in paragraph 1 (d) (ii)."

The Conference of the Parties to the Basel Convention, at its fourteenth meeting in May 2019 adopted:

- The updated general technical guidelines for the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants (UNEP/CHW.14/7/Add.1/Rev.1); and
- The updated guidelines for the environmentally sound management of wastes consisting of, containing or contaminated with hexabromodiphenyl ether and heptabromodiphenyl ether, or tetrabromodiphenyl ether and pentabromodiphenyl ether or decabromodiphenyl ether (UNEP/CHW.14/7/Add.3/Rev.1).

The general technical guidelines developed under the Basel Convention address matters relate to all three of the outstanding definitional issues raised in paragraph 2 of Article 6 of the Stockholm Convention.

These two documents provide the framework for the environmentally sound management (ESM) of PBDE wastes.

Further guidance relevant to matters under Article 6 of the Convention is contained in:

WEEE:

- Guidance document on environmentally sound management of used and end-of-life computing equipment (UNEP/CHW.13/INF/31/Rev.1);
- Technical guidelines on transboundary movements of electrical and electronic waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention (UNEP/CHW.14/7/Add.6/Rev.1).

Plastic wastes:

- Technical guidelines for the identification and environmentally sound management of plastic wastes and for their disposal (UNEP/CHW.6/21). These technical guidelines are currently being updated, UNEP/CHW/OEWG.12/INF/14.

Co-processing of hazardous wastes in cement kilns:

- Technical guidelines on the environmentally sound co-processing of hazardous wastes in cement kilns (UNEP/CHW.10/6/Add/3/Rev.1).

Landfills:

- Draft updated technical guidelines on specially engineered landfill (D5) (UNEP/CHW.14/INF/12). These technical guidelines are currently being updated, UNEP/CHW/OEWG.12/INF/12.

Incineration:

- Draft updated technical guidelines on incineration on land (D10) (UNEP/CHW.14/INF/11). This technical guideline is currently being updated, UNEP/CHW/OEWG.12/INF/11.

# 3. General principles and guidance on BAT and BEP for managing PBDEs

## 3.1. Environmental management systems (EMS)

A number of environmental management techniques are determined as BEP. An Environmental Management System (EMS) is a tool that operators can use to address these design, construction, maintenance, operation and decommissioning issues in a systematic, demonstrable way. An EMS includes the organizational structure, responsibilities, practices, procedures, processes and resources for developing, implementing, maintaining, reviewing and monitoring the environmental policy. Environmental Management Systems are most effective and efficient where they form an inherent part of the overall management and operation of an installation. The scope and nature of an EMS will generally be related to the nature, scale and complexity of the facility, and the range of environmental impacts it may have (GTZ 2008, ZDHC 2015).

BEP is to implement and adhere to an EMS that incorporates the following features:

- Commitment, leadership and accountability of the management, including senior management, for the implementation of an effective EMS;
- An analysis that includes the determination of the organisation's context, the identification of the needs and expectations of interested Parties, the identification of characteristics of the installation that are associated with possible risks for the environment (or human health) as well as of the applicable legal requirements relating to the environment;
- Definition and/or development of an environmental policy for implementation that includes the continuous improvement of the environmental performance of the installation led by top management (senior corporate leadership commitment and accountability is regarded as a precondition for a successful application of the EMS);
- Establishing objectives and performance indicators in relation to significant environmental aspects, including safeguarding compliance with applicable legal requirements;
- Planning and establishing of the necessary procedures (including corrective and preventive actions where needed), to achieve the environmental objectives and avoid environmental risks;
- Implementation of the procedures, paying particular attention to:
  - Organizational structure and responsibility;
  - Provision of the financial and human resources needed;
  - Training, awareness and competence;
  - Communication (internal and external);
  - Employee involvement;
  - Documentation;
  - Efficient operational planning and process control;
  - Maintenance programme;
  - Emergency preparedness and response;
  - When (re)designing a (new) installation or a part thereof, consideration of its environmental impacts throughout its life, which includes construction, maintenance, operation and decommissioning;
  - Implementation of a monitoring and measurement programme;
  - Safeguarding compliance with environmental legislation;

- Performance checks and taking corrective action:
    - Monitoring and measurement;
    - Records Maintenance;
    - Establishing objectives and performance indicators in relation to significant environmental aspects, including safeguarding compliance with applicable legal requirements;
    - Performing independent (where feasible) internal auditing to determine whether or not the EMS conforms to planned arrangements and has been properly implemented and maintained;
    - Evaluation of causes for nonconformities, implementation of corrective actions in response to nonconformities, review of the effectiveness of corrective actions and determination of whether similar nonconformities exist or could potentially occur.

Four additional features are considered as progressive measures; their absence, however, is generally not inconsistent with BEP:

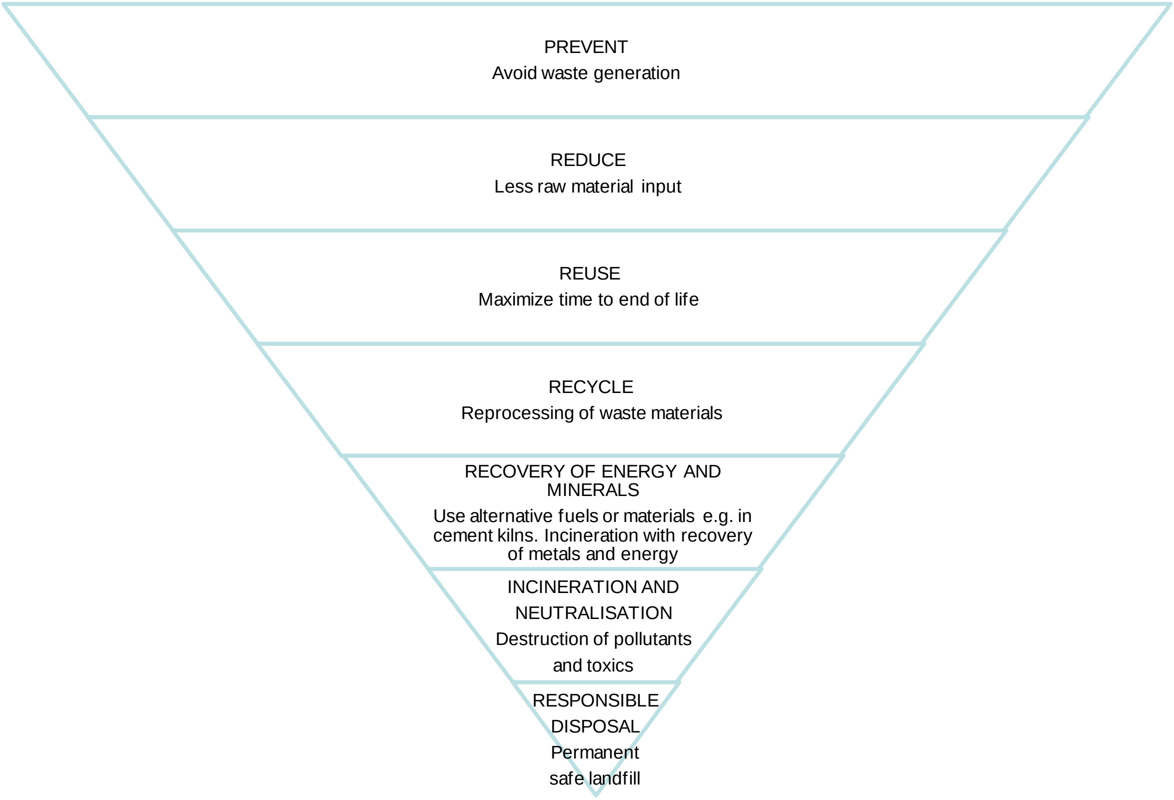
- Examination and validation of the management system and audit procedure by an accredited certification body or an external EMS verifier;
- Preparation and publication of a regular environmental statement describing all the significant environmental aspects of the facility, allowing for year-by-year comparison against environmental objectives and targets as well as with sector benchmarks as appropriate (i.e., continuous improvement plan and annual progress report);
- Consideration of applicable industry-specific standards, when available;
- Implementation and adherence to an internationally accepted EMS, such as ISO 14001 or the Eco Management and Audit Scheme (EMAS).

This last voluntary step could give higher credibility to the EMS, particularly internationally accepted and transparent standards, such as ISO9001 and ISO14001. Non-standardized systems can in principle be equally effective provided that they are properly designed and implemented.

## 3.2. Material and waste management

Many processes described in this document are related to products/materials after their product lives are complete. They involve recycling, material/energy recovery or disposal as these are the most relevant for PBDE-containing material flows. The generic BAT/BEP described herein aims to improve the knowledge of incoming materials and waste relevant to recycling operations, as well as the knowledge of material and waste leaving the facility.

When considering PBDE-containing material management options, it is important to have in mind that the principles of the waste hierarchy (Figure 3-1, UNEP 2007/2019) are not always applicable and this will be addressed/included in the individual chapters. Key issues to be considered on the reuse of PBDE-containing articles are described in the relevant chapters, along with the recycling options and separation technologies (Chapter 5). The presence of PBDEs in the large associated material flows creates challenges associated with the reuse and recycling of such articles. A precautionary approach is needed for the reuse and recycling of materials containing hazardous chemicals wherever possible in closed material cycles at higher recycling rates.



(UNEP 2007/2019)

**Figure 3-1:** Waste management hierarchy

The Basel Convention general technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with POPs and the technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with hexabromodiphenyl ether and heptabromodiphenyl ether, or tetrabromodiphenyl ether and pentabromodiphenyl ether or decabromodiphenyl ether (UNEP/CHW.14/7/Add.1/Rev.1, UNEP/CHW.14/7/Add.3/Rev.1) provide the umbrella guide for the ESM of wastes consisting of, containing or contaminated with PBDEs.

In addition, it is equally important to note that a circular economy model, which employs not only waste management, but reuse, recycling and responsible manufacturing, could further contribute to reducing releases and increasing efficient use of resources (including energy, water and input materials) (Figure 3-2).

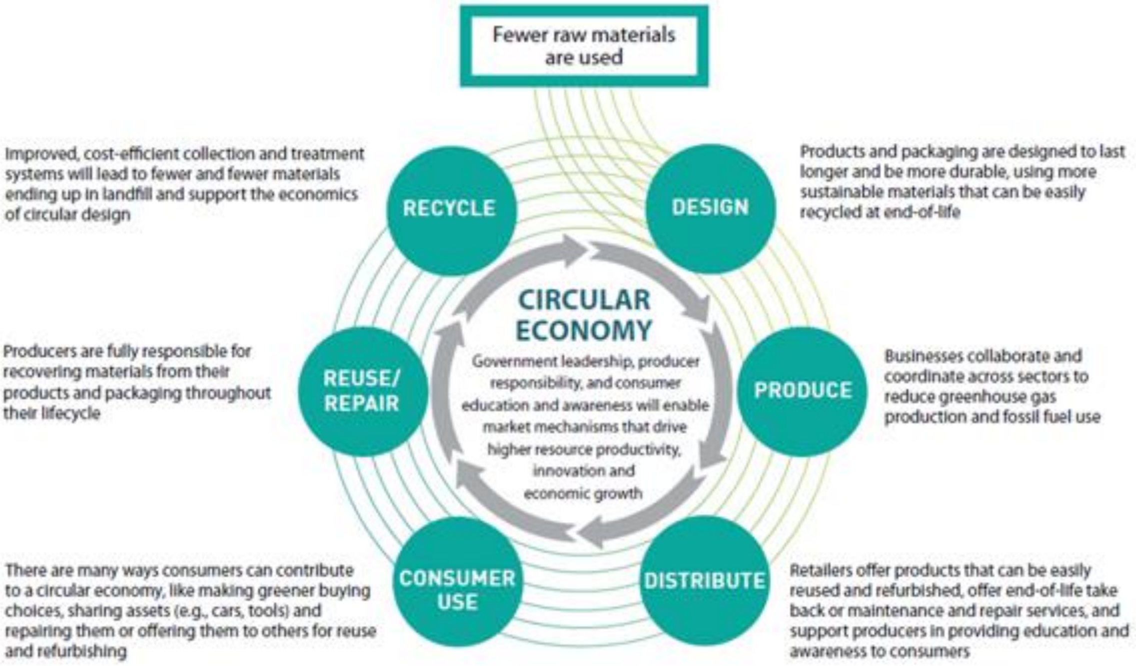


**Figure 3-2:** Circular economy model

### *Material/Waste management systems*

The objective is to put in place a system to guarantee the traceability of materials and wastes containing the following features:

a. A procedure to document the use and treatments of materials and wastes by flow charts and mass balances.

b. A procedure to carry out data traceability through several operational steps (e.g. pre-acceptance/acceptance/storage/treatment/dispatch). Records can be made and kept up-to-date on an ongoing basis to reflect deliveries, on-site treatment and dispatches. Records are typically held for a minimum of six months after the waste has been dispatched.

c. A clear reference and recording system on waste characteristics and the source of the waste stream that is available at all times.

d. This may consist of a computer database or a series of database, which are regularly backed up. The tracking system for a material/waste inventory/stock control system should include the date of arrival on-site, waste producer details, an unique identifier code, pre-acceptance and acceptance analysis results, a description of package type and size, intended treatment/disposal routes, an accurate record of the nature and quantity of materials/wastes held on-site including all hazards details on where the material/waste is physically located in relation to a site plan, at which point in the designated treatment route the material/waste is currently positioned.

e. Drums and other mobile containers should be moved between different locations (or loaded for removal off site) only under instructions from the appropriate manager, ensuring that the waste tracking system is amended to record these changes.

Have and apply mixing/blending rules oriented to restrict the types of wastes that can be mixed/blended together in order to avoid increasing pollution emission of down-stream waste treatments. These rules need to consider the type of materials/waste (e.g. hazardous, non-hazardous), waste treatment to be applied as well as the following steps that will be carried out to the waste OUT (see below).

A segregation and compatibility procedure should be in place that includes:

a. Detailed and accurate records of the testing, including any reaction giving rise to safety parameters (increase in temperature, generation of gases or pressure spikes); a record of the operating parameters (viscosity changes and separation or precipitation of solids) and any other relevant parameters, such as the generation of odours.

b. packing containers of chemicals into separate drums based on their hazard classification. Chemicals which are incompatible (e.g. oxidisers and flammable liquids) should not be stored in the same drum.

Have an approach for improving waste treatment efficiency. This typically includes the finding of suitable indicators to report waste treatment efficiency and a monitoring programme.

Produce a structured accident management plan and have and properly use an incident diary.

### *Incoming materials and wastes*

To improve the knowledge of the incoming material and waste, the BAT/BEP should record accurate information about incoming material/wastes in respective facilities. Such knowledge needs to take into account the outgoing material/waste, treatment to be carried out, type of material/waste, origin of the material/waste, recommended procedures and risks involved.

Implement a pre-acceptance procedure containing at least the following items:

a. tests for the incoming material/waste with respect to the planned treatment.

b. making sure that all necessary information is received on the nature of the process(es) producing the material/waste, including the variability of the processes. The personnel having to deal with a possible pre-acceptance procedure need to be able due to his profession and/or experience to deal with all necessary questions relevant for the treatment of the materials/wastes in the facility.

c. a system for providing and analysing a representative sample(s) of the material/waste from the production process producing such material/waste from the current holder. If, for example, a WEEE recycling facility want to send plastics for further recycling it could be required that they provide data on the PBDE content. A methodology for sampling and analysis of PBDE in WEEE plastic is described in UNEP (2017b).

d. a system to carefully verify, if not dealing directly with the waste producer, the information received at the pre-acceptance stage. This should include the contact details for the waste producer and an appropriate description of the material/waste regarding its composition and hazardousness.

e. making sure that the classification is according to the national legislation and is provided.

f. identifying the appropriate treatment for each waste to be received at the installation by identifying a suitable treatment method for each new material/waste enquiry and having a clear methodology in place to assess the treatment of waste. This should consider the physico-chemical properties of the individual material/waste and the specifications for the treated material/waste.

Implement an acceptance procedure containing at least the following items:

a. a clear and specified system allowing the operator to accept material/wastes at the receiving plant only if a defined treatment method and disposal/recovery route for the output of the treatment is determined.

Regarding the planning for the acceptance, it needs to be guaranteed that the necessary storage treatment capacity and dispatch conditions (e.g. acceptance criteria of the output by the other installation) are also respected.

b. measures are in place to fully document and deal with acceptable material/wastes arriving at the site, such as a pre-booking system, to ensure e.g. that sufficient capacity is available.

c. clear and unambiguous criteria for the rejection of wastes and the reporting of all conformance violations.

d. a system be in place to identifying the maximum capacity limit of material/waste that can be stored at the facility.

e. visually inspect the incoming material/waste to make sure it complies with the description received during the pre-acceptance procedure.

Implement different sampling procedures for all different incoming material/wastes delivered in bulk and/or containers. These sample procedures may contain the following items:

a. sampling procedures based on a risk approach. Some elements to consider are the type of materials/waste (e.g. hazardous or non-hazardous) and the knowledge of the customer (e.g. waste producer).

b. check on the relevant physico-chemical parameters. The relevant parameters are related to the knowledge of the material/waste needed in each case to register of all waste/materials.

d. have appropriate sampling procedures. The procedure should contain a system for recording the number of samples and degree of consolidation.

e. sample prior to acceptance.

f. a system for determining and recording.

g. a system to ensure that the material/waste samples are analysed if needed. PBDE might be analysed in case that the material is considered for further recycling and the material. The screening of bromine (see Chapter 5) can be used as a surrogate parameter for further decisions.

Have a reception facility that meets at least the following criteria:

a. a laboratory to analyse the samples at the speed required by BAT. Typically this requires having a robust quality assurance system, quality control methods and maintaining suitable records for storing the analyses results. Particularly for hazardous wastes, this often means that the laboratory needs to be on-site. Since PBDEs require a rather sophisticated analysis (see Guidance on analysis of new POPs in articles) such monitoring is normally not done on-site.

b. have a dedicated quarantine waste storage area as well as written procedures to manage rejected waste. If the inspection or analysis indicates that the wastes fail to meet the acceptance criteria (including, e.g. damaged, corroded or unlabelled drums) then the material/wastes can be temporarily stored there safely. Such storage and procedures should be designed and managed to promote the rapid management (typically a matter of days or less) to find a solution for that material/waste.

c. have a clear procedure dealing with wastes where inspection and/or analysis prove that they do not fulfil the acceptance criteria of the plant or do not fit with the material/waste description received during the pre-acceptance procedure. The procedure should include all measures as required by the permit or national/international legislation to inform competent authorities, to safely store the delivery for any transition period or to reject the material/waste and send it back to the waste producer or to any other authorized destination.

d. move material/waste to the storage area only after acceptance.

e. mark the inspection, unloading and sampling areas on a site plan.

f. have a sealed drainage system if needed.

g. a system to ensure that the installation personnel who are involved in the sampling, checking and analysis procedures are suitably qualified and adequately trained, and that the training is updated on a regular basis.

h. the application of a waste tracking system unique identifier (label/code) to each container at this stage. The identifier will contain at least the date of arrival on-site and the waste code.

### Storage and handling

PBDE-containing materials (e.g. electronic waste, shredder residues, PUR foams) and wastes often have to be stored and handled prior to treatment or final disposal. BAT/BEP storage should include the following techniques:

a. enclosing and locating storage areas away from water courses and sensitive perimeters, and in such a way so as to eliminate or minimise the double handling of wastes within the installation.

b. ensuring that the storage area drainage infrastructure can contain all possible contaminated run-off and that drainage from incompatible wastes cannot come into contact with each other.

c. using a dedicated area/store which is equipped with all necessary measures related to the specific risk of the wastes for sorting and repackaging laboratory smalls or similar waste. These wastes are sorted according to their hazard classification, with due consideration for any potential incompatibility problems and repackaged if needed. After that, they are moved to the appropriate storage area.

g. considerations are given to appropriate fire safety measures required for storage of plastic wastes (see UNEP 2002).

h. storing organic waste liquid with a low flashpoint under a nitrogen atmosphere to keep it inert. Each storage tank is put in a waterproof retention area. Gas effluents are collected and treated.

Apply the following techniques when handling waste.

a. having systems and procedures in place to ensure that wastes are transferred to the appropriate storage safely.

b. having in place a management system for the loading and unloading of materials/waste in the installation, which also takes into consideration any risks that these activities may incur.

c. ensuring that a qualified person attends the waste holder site to check the old original waste, waste from an unclear origin or undefined waste (especially if drummed), to classify the substances accordingly and to package into specific containers. In some cases, the individual packages may need to be protected from mechanical damage in the drum with fillers adapted to the packaged waste properties.

d. Adopt handling procedures that avoid the emission of fugitive dust and gas emission, using, as a priority, areas with capture and treatment of atmospheric emissions.

Maximise the use of re-usable packaging (drums, containers, IBCs, palettes, etc.)

### Outgoing materials and wastes

To improve the knowledge and management on the outgoing waste/material BAT/BEP is to:

- analyse and guarantee the quality and composition of the material/waste OUT according to the relevant parameters important for the receiving company/facility.
- assess how and where wastes could be re-used, consistently with environmentally sound management, as feedstock for another industry.
- assure that the materials and wastes are labelled according to the waste management catalogue and other labelling criteria of the country.
- assure that contaminated materials are only delivered to companies with appropriate treatment capacity and management frames in place. For wastes the appropriateness of the

treatment technologies is to be assured (e.g. landfill category, co-incineration in BAT cement kilns, BAT incinerators).

## 3.2. Producer responsibility

The Stockholm Convention's BAT/BEP guidelines (UNEP 2007/2019) describe principles such as sustainable development, sustainable consumption, the precautionary approach, integrated pollution, internalization of environmental costs, extended producer responsibility, cleaner production, life cycle assessment, and life cycle management. These principles are all relevant to secure BAT/BEP for the management of PBDEs-containing material flows, in particular that of producer responsibility.

Producers' and other stakeholders' responsibilities have been established through initiatives such as the EU's integrated product policy;[3] its thematic strategy on the prevention and recycling of waste[4] and associated framework directives;[5] the extended producer responsibility programme of the Organisation for Economic Co-operation and Development and related guidance (OECD 2001); the concept of product stewardship; and through other initiatives. In some cases it may be useful to oblige producers to take back certain end-of-life products and to assure their environmentally sound treatment.

PBDE-containing articles include important material flows for which producer responsibility could be the key for their global management. Such regulatory schemes already exist in some regions for vehicles and EEE (for instance in the EU), giving the producer the responsibility for end-of-life management. Other PBDE material flows, such as insulation foam, mattresses or furniture, could be addressed using this approach. Examples for extended producer responsibility for furniture are available from France.

## 3.3. Life cycle management

Life cycle management (LCM) is an integrated concept for managing the total life cycle of goods and services towards more sustainable production and consumption, building on the existing procedural and analytical environmental assessment tools and integrating economic, social and environmental aspects. Life cycle assessment (LCA) is a comprehensive technique that quantifies ecological and human health impacts of an article or system over its complete life cycle (UNEP 2011a; European Commission JRC-IES 2010). A targeted version of the LCA/LCM approach, which defines the boundaries, could be useful to formulate PBDE management strategies in developing countries and countries with economies in transition, with recycling technologies and approaches that are more labour intensive. This approach could lead to better separation and sorting of recycled materials at WEEE dismantling facilities, and thus achieve higher values and improved recycling business operations.

## 3.4. Monitoring of PBDEs/bromine in polymers

COP-5 recommended that separation of PBDE-containing articles require screening and detection of PBDEs or bromine-containing materials. One challenge, and prerequisite, is quick and reliable detection of PBDEs in articles, which would allow the separation of PBDE-containing materials in recycling processes. These technologies are discussed in the *Guidance on screening and analysis of POPs in Articles and Products* (UNEP 2017b). This document provides step by step guidance on monitoring (sampling, screening and analysis) in articles, products and recycling streams. Their applicability and potential use are then discussed in the sections describing BAT/BEP for treating material and recycling streams (see Chapter 5). Technologies for screening (and separation) of PBDEs are further evaluated for their practical applicability including developing country considerations in the following sections. It should be noted that the ongoing recycling exemption under the Stockholm Convention only applies to tetra-, penta-, hexa-, and heptaBDE for those Parties registered in the register of specific exemptions (N.B. the recycling exemption does not apply to decaBDE).

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[3] http://ec.europa.eu/environment/ipp/

[4] http://ec.europa.eu/environment/waste/strategy.htm

[5] http://ec.europa.eu/environment/waste/framework/index.htm

# 4. BAT and BEP measures for the use of decaBDE

## 4.1. Plastics (parts for use in vehicles and in aircraft, additives in plastic housings and parts used for heating home appliances, irons, fans, immersion heaters)

### 4.1.1. Process description

DecaBDE is an additive flame retardant. Additive flame retardants are incorporated into polymers via physical mixing, and are not chemically bound to the polymer. As a result, the polymer/additive mixture is less susceptible to combustion than the polymer alone. Typically decaBDE is used in plastics/polymers at loadings of 10-15% by weight, though in some cases loadings as high as 20% may be required (ECHA 2013). A formulation stage precedes the actual manufacturing of the finished article. For plastics, this stage usually takes the form of a resin or masterbatch production or compounding.

The compounding process involves mixing the polymer with the additives in an extrusion screw. The compounding process usually takes place in temperatures below 200°C but the forming of semi-finished or finished articles from that plastic often requires higher temperatures (RIKZ 2000). The processing temperature depends on the melting point of the plastic. The mixture then solidifies and is reduced in size to form pellets, which are dried and packaged.

The resins or plastic pellets can be used downstream by manufacturers of finished articles or for plastic components in other articles. They can then be turned into plastic articles by a variety of techniques, but most commonly by extrusion and injection moulding.

DecaBDE has been used as an additive flame retardant with a variety of materials (Table 4-1). The main EEE application has traditionally been enclosures made of HIPS, especially for TV-sets, but also for printers, scanners, fax machines, etc. Other EEE applications are connectors, switches, and other internal parts made of engineering plastics like thermoplastic polyesters (PBT/PET) and nylon (PA), and wires and communication cables made of polyolefins (PP and PE).

In EEE, decaBDE was typically used in concentrations ranging from 10 to 15% (up to 20%). Levels of decaBDE in vehicle components is variable, with levels above 2% particularly found in seat cover materials from old cars. Information on the use of decaBDE in the construction sector is scarce. Typical decaBDE/BDE-209 would be used in concentrations between 10 and 30% in electrical insulation and is below 30% in epoxy adhesives (UNEP 2020, Potrykus et al. 2019).

Table 4-1: Overview over plastic types where decaBDE has been used and their applications.

| Plastic | Type | Typical applications |
|---|---|---|
| Polypropylene (PP) | Polyolefin | Injection moulded parts, stadium seating, shipping pallets, roofing membranes, cladding panels |
| Polyethylene (PE) | Polyolefin | PE/wood composites, power cables, conduits, electrical connectors and boxes, wire and cable insulation, heat shrinkable material |
| Ethylene Vinyl Acetate (EVA) | Polyolefin / Elastomer | Wire and cable insulation, extrusion, coatings |
| High Impact Polystyrene (HIPS) | Polystyrenic | Plastic parts, panels, keyboards, casings of TV |
| Acrylonitrile / Butadiene Styrene (ABS) | Polystyrenic | General appliance moulding, car bumpers |
| Polyphenylene Oxide / Polystyrene blends (PPO/PS) | Polystyrenic | Instrument housings and internal components in electrical equipment |
| Polyethylene Terephthalate (PET) | Polyester | Textile fibres, plastic parts, switches, sockets, electrical appliances |
| Polybutylene | Polyester | Circuit breakers, sockets and electrical connectors, textiles, |

| | | |
|---|---|---|
| Terephthalate (PBT) | | switches |
| Polyamides (nylon) | Engineering thermoplastic | In injection moulding for transport apps: (e.g. wheel covers and handles, chair and seat-belt mechanisms, under hood applications). High temp. engineering application, textile fibres, coils, electrical components |
| Polycarbonates (PC) including PC/ABS | Engineering thermoplastic | Mirror housings, lights for cars, bumpers, window housings for trains and aircraft, casings, panels, keyboards |
| Polyimides (PI) | Engineering thermoplastic | Bearings in aircraft, seals, gaskets |
| Melamine | Thermoset | Textile finishing |
| Unsaturated Polyester Resins (UPR) | Thermoset | Articles for construction (modular building parts, roofing materials, porch canopies, decorative mouldings)<br>Fibre reinforced plastics, automobile parts |
| Epoxy resins | Thermoset | Adhesives, electronics, construction, aerospace |
| Ethylene Propylene Diene Monomer (EPDM) | Elastomer | Car radiator hoses, roofing membranes, cable and wire insulation |
| Styrene Butadiene Rubber (SBR) | Elastomer | Latex, carpet reinforcements, interior redecoration. |
| Thermoplastic Polyurethanes (TPU) | Elastomer | Automotive, wire and cable applications, gaskets |
| Emulsions/coatings PVC, Ethylene Vinyl Chloride emulsion acrylic | Waterborne emulsions | Adhesive applications (e.g. wall coverings, furniture, flooring), protective coatings, saturation of fibrous materials (paper, textiles) |

*(ECHA 2012, Plasticseurope 2013, RPA 2014 and UNEP 2014)*

### 4.1.2. BAT and BEP (incl. availability of alternatives)

The Reference Document on Best Available Techniques in the Production of Polymers (European Commission 2007) addresses a wide variety of BAT and BEP measures spanning the whole polymer production process. This document is being revised in the Draft BREF WGC (Waste Gas Treatment in the Chemical Sector), where also the production of polymers is included (European Commission 2019). For issues regarding waste water the Reference Document on Best Available Techniques for common waste water/waste gas treatment /management in the chemical sector (European Commission 2016) applies.

General measures (applicable to all production processes) include:

- Implementation of an EMS (See Chapter 3 of this guidance document)
- Establishment, maintenance and regular review of a channelled and diffuse emissions to air inventory as part of the EMS
- Use of an integrated waste gas management and treatment strategy that includes process integrated recovery and abatement techniques
- Limiting the number of emission points. The combined treatment of waste gases with similar characteristics ensures more effective and efficient treatment.

Measures for the reduction of channelled emissions are:

- Use of the following techniques to reduce channelled emission to air of organic compounds: adsorption, absorption, catalytic oxidation condensation, thermal oxidation
- Use of the following techniques to reduce channelled emissions to air of PCDD/F: optimised catalytic or thermal oxidation, rapid waste-gas cooling, adsorption using activated carbon
- The use of absolute filter, absorption, fabric filter and/or high-efficiency air filter to reduce channelled emissions to air of dust and particulate-bound metals

Monitoring diffuse VOC emissions are:

- Monitoring diffuse VOC emissions from the use of solvents by compiling a solvent mass balance
- Establishing and implementing a lead detection and repair (LDAR) programme for fugitive VOC emissions and reviewing and updating the programme for the next campaign
- Establishing and implementing a detection and reduction programme for non-fugitive VOC emissions and reviewing and updating this programme
- Estimation of diffuse and fugitive VOC emissions to air using a combination of different techniques (emission factors, mass balance, thermodynamic models)

Measures to prevent or reduce diffuse VOC emissions:

- Limiting the number of emission sources (like e.g. minimising pipe lengths, reducing number of pipe connectors and valves, using welded fittings and connections, using compressed air or gravity for material transfer)
- Collection of diffuse emissions and treating off-gases
- Facilitating access to potentially leaky equipment (installing platforms, using drones for monitoring)
- Use of high-integrity equipment
  - valves with bellow or double packing seals or equally efficient equipment
  - magnetically driven or canned pumps/compressors/agitators, or pumps/compressors/agitators using double seals and liquid barrier
  - certified high-quality gaskets
  - corrosion-resistant equipment
- tightening of gaskets, installing tight caps on open ends
- replacement of leaky equipment parts
- review and update of operating conditions (e.g. frequency and duration of reactor opening, preventing corrosion)
- use of closed systems
- use of techniques to minimise emissions from surface areas
  - installing oil creaming systems on open surfaces
  - periodically skimming open surfaces
  - installing anti-evaporation floating elements on open surfaces
  - treating waste water streams to remove VOCs and send them to recovery and/or abatement
  - installing floating roofs on tanks

Measures referring to water emissions:

- Establishment and maintenance of an inventory of waste water and waste gas streams as part of the environmental management system
- Monitoring of emissions to water using EN, ISO, national or international standards with a minimum frequency
- Use of an integrated waste water management and treatment strategy that includes a combination of the following techniques: process-integrated techniques, recovery of pollutants at source, waste water pre-treatment, final waste water treatment

- Pre-treatment of waste water that contains pollutants that cannot be dealt with adequately during final waste water treatment (e.g. remove toxic compounds)
- Preventing water pollution by appropriate piping design and materials, e.g.:
  - pipes and pumps placed above ground
  - pipes placed in ducts accessible for inspection and repair.
- Measures for water pollution prevention also include separate effluent collection systems for:
  - contaminated process effluent water
  - potentially contaminated water from leaks and other sources, including cooling water and surface run-off from process plant areas, etc.
  - uncontaminated water.
- Use of efficient waste water treatment techniques.
- The treatment of the air purge flows coming from degassing silos and reactor vents, e.g.
  - Recycling
  - Thermal oxidation
  - Catalytic oxidation
  - Flaring (only discontinuous flows)

The Source Control of Priority Substances in Europe (SOCOPSE) project Fact Sheet for Polybrominated diphenyl ethers (PBDEs) documents the following specific measures to contain releases of decaBDE:

- When handling raw materials for plastic processing, significant amounts of decaBDE could be lost in dust (which mainly ends up in solid waste).
  - The packaging material should be durable to avoid leakages during transportation and handling
  - Where possible the material should be in traded as coarse powder instead of fine powder that is prone to handling losses
  - The material must be stored in an enclosed area with extraction system that has appropriate dust capturing system
  - Losses can be minimised by a combination of options: Careful handling of decaBDE packaging should avoid dust emissions from wear and tear, while scraping instead of rinsing will avoid further emissions to wastewater. Also, decaBDE powder should be handled under local exhaust ventilation with filter, and any loose dust should be vacuumed up before washing the working area.
  - Handling of decaBDE powder under local exhaust ventilation with filter also limits exposure to antimony compounds.
- The compounding process (blending of the base polymer with additives including flame retardants) may lead to dust formation (mainly in the first stages of the mixing cycle) and volatilisation (due to elevated processing temperatures).
  - The decaBDE should be added gently close to the mixing vessel level to avoid dust formation
  - The mixing vessel should be connected to extraction system that has appropriate dust capturing system

  - Options such as localised containment may be implemented to collect and recycle the decaBDE-containing dust material. Dust emissions can also be reduced with an air aspiration system which sucks the air stream into the mixer when dosing.
  - Washing of equipment/vessels may lead to additional losses with wastewater. To avoid discharge to local sewer, an industrial wastewater treatment plant with a solid extraction system is needed. The efficiency of decaBDE removal with a solid extraction system is unknown, but it is expected that discharge of decaBDE to sewer be negligible.
  - Handling of decaBDE powder under local exhaust ventilation with filter also limits exposure to antimony compounds.
- The conversion process (production of final products) may lead to volatilisation (due to elevated processing temperatures).
  - Avoid addition of excess amount of the decaBDE in the mixing vessel
  - Possible measures to avoid atmospheric emissions include operating in a closed system with collecting and treating waste gas containing decaBDE.

The Voluntary Emissions Control Action Programme (VECAP) is a voluntary industry programme established to identify, control and reduce the potential for emissions of polymer additives into the environment. VECAP published an addendum to the Code of Good Practice, including BAT for emptying bags containing brominated flame retardants, documents for (in)direct users in the plastics and textiles sector. VECAP (2019) recommends best practices for the following stages of the production and use processes:

- Transport and storage

Solid chemicals are transported to warehouses in bags that, on arrival, are brought to a storage area in the factory. During this stage in the process potential emissions of chemicals could occur as bags could break. VECAP best practice recommends that bags are carefully checked on arrival, and when removed from storage, to ensure that they are not damaged and that all seals are intact. Any tears should be repaired immediately and spills cleaned up.

- Opening and emptying of packaging

At this stage chemicals might spill on the floor, be discharged into the air as dust, or adhere to the personal protective clothing of workers. Emptying bags and intermediate bulk containers (IBCs) is also a critical point since any residues left in packaging could lead to environmental emissions during packaging disposal.

VECAP best practices recommend that when using a chemical in powder form, bags should only be opened in a sealed environment, with all windows and doors in the surrounding areas firmly closed. Furthermore, in well maintained places where powder materials are handled, a local exhaust ventilation system should be in place, preferably a tiered system composed of several filters. This limits the risk of environmental emissions, allowing for the air to be filtered and appropriate disposal of residual dust. When making liquid slurry, the recommended practice is that bags are securely connected to the entrance of the machine (the mal) before opening them.

Bags should be thoroughly emptied shaking all four corners of the bag carefully to ensure the maximum content is removed. IBCs should be tilted in order to allow remaining product to be accessed and removed.

In the event that chemicals spill on the floor at any stage of the process, spillage should be cleaned immediately, preferably with dry cleaning via a vacuum system. If using a wet clean process, cleaning water should be collected and treated, either on site or at a municipal water treatment facility. Sludge collected from waste water treatment should be incinerated.

- Ventilation

To reduce dust emissions to air, an exhaust ventilation system equipped with well-operated fabric filters should be the minimum in place. In addition, sucking the air stream into the mixer further reduces dust emissions including from doors and workers' clothing. The filter system should be properly maintained and filter dust and spent filters properly disposed of.

- Disposal of packaging at the end of the production process

VECAP best practices extend to the end of the production process and the safe disposal of packaging and waste.

The technical guidelines on POPs wastes and on PBDEs wastes should be considered to ensure the environmentally sound management of wastes generated through the process (UNEP 2019c, d).

### Labelling of PBDE-containing plastic fractions and articles

BEP can imply that plastic fractions or mixed plastic for recycling from WEEE are labelled or otherwise marked so that their origin is known when they are exported/imported or used by industries for producing new articles. Such products made from PBDEs-containing materials would be labelled (see *POPs Labelling–considerations,* UNEP 2019e) to guarantee their appropriate end-of-life management as required by the Stockholm Convention.

The labelling/classification of PBDE-containing fractions also need to ensure that the plastic fraction containing PBDEs and other plastics fractions from WEEE recycling[6] are not recycled into sensitive uses.

Labelling of plastic in EEE has been established. European standards enforced on plastics marking, including the information on plastic type and additives like flame retardants include:

- ISO 1043-1 Plastics - symbols and abbreviated terms. Part 1: Basic polymers and their special characteristics.
- ISO 1043-2 Plastics - symbols and abbreviated terms. Part 2: Fillers and reinforcing materials.
- ISO 1043-4:1998 Plastics — Symbols and abbreviated terms — Part 4: Flame retardants.

In Japan, the Japanese Industrial Standard (JIS) for optimizing the recycling of plastics in electric home appliances, "marking for identification of plastic parts for electrical and electronic equipment (JIS-C9912[7])" requires the marking of plastic parts such as flame retardants, recycled plastics and dismantling procedures. Thus, the information flow is linked with the mass flow. In particular, the marking system includes plastics already recycled by "closed-loop recycling" (recycling from plastics of electric home appliances to plastics of electric home appliances).

### Alternatives to the use of decaBDE as a flame retardant in polymer applications

A case-by-case assessment is necessary to find the best alternative suitable for a specific use. It is important to consider all the available health and environmental data to obtain a comprehensive and robust understanding of the toxicological and ecotoxicological effects and performance of the alternatives (USEPA 2014; ECHA 2014). Furthermore, some alternatives may be subject to controls in specific jurisdictions.

Substitution of decaBDE in a given polymer application can take place at three levels:

**1. DecaBDE can be replaced by another flame retardant with similar properties without changing the resin:**

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[6] These polymers can contain other hazardous substances like heavy metals (including antimony, cadmium), other BFRs, PFRs or softeners.

[7] JIS-C9912 (Japan Standard Association 2007)

Table 4-2: Flame retardant chemicals reported to be used for polymer applications.

| Name | CAS No | Examples of trade name | Polymer applications |
|---|---|---|---|
| **Halogen-containing FRs** | | | |
| Ethane-1,2-bis(pentabromophenyl) | 84852-53-9 | Ethane-1,2-bis(pentabromophenyl) (SAYTEX® 8010) (Albemarle Corp.), Decabromodiphenylethane, DBDE (Firemaster® 2100) (LANXESS) | ABS, HIPS, PA, PBT/PET, PC, PP, PE, SAN, PC/ABS, HIPS/PPE, Thermoplastic elastomers, silicone, PVC, EPDM |
| Ethylene bis(tetrabromophthalimide) | 32588-76-4 | SAYTEX® BT-93 (Albemarle Corp.), BT-93 (Jiangsu Huading Refining Chemical Industry Co. Ltd., China) | ABS, HIPS, PA, PBT/PET, PC, PP, PE, SAN, PC/ABS, HIPS/PPE, Thermoplastic elastomers, silicone, PVC, EPDM |
| Brominated epoxy polymer | 68928-70-1 | FR 2300 (ICL Industrial Products) | PBT, HIPS, ABS, PC/ABS |
| Brominated epoxy resin end-capped with tribromophenol | 135229-48-0 | Pratherm EC 20 | ABS, HIPS, PBT, UPE |
| Tetrabromobisphenol-A (TBBPA) | 79-94-7 | SAYTEX® CP-2000 (Albemarle Corp.), BA-59P (LANXESS), FR-1524 (TBBA) (ICL Industrial Products) | ABS, HIPS, PC |
| TBBPA carbonate oligomer | 94334-64-2,<br>71342-77-3 | 94334-64-2: LANXESS BC-52, 71342-77-3: LANXESS BC-58HP MSDS | PBT/PET, PC, ABS, PC/ABS, polysulfone, SAN |
| TBBPA bis (2,3-dibromopropyl ether) | 21850-44-2 | SAYTEX® HP-800A, HP-800AG, and HP-800AGC (Albemarle Corp.), PE-68 (LANXESS ), FR-720 (ICL Industrial Products), 403AF (LG Chem) (HIPS with Tetrabromobisphenol A bis (2,3-dibromopropyl ether) | HIPS, PP, PE, crystal PS |
| Tetradecabromodiphenoxy benzene | 58965-66-5 | SAYTEX 120 (Albemarle Corp.) | ABS, HIPS, PA, PBT/PET, PC, PP, PE, SAN, PC/ABS, HIPS/PPE, silicone, EPDM |
| Tris(tribromophenoxy) triazine | 25713-60-4 | FR 245 (ICL Industrial Products) | PE, ABS, HIPS |
| Bis(tribromophenoxy) ethane | 37853-59-1 | FF-680 (LANXESS) | HIPS, ABS, PC, UPE |
| Tris(bromopentyl) phosphate | 19186-97-1 | EcoFlameRetardant B-37 (UniBrom USA) | PP, HIPS |
| Poly(pentabromobenzyl acrylate) | 59447-57-3 | FR-1025 (PBB-PA) (ICL Industrial Products) | PBT, PET, PA, styrenic copolymers |
| Brominated polystyrene | 88497-56-7 | SAYTEX® HP-3010; SAYTEX® HP-7010G; SAYTEX® PBT-620 (blend with polyester resin); PYRO-CHEK®68PB (Albemarle Corp.), FIREMASTER® PBS-64 (LANXESS), FIREMASTER®BP 411 (LANXESS), Firemaster® CP-44HF (LANXESS) (Note: For CP-44HF and PBS-64 the Technical Data Sheet identifies CAS No. 148993-99-1 whereas the Safety Data Sheets identifies CAS No. 88497-56-7) | PA, PP, PBT/PET/PCT, PC/ABS, HIPS/PPO |
| Poly(dibromostyrene) | 148993-99-1 | PDBS-80 (LANXESS) | PBT/PET, PA |
| Dodecachlorododecahydro-dimethanodibenzocyclooctene* | 13560-89-9 | Dechlorane Plus® series (Occidental Petroleum Corporation) | PA, ABS, PP, Epoxy |
| **Non-halogen organo-phosphorous FRs** | | | |

| | | | |
|---|---|---|---|
| Resorcinol bis(diphenylphosphate) (RDP) | 125997-21-9; 57583-54-7 | Reofos RDP (LANXESS), Fyrolflex RDP (Supresta/Akzo Nobel) | PC/ABS |
| Bisphenol A bis(diphenyl phosphate) (BAPP) | 5945-33-5;<br>181028-79-5 | Reofos BAPP (LANXESS), NcendX P-30 (Albemarle Corp.) | PC/ABS, PPE/HIPS blends |
| Bisphenol A bis(diphenylphosphate) (BDP) | 5945-33-5 | Fyrolflex BDP (Akzo Nobel/Supresta) | ABS, HIPS, PPE/PC |
| Cresyl diphenyl phosphate (CDP) | 26444-49-5 | Disflamoll® DPK (Lanxess) | PC/ABS, PF, Epoxy, PUR-foams |
| Triphenyl phosphates (TPP) | 115-86-6 | Reofos TPP (LANXESS), Fyrolflex TPP (Akzo Nobel/Supresta), Disflamoll® TP (Lanxess) | PC/ABS, modified PPO, Phenolic |
| Triaryl phosphates butylated | 68937-40-6 | Reofos 507 (LANXESS) | PC/ABS |
| **Other non-halogen FRs** | | | |
| Intumescent FR systems based on phosphor and nitrogen compounds | | Clariant (Exolit), LANXESS (Char-Guard), Budenheim (Budit), Unitex Chemical (Uniplex 44-94S) | PP, PE |
| Red phosphorous | 7723-14-0 | Exolit RP 690 and others in the RP series (Clariant GmbH) | PA, PE |
| Ammonium polyphosphate | 14728-39-9<br>68333-79-9 | Exolit AP 750 (TP) and others in the AP series (Clariant GmbH) | PE, PP |
| Melamine cyanurate | 37640-57-6 | MELAPUR® MC XL, MELAPUR® MC50, MELAPUR® MC25 (Ciba), FR-6120 (ICL Industrial Products) | PA, thermoplastic PUR |
| Melamine polyphosphate | 15541-60-3;<br>218768-84-4 | MELAPUR® 200/70 (Ciba), Exolit AP 750 (Clariant GmbH) | PA, TPU |
| N-alkoxy Hindered Amine Reaction Products | 191680-81-6 | 1,3-Propanediamine, N1,N1'-1,2-ethanediylbis-, reaction products with cyclohexane and peroxidized N-butyl-2,2,6,6-tetramethyl-4-piperidinamine-2,4,6-trichloro-1,3,5-triazine reaction products; Flamestab Nor 116 | PE/PP thin films and fibers |
| Organic phosphinates | 225789-38-8 | Exolit® OP 1312 M1; Exolit® OP 1311 and others in the series (Clariant GmbH) | PA, PBT |
| Phosphonate Oligomer, Polyphosphonate | 68664-06-2 | Nofia® oligomers; FRX Oligomers (phosphonate oligomers); Phosphonic acid, P-methyl-, diphenyl ester, polymer with 4,4'-(1-methylethylidene)bis[phenol] (not a copolymer) | Thermosets, elastomers, thermoplastic |
| Poly[phosphonate-co-carbonate] | 77226-90-5 | Nofia® CO3000; Nofia® CO6000; Carbonic acid, diphenyl ester, polymer with diphenyl P-methylphosphonate and 4,4'- (1-methylethylidene)bis[phenol]; FRX CO35; FRX CO60 | Elastomers, thermoplastic |
| Phosphoric acid, mixed esters with [1,1'-bisphenyl-4,4'-diol] and phenol; BPBP | 1003300-73-9 | Phosphoric acid, P,P'-[1,1'-biphenyl]-4,4'-diyl P,P,P',P'-tetraphenyl ester; Biphenyl-4,4'-diyl tetraphenyl bis(phosphate); BPBP; ADK STAB FP-800; T-1752F | PC/ABS, PPE/HIPS, PC |
| Aluminum diethylphosphinate | 225789-38-8 | Exolit OP 930; Aluminium diethylphosphinate; Aluminium tris(diethylphosphinate) | PA, PBT, PE, thermoplastic PUR |
| Aluminium hydroxide | 21645-51-2;<br>8064-00-4 | AB H-Series Alumina Trihydrate, Actilox, ALH-, ALOLT-, Aluminium hydrate, Aluminiumhydroxid, Apyral, BARIACE, | PVC, ABS, PE |

| | | | |
|---|---|---|---|
| | | BARIFINE, Bayerit, Geloxal, Hydrated alumina, hydroxid hlinitý, HYMOD® Surface-Treated Alumina Trihydrate | |
| Antimony trioxide (Used as a synergist only) | 1309-64-4 | Antimony oxide; Antimony white; Antimony (III) oxide; Antimonious oxide; Antimony sesquioxide; C.I. Pigment White 11; Diantimony trioxide; Patox C; Thermoguard B; Timonox; Timonox White Star; Flowers of antimony; Exitelite; Senarmonite; Valentinite; Weiss-piessglanz | PE, PP, PVC, HIPS, elastomers, thermosets, thermoplastics |
| Magnesium hydroxide | 1309-42-8 | MAGNIFIN® H-7 C (Albemarle Corp.) | Thermoplastic polyester and elastomers, polyolefin, PVC, EPDM, PE/ EVA |
| Zinc borate (Synergist for halogen and non-halogen) | 1332-07-6, 138265-88-0 | Boric acid, zinc salt; Boron zinc hydroxide oxide; Alcanex FR 100; Alcanex FRC 600; Bonrex FC; Borax 2335; Borogard ZB; Climax; ZB 467; 128859; FRC 600; Firebrake 415; Firebrake 500; Firebrake ZB; Flamtard Z 10; JS 9502; SZB 2335; Storshield ZB2335; XPI 187; ZB 112; ZB 113; ZB 223; ZB 237; ZB 325; ZB 467 Lite; ZB-Shield; ZN 100; ZSB 2335; ZT; Zinc borate | PE, PP |

*(UNEP 2019b, RPA 2014, USEPA 2014, ECHA 2014, 2012, Danish EPA 2006)*

* Dechlorane Plus has been identified as vPvB (very persistent and very bioaccumulative) under REACH and, as of 2020, is under review as a candidate POP by the POPs review Committee.

**2. The plastic material, i.e. the resin with flame retardants and other additives, can be replaced by another plastic material (incl. copolymers) with similar properties:**

*Alternative materials*

Metal or inherently fire-resistant plastics can be used as alternative materials in certain electronic products. New inherently fire-resistant materials are increasingly being mentioned in the literature or on commercial websites, often promoted as replacements for decaBDE (UNEP 2015, 2019b; ECHA 2012).

The following plastics are inherently fire-resistant and could replace polymers typically treated with decaBDE such as poly(butylene terephthalate) (PBTE) and polyamide/nylon (PA) (Danish EPA 2006):

(a) Halogen-free polyketone;

(b) High performance thermoplastics such as polysulphone, polyaryletherketone (PAEK), or polyethersulphone (PES).

Polymers that char, such as polyimides, polyaramides, liquid crystal polyesters, polyphenylene sulphide, polyarylenes, and many thermosets, also tend to have greater fire resistance.

Halogenated polymers such as PVC also have flame retardant properties because they release halogen radicals during combustion. The effect is often enhanced by the addition of synergists such as ATO to halogenated polymer blends. However, like brominated flame retardants, PVC can form dioxins and acids upon combustion, and is therefore not a preferred alternative material (Blomqvist et al. 2007).

*Fire barriers*

Using fire-resistant metal barriers to separate or isolate the most flammable parts from the rest of the product can eliminate the need for flame retardants such as decaBDE (LCSP 2005).

*Intumescent systems*

In plastics, like in textiles, fire safety may be achieved via the use of intumescent systems (Klif 2011; USEPA 2014). Intumescence is the formation of a foamed char, which acts as heat insulation. An intumescent system is generally a combination of a source of carbon to build up char, an acid-generating compound, and a decomposing compound that generates blowing gases to produce foamed char (Weil and Levchik 2009). This foam attains a thickness of 10 to 100 times that of the originally applied coating and insulates the substrate material through its low thermal conductivity. This makes intumescent systems efficient at reducing both flammability and exposure to toxic gases and fumes (KemI 2006). Intumescent systems include use of expandable graphite impregnated foams, surface treatments, and some barrier technologies (Klif 2011).

**3. The need for flame retardants can be eliminated by design changes, or the entire product can be replaced by a different product with similar performance:**

Electronic and electrical equipment can be redesigned to eliminate or reduce the need for chemical flame retardants. Possible redesign strategies include (UNEP 2019b):

(a) Separating the high-voltage components that need greater ignition protection from the low-voltage components;

(b) Reducing the operating voltage requirements, therefore reducing the need for fire-resistant enclosure materials;

(c) Separating the power supply from the product, which reduces the fire-retardancy requirements of the electronic enclosure;

(d) Shielding power supplies with metal to eliminate the need for additive flame retardants.

## 4.2. Textile products that require anti-flammable characteristics excluding clothing and toys

### 4.2.1. Process description

A large number of textile applications such as work clothing, firefighter and military apparel, institutional and commercial carpet, draperies and upholstery, transportation (train, airplane, bus, boat: blankets, seat covers, carpets), bedding, require stringent anti-flammable properties and a large number of specific fire standards with specific fire requirements for textiles have been developed internationally for various widely differing situations. Some examples are given below.

Table 4-3: Examples of standard test methods for flame retardant textiles.

| Textile type | Standard test methods | Remarks |
|---|---|---|
| Furnishing fabrics | BS 5852: Pts 1 and 2: 2006<br>BS 5852: 1990(1998)<br>ISO 8191: Pts 1 and 2 (same as BS 5852: 1990<br>BS EN 102 1–1: 2006<br>BS EN 102 1–2: 2006<br>BS 6 807: 2006<br>BS 5867: Part 2: 1980 (1990) | Cigarette and simulated match flame (20 s ignition)<br>Small flames and wooden cribs applied to small and full scale tests<br>Cigarette<br>Simulated match flame (15 s ignition)<br>Ignitability of mattresses or divans<br>Small flame test for curtains and drapes |
| Nightwear | BS 5722: 1991<br>AS1249 | Small flame |
| Bedding | BS 7175: 1989 (1994)<br>BS ISO 12952–1/4: 1999<br>BS ISO 12952–2/3: 2001<br>France Decree 2000–164 | Ignitability of bed covers and pillows<br>Ignitability of bedding items by cigarette and small flame sources<br>French Standard for bedding (cigarette resistance) |
| Protective clothing | EN 533, NF P92 503 (M1),<br>BS 7175 Crib 5 | |
| Carpet | DIN 4102(B1), FAR25–853 | |
| Non-woven | Non-woven NF P92 503 | |
| Textiles in aircrafts | ASTM E 906 1983 | Irradiate under 35 kW/m 2 |

| | | |
|---|---|---|
| | NF P 92501: 1995 French 'M test' | with small flame igniter<br>Irradiate with small burner |

(Gaan et al. 2011, KEMI 2004)

Although fire regulations are mandatory for the market, these do not require the use of certain FRs in order to comply with these standards or regulations. The choice of flame retardant is left entirely to the manufacturer (UNEP 2019d).

DecaBDE has traditionally been applied to textiles as a backcoating in combination with antimony oxide (ATO) as a synergist (LCSP 2005; UNEP 2019b). Through this process, a fire-resistant layer is attached to one side of the finished textile. Antimony–halogen FRs are the most successful FRs for textile backcoating, based on cost and efficacy (RPA 2014). Unlike the fibre-reactive, durable phosphorus- and nitrogen-containing FRs used for cellulosic fibres, they can only be applied topically in a resin binder, usually as a backcoating.

DecaBDE is first mixed with ATO to form an aqueous dispersion. Then this dispersion is mixed with a polymer emulsion, containing for example natural or synthetic rubber, EVA, styrene-butadiene copolymer or PVC (ECHA 2012; RPA 2014). An effective mass ratio for the backcoating mixture is one part ATO to three parts incorporated bromine (each decaBDE contains 10 incorporated bromine atoms), which translate to roughly one part ATO to two parts decaBDE to three parts resin (or 20–30% w/w FR in the mixture) (KemI 2005; RPA 2014). Typically, the FR mixture consists of about 67–75% DecaBDE and properties of the fabric.

Such backcoatings are effective on a wide range of fabrics, including nylon, polypropylene, acrylics, and other blends, such as nylon–polyester. They have important applications in domestic, industrial and automotive upholstered furniture, as well as draperies for hotels and other public buildings. The versatility of decaBDE backcoating is among the main reasons it is considered a good choice for the textile industry (RPA 2014).

During the backcoating process, the flame retardant formulation is applied to the back of the fabric with a running roller and then passed through an oven at 130–140°C to dry the new coat. The loading will usually be 7.5–20% depending on the weight of the fabric (ECB 2002). ECB has suggested the following loadings as typical (the figures refer to g of dry coating/m2 of fabric; decaBDE makes up around 30–40% of the dry coating weight):

- Velour pile fabrics: 70–80 g/m2
- Cotton: 30–40 g/m2
- Flat woven (other types): 30–80 g/m2 (likely to be 40–50 g/m2).

### 4.2.2. BAT and BEP (incl. availability of alternatives)

Typically for textile applications, the compounding process is the first step where decaBDE is mixed with antimony trioxide and water in the pre-mixer, then stored in a large tank, and lastly mixed with the base polymer in the mixing vessel to give the formulation (viscous paste).

The backcoating is the second step where the formulation is applied to the back of the textile by a running roll and the whole textile is dried in oven at 130-140°C for a few seconds.

Both compounding and backcoating are batch processes (ECB 2002).

The Reference Document on BAT for the Textiles Industry (European Commission 2003, under revision) mentions backcoating and decaBDE in Chapter 8.8.4 (flame retardants). The revised Draft BREF from December 2019 lists emission concentrations to water of decaBDE of different European installations in table 3.4. According to BAT 7 in the Draft BREF 2019 brominated flame retardants have to be monitored at least once every three months, a possible standard to use is EN16694. The monitoring only applies when the substance(s)/parameter, including groups of substances or individual substances in a group of substances, concerned is identified as relevant in the waste water stream based on the inventory of inputs and outputs mentioned in BAT 2. No BAT associated emission level to water is given for this substance in the Draft BREF.

When finishing with flame retardants BAT49 the following two techniques are BAT according to the Draft BREF 2019:

- Use of textiles with inherent flame retardance properties (no flame retardants are necessary)
- Selection of flame retardants according to their persistence and toxicity

Measures according to the Draft BREF on Textiles include:

- Establishment, maintenance and regularly review of an inventory of inputs and outputs as part of the environmental management system
- Usage of an advanced process monitoring and control system
- Use of textile materials with low contents of contaminants and with reduced processing needs
- Monitoring of emissions of brominated flame retardants to water once every 3 months in the case of finishing with flame retardants
- Elaboration and implementation of a chemicals management system (CMS) as part of the environmental management system (e.g. monitoring of changes related to hazardous chemicals, assessment of risks associated to the chemicals based on the chemicals' hazards, concentrations and amounts, regular checks aiming at identifying potentially new available and safer alternatives to the use of hazardous chemicals)
- Elaboration and implementation of a chemicals inventory and tracking system as part of the CMS

DecaBDE would be largely retained by the sludge in the waste water treatment system. However, since the amount/load of active substance applied on the fabric is typically in the order of 20 – 30% w/w, the amount of flame retardant not retained by the sludge and therefore potentially released into the environment may be significant. Process design and operation should avoid the discharge of concentrated liquors to waste water, minimise losses to the effluent, and ensure that adsorption to the sludge is effective in the waste water treatment plant.

The Source Control of Priority Substances in Europe (SOCOPSE) project Fact Sheet for Polybrominated diphenyl ethers (PBDEs) documents the following specific measures to contain releases of decaBDE during the compounding process and the backcoating process:

- Dust formation when emptying decaBDE powder into the pre-mixer and the wastewater from washing mixing vessels are main potential sources of decaBDE emissions from the compounding process.
    - To minimise dust emissions, decaBDE powder should be handled under local exhaust ventilation with filter, and any loose dust should be vacuumed up before washing the working area.
    - Handling of decaBDE powder under local exhaust ventilation with filter also limits exposure to antimony compounds.
    - With regard to vessel washing, less than 0.1% of decaBDE can be expected to be lost in wastewater (ECB 2002). To avoid discharge to local sewer, an industrial wastewater treatment plant with a solid extraction system is needed. The solid extraction system will remove the viscous mixture that decaBDE forms with the polymer at this stage. The efficiency of decaBDE removal with such a system is unknown, but it is expected that discharge of decaBDE to sewer be negligible. The last stage consists in safely disposing

of the solid residue (incineration or landfill) since PBDEs cannot be degraded in wastewater treatment plants.

- During the backcoating process the washing of equipment between batches is an important source.
    - Possible measures include cleaning of the coating rolls with rubber knives and paper and safe disposal of waste instead of washing; the reduction at the minimum of the frequency of washing; and the wastewater collection after washing by an industrial wastewater treatment plant followed by suitable waste disposal.

The VECAP addendum to the Code of Good Practice including best available technique for emptying bags containing brominated flame retardants is equally relevant for users in textiles sector (see VECAP 2019 and related information included in section 4.1.2).

To ensure the environmentally sound management of wastes generated through these processes, the technical guidelines on POPs wastes and PBDEs wastes are applicable (UNEP 2019c, d).

### Alternatives to the use of decaBDE as a flame retardant in textile applications

**1. Substitution of decaBDE by another flame retardant with similar properties:**

Table 4-4: Flame retardant chemicals reported to be used for textile backcoating.

| Name | CAS No. | Examples of trade name | Applications |
|---|---|---|---|
| | | **Halogen-containing FRs** | |
| Ethylene bis(tetrabromophthalimide) | 32588-76-4 | SAYTEX® BT-93 (Albemarle Corp.), BT-93 (Jiangsu Huading Refining Chemical Industry Co. Ltd., China) | Additive flame retardant in polypropylene, polyethylene and polycarbonate with end uses in electrical and electronic equipment, wire and cable, construction materials and textiles. The loadings required are similar to those for decaBDE but it is a more expensive product. It is non-blooming, has greater heat and UV stability than decaBDE and in some cases generates less smoke. It can be used where discolouration needs to be minimised. |
| Tetrabromobisphenol A bis (2,3-dibromopropyl ether) (TBBPA) | 21850-44-2 | SAYTEX® CP-2000 (Albemarle Corp.), BA-59P (LANXESS.), FR-1524 (TBBA) (ICL Industrial Products) | Mainly used as a reactive flame retardant in epoxy resins (printed circuit boards), polycarbonates and unsaturated polyesters (RPA, 2003). On its own it is not effective as a flame retardant in polyolefins (Weil and Levchik, 2009). It can be used as a flame retardant in polymers such as ABS, polystyrenes, phenolic resins, adhesives, paper, and textiles but has poor colour stability so its use tends to be limited to applications where discolouration caused by exposure to light can be tolerated |
| Ethane-1,2-bis(pentabromophenyl) | 84852-53-9 | Ethane-1,2-bis(pentabromophenyl) (SAYTEX® 8010) (Albemarle Corp.), Decabromodiphenylethane, | This substance is marketed as a drop in replacement for decaBDE and is used at similar loadings. It is particularly suited for polymers that are processed at high temperature.<br>Typical substrate: Cotton, polyester, |

| | | | |
|---|---|---|---|
| | | DBDE (Firemaster® 2100) (LANXESS) | acrylic, leather, leather imitation (PUR, PVC) |
| Tris(tribromophenoxy) triazine | 25713-60-4 | FR 245 (ICL Industrial Products) | Used as Tris(tribromophenyl)Triazine + Antimony imitation (PUR, PVC) synergists (TTBPT)<br>Typical substrate: Cotton, polyester, acrylic, leather, leather imitation (PUR, PVC) |
| Tris(1,3-dichloro-2-propyl) phosphate | 13674-87-8 | 1,3-dichloro-2-propanol phosphate (3:1), 2-propanol, 1,3-dichloro-, phosphate (3:1), Amgard TDCP, Antiblaze 195, Antiblaze TDCP, FR2, Fyrol FR-2 | Used in textile backcoating |
| **Non-halogen organo-phosphorous FRs** | | | |
| 2,2'-oxybis[5,5-dimethyl-1,3,2-dioxaphosphorinane] 2,2'-disulphide | 4090-51-1 | Mileflame FR 5060 (MPI Chemie Bv) | Viscose FR that can be applied to wide array of synthetic materials incl. plastic, rubber and textile industry. |
| **Other non-halogen FRs** | | | |
| Red phosphorous | 7723-14-0 | Exolit RP 690 and others in the RP series (Clariant GmbH) | Best suited to materials with high oxygen content (e.g. cellulose and oxygen containing plastics/fibres). Otherwise, a synergist will need to be used e.g. nitrogen or halogen containing compound.<br>Cotton, polyester |
| Ammonium polyphosphate | 14728-39-9;<br>68333-79-9 | Exolit AP 750 (TP) and others in the AP series (Clariant GmbH) | Ammonium polyphosphate (microencapsulated) (APP)<br>Cotton, polyester |
| Melamine cyanurate | 37640-57-6 | MELAPUR® MC XL, MELAPUR® MC50, MELAPUR® MC25 (Ciba), FR-6120 (ICL Industrial Products) | Cotton, polyester |
| Melamine polyphosphate | 15541-60-3;<br>218768-84-4 | MELAPUR® 200/70 (Ciba), Exolit AP 750 (Clariant GmbH) | Cotton, polyester |
| Organic phosphinates | 225789-38-8 | Exolit® OP 1312 M1; Exolit® OP 1311 and others in the series (Clariant GmbH) | |
| Aluminium hydroxide | 21645-51-2 | AB H-Series Alumina Trihydrate, Actilox, ALH-, ALOLT-, Aluminium hydrate, Aluminiumhydroxid, Apyral, BARIACE, BARIFINE, Bayerit, Geloxal, Hydrated alumina, hydroxid hlinitý, HYMOD® Surface-Treated Alumina Trihydrate | Can be used in combination with phosphorus based flame retardants, with lower loadings required<br>Cotton, polyester |

*(UNEP 2019b, RPA 2014, USEPA 2014, ECHA 2014, 2012, Danish EPA 2006)*

## 2. Use of alternative fibres / processes with similar properties:

*Alternative fibres*

Natural fibres are easier to chemically flame retard than synthetics. Several non-halogenated decaBDE chemical substitutes are available for natural cellulose or protein fibres such as cotton, wool, rayon (viscose, modal, and lyocell), and linen, including:

(a) Ammonium polyphosphates;

(b) Dimethylphosphono (N-methylol) propionamide;

(c) Phosphonic acids such as (3-{[hydroxymethyl]amino}-3-oxopropyl)-dimethyl ester;

(d) Tetrakis (hydroxymethyl) phosphonium urea ammonium salt.

Furthermore, some natural materials like leather and wool have inherently fire-resistant properties and, depending on the thickness of the weave, can meet fire safety requirements without additional chemical treatment (Klif 2011; Weber et al. 2018).

Nonwoven fabrics are also inherently fire-resistant, as are a number of synthetic fibres including aramids, viscose, novoloid, polyamides, melamine, and polyester. Some of these fire-resistant fibres, such as polyhaloalkenes, contain PVC, vinyl bromide, and other halogens, while others, such as polyaramides and melamine, are halogen-free (LCSP 2005; UNEP 2015).

Some fabrics for upholstery, mattresses, and drapery are made from blends of inherently fire-resistant fibres with fibres of lower flame performance. For instance, cotton is usually blended with polyester ('poly-cotton' blend), nylon, or melamine to reduce its flammability (DEFRA 2010).

*Fire barriers*

Fire-resistant barrier layers can be used between the surface fabric and the interior foam core in furniture and mattresses. They fully encapsulate the interior materials and must be combined with fire-resistant border seams, tape, and threads (LCSP 2005). Fire barriers are made from inherently fire-resistant fibres such as wool, para aramids, melamines, modacrylics, or glass fibre, without the need for flame retardant chemicals. Moreover, many of these fibres are made from non-halogen materials. Some barriers can also be made from blends of inexpensive fibres and expensive inherently fire-resistant fibres. In addition to fibre blends, many manufacturers use cotton-batting materials treated with boric acid. Plastic films have also been used as barriers, especially films made of inherently fire-resistant plastics such as neoprene (polychloroprene) (LCSP 2005).

*Intumescent systems*

In textiles, like in plastics, fire safety may also be achieved via the use of intumescent systems (Klif 2011; USEPA 2014). Intumescence is the formation of a foamed char, which acts as heat insulation. An intumescent system is generally a combination of a source of carbon to build up char, an acid-generating compound, and a decomposing compound that generates blowing gases to produce foamed char (Weil and Levchik 2009). This foam attains a thickness of 10 to 100 times that of the originally applied coating and insulates the substrate material through its low thermal conductivity. This makes intumescent systems efficient at reducing both flammability and exposure to toxic gases and fumes (KemI 2006). Intumescent systems include use of expandable graphite impregnated foams, surface treatments, and some barrier technologies (Klif 2011).

Intumescent systems typically consist of three components (KemI 2004, ECHA 2014):

- Acid source
- Carbon source
- Gas source.

The acid acts as a catalyst when the carbon source decomposes with the formation of gas, for example water vapour. The acid may also be a compound that forms acid in contact with heat. The carbon source consists of polyols (polyalcohols) that lose their hydrogen to form a "carbon foam" of suitable density and thickness to create good safety against continued spread of fire. The gas source is the third component. Gases are formed that are not combustible - for example hydrochloric acid, ammonia, water or carbon dioxide – depending on what the chemical system is like (KemI, 2004).

The composition of intumescent systems depends on each specific situation (KemI, 2004):

- Desired flame-retardant properties
- Polymer composition in application concerned
- Any presence of fillers and additives in the polymer systems concerned.

The most common intumescent systems for textiles are listed below (KemI 2004).

| **Component** | **Example substance** |
|---|---|
| Dehydrating substance:<br>Carbonising substance that releases acid for esterification of hydroxyl groups | Monoammonium phosphate<br>Diammonium phosphate<br>Ammonium polyphosphate<br>Melamine phosphate<br>Guanyl urea phosphate<br>Urea phosphate<br>Diammonium sulphate<br>Ammonium tetraborate |
| Carbonising substance:<br>Contains large quantities of carbon<br>Thermal decomposition results in carbon skeleton | Polyols<br>Erythritol<br>Pentaerythritol<br>Pentaerythritol dimer<br>Pentaerythritol trimer<br>Arabitol<br>Sorbitol<br>Inositol<br>Polyhydrophenols<br>Resorcinol<br>Sugars<br>Glucose<br>Maltose |
| Gas sources:<br>Produce non-combustible gases in connection with thermal decomposition | Dicyandiamide<br>Melamine<br>Guanidine<br>Glycin<br>Urea<br>Chloroparaffins |

KemI (2004) noted that intumescent systems require special handling in application, for example on a backcoating, so that they work as intended. As the three-component system is stable and in solid form, it is important to find the best conditions and combinations of the three different components in an evenly and well-distributed dispersion in the textile application to achieve the desired flame protection.

## 4.3. Polyurethane foam for building insulation

### 4.3.1. Process description

Polyurethane belongs to the thermoset plastic group and is a multifunction polymer material with wide-ranging applications. The main applications of polyurethanes are in rigid foams, flexible foams, coatings, and elastomers. Rigid polyurethane foam for building insulation is marketed both as factory-made insulation boards/blocks, as sandwich panels, and as spray insulation foamed directly at the building site. Sprayed polyurethane foam provides weatherproof sealants, forms a seamless layer of insulation, fills gaps and seams during application, and covers irregular, hard-to-insulate shapes (American Chemical Council 2018; UNEP 2019b).

The leading method for flame retarding rigid foam is to use additives, although reactive flame retardants are also in use (Weil and Levchik 2004; Shaw et al. 2014).

According to RPA 2014, DecaBDE seems not to be used as a FR for PU foam. TCPP (Tris(1-chloro-2-propyl) phosphate) and TDCPP (Tris(1,3-dichloro-2-propyl) phosphate) seem to be predominantly used as FRs in PU foams.

## 4.3.2. BAT and BEP (incl. availability of alternatives)

The measures described in section 4.1.2 are applicable to all types of polymers including PU foam.

### *Alternatives to the use of decaBDE as a flame retardant in PU foam for building insulation*

**1. Substitution of decaBDE by another flame retardant with similar properties:**

Table 4-5: Flame retardant chemicals reported to be used for PU foam.

| Name | CAS No. | Examples of trade name | Applications |
|---|---|---|---|
| **Halogen-containing FRs** | | | |
| Ethylene bis(tetrabromophthalimide) | 32588-76-4 | SAYTEX® BT-93 (Albemarle Corp.), BT-93 (Jiangsu Huading Refining Chemical Industry Co. Ltd., China) | Additive flame retardant, similar applications |
| Ethane-1,2-bis(pentabromophenyl) | 84852-53-9 | Ethane-1,2-bis(pentabromophenyl) (SAYTEX® 8010) (Albemarle Corp.), Decabromodiphenylethane, DBDE (Firemaster® 2100) (LANXESS) | Additive flame retardant, similar applications |
| Tris(1,3-dichloro-2-propyl) phosphate | 13674-87-8 | 1,3-dichloro-2-propanol phosphate (3:1), 2-propanol, 1,3-dichloro-, phosphate (3:1), Amgard TDCP, Antiblaze 195, Antiblaze TDCP, FR2, Fyrol FR-2 | Additive flame retardant, similar applications |
| **Non-halogen organo-phosphorous FRs** | | | |
| Cresyl diphenyl phosphate (CDP) | 26444-49-5 | Disflamoll® DPK (Lanxess) | Flame retarding characteristics in PF and EP resins, in TPU's, PC/ABS blends and PUR foams (rigid and flexible). |
| Substituted amine phosphate mixture (P/N intumescent systems) | 66034-17-1 | Diphosphoric acid, compd. with piperazine | - |
| **Other non-halogen FRs** | | | |
| Red phosphorous | 7723-14-0 | Exolit RP 690 and others in the RP series (Clariant GmbH) | Additive flame retardant, suited to materials with high oxygen content |
| Ammonium polyphosphate | 14728-39-9; 68333-79-9 | Exolit AP 750 (TP) and others in the AP series (Clariant GmbH) | Additive flame retardant, similar applications |
| Aluminium hydroxide | 21645-51-2 | AB H-Series Alumina Trihydrate, Actilox, ALH-, ALOLT-, Aluminium hydrate, Aluminiumhydroxid, Apyral, BARIACE, BARIFINE, Bayerit, Geloxal, Hydrated alumina, hydroxid hlinitý, HYMOD® Surface-Treated Alumina Trihydrate | ATH can be used in combination with phosphorus based flame retardants, with lower loadings required |
| Magnesium hydroxide | 1309-42-8 | MAGNIFIN® H-7 C (Albemarle Corp.) | Can be used for high temperature applications |

*(UNEP 2019b, RPA 2014, USEPA 2014, ECHA 2014, 2012, Danish EPA 2006)*

**2. Resin/Material substitution:**

A variety of insulation materials are used in buildings, each having some advantages for specific applications determining its use, and many with general application. In terms of market volumes, major insulation alternatives are expanded polystyrene (EPS) and extruded polystyrene (XPS), mineral wool, and fibre glass wool, but a number of other insulation materials are used to some extent (UNEP 2019b).

- Expanded and extruded polystyrene (EPS/XPS)

EPS/XPS are major insulation used in a variety of installations for the entire building envelope. EPS is a closed-cell insulation that’s manufactured by “expanding” a polystyrene polymer. XPS is a rigid insulation that’s also formed with polystyrene polymer but manufactured using an extrusion process.

- Stone wool

Stone wool is made from volcanic rock, typically basalt or dolomite, an increasing proportion of which is recycled material in the form of briquettes. Slag wool is made from blast furnace slag (waste). The stone wool is a subgroup of the mineral wool together with glass wool. Over the last decade, glass wool, rock (stone) wool and slag wool have together met just over half of the world demand for insulation. The structure and density of the product can be adapted to its precise final usage. Inorganic rock or slag is the main components (typically 98%) of stone wool. The remaining 2% organic content is generally a thermosetting resin binder (an adhesive), usually phenol formaldehyde and a little mineral oil.

- Glass wool (fibre glass insulation)

For glass wool, the raw materials are sand, limestone and soda ash, as well as recycled off cuts from the production process. The glass wool is a subgroup of the mineral wool. Small quantities of binding agents are added to the fibres. Glass wool products usually contain 95% to 96% inorganic material.

- Phenolic foams

Phenolic foam insulation is made by combining phenol-formaldehyde resin with a foaming agent. In the process phenol is polymerized by substituting formaldehyde on the phenol's aromatic ring via a condensation reaction and a rigid thermoset material is formed.

- Natural fibre-based insulation materials

Various modern insulation materials are based on natural fibres, primarily plant fibres but also sheep wool. Some of these have been known for centuries but have got a renaissance over the last decades with the growing interest for environment friendly building techniques. They are available as loose insulation fill, as insulation batts or/and as rolls. A number of the other natural fibre-based insulation materials have been considered as alternatives.

# 5. BAT and BEP measures for environmentally sound recycling of PBDE-containing articles (excluding decaBDE)

## 5.1. Plastic in EEE/WEEE

The management of PBDE-containing plastics needs to be assessed and addressed in the larger frame of BAT/BEP for the management and treatment of EEE and WEEE. BAT/BEP for the management of (selected) WEEE is established e.g. in the framework of the Basel Convention. The first international guidance in this respect has been established for information and communications technology (ICT) equipment under the Partnership for Action on Computing Equipment PACE (UNEP/CHW.13/INF/31/Rev.1).

The following guidance documents should be consulted:

- *Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling from E-waste to Resources* (UNEP and StEP 2009).
- *Technical Review of the Implications of Recycling Commercial Penta and Octabromodiphenyl Ethers and Annexes* (UNEP 2010a, b).
- *Guidance document on Environmentally Sound Material Recovery/Recycling of End-of-Life Computing Equipment* (UNEP 2017c).
- *Technical guidelines on transboundary movements of electronic and electrical waste and used electrical and electronic equipment, in particular regarding the distinction between waste and non-waste under the Basel Convention* (UNEP 2019f).

In the EU, minimum treatment requirements for WEEE are laid down in Directive 2012/19/EU (WEEE Directive). These requirements include the obligation to remove plastic containing brominated flame retardants from separately collected WEEE (Annex VII). In order to assist relevant operators in fulfilling the requirements of the WEEE Directive the European Committee for electrotechnical standardization (CENELEC) has developed – mandated by the European Commission - a series of European standards for the treatment of WEEE (EN 50625 series “Collection, logistics & Treatment requirements for WEEE”). Especially the following documents contain guidance on how to deal with plastics containing brominated flame retardants:

- *EN 50625-1: 2014 - Collection, logistics & treatment requirements for WEEE - Part 1: General treatment requirements*
- *TS 50625-3-1: 2015 - Collection, logistics & treatment requirements for WEEE – Part 3-1: Specification for de-pollution – General*

On a national level, there are also examples of legal requirements and guidance linked to the removal of plastics containing brominated flame retardants from WEEE, e.g. in Germany, Austria.

### 5.1.1. Reuse of EEE

According to the waste management hierarchy, repair and reuse of used EEE is the preferred option before end-of-life management (see Figure 2-1). Reuse and refurbishing of EEE extends the life span of products, hence saving energy for the manufacturing of new equipment and lowering the environmental impacts of mining for raw materials. Most uses of c-octaBDE in EEE were phased out before 2000, therefore the impact on the reuse sector for many EEE items is likely limited. However, there is a high relevance of decaBDE used for EEE products (and in waste and recyclate) due to long lifetimes.

### 5.1.2. Material recycling considerations

Recycling of PBDE-containing waste leads to a cycling of PBDEs if they are not separated from the waste. The recommendations of the POPs Review Committee (POPRC), which were adopted by COP-5 (decision SC-5/5), emphasise the importance of separating PBDEs-containing materials. POPRC recommended to eliminate PBDEs from the recycling streams as soon as possible (POPRC-6/2). To meet this recommendation articles or fractions containing PBDEs should be removed from the waste stream before the end of the recycling process and be subsequently treated in ESM.

From an economic perspective, the combination of separation technologies can lead to an economic process for producing PBDE-free plastic fraction from WEEE which can be recycled (Table 5-1).

#### *Types and composition of PBDE-containing plastics*

The four main reasons for the limited recycling of mixed plastics from WEEE are (UNEP 2010b):

- Industry using secondary plastic materials has tight specifications in relation to plastic quality, both chemical requirements (for example compliance to RoHS Directive 2011/65/EU and respectively the EU-POP Regulation No. 2019/2021), and mechanical material properties have to be taken into consideration.
- WEEE plastic fractions often contain 15 or more different plastic types and a degree of cross-contamination is inevitable in practice (see Figure 4-2; Dimitrakakis et al. 2009). While three polymers (ABS, PS, PP[8]) account for between 50% and 85% of the total, the efficient sorting of the mixtures presents difficult technical challenges.
- WEEE plastics could contain PBDEs.
- Some of the currently available technologies to separate PBDE-containing plastics from PBDE free plastics - as XRF determining the total bromine content or density separation – might also sort out plastics containing non-POP brominated flame retardants and plastics of a particular specific weight even if not containing PBDEs.
- Many major manufacturers require production of large volumes with identical properties and performance and this is difficult from heterogeneous plastic from WEEE.
- Comparable low costs for alternative waste management routes (incineration, landfilling)

In the EU, the WEEE Directive (Directive 2012/19/EU) specifies minimum recycling targets for WEEE (with recycling and reuse targets of 55 to 80% (depending on the WEEE category) from 2018 onwards). The latter targets make increased recycling of WEEE plastics inevitable.

In general, whereas plastics from large household appliances and from cooling and freezing appliances are considered containing POP-BFR concentrations below the limits for obligatory separation (as specified e.g. in the European standard EN-50625 series on the collection, logistics & treatment requirements for WEEE[9]), plastics from small equipment (household and IT equipment) and screens are relevant in the context of PBDE content and separation.

This final polymer rich fraction from WEEE can have an average composition as shown in Figure 5-1 and 5-2 below.

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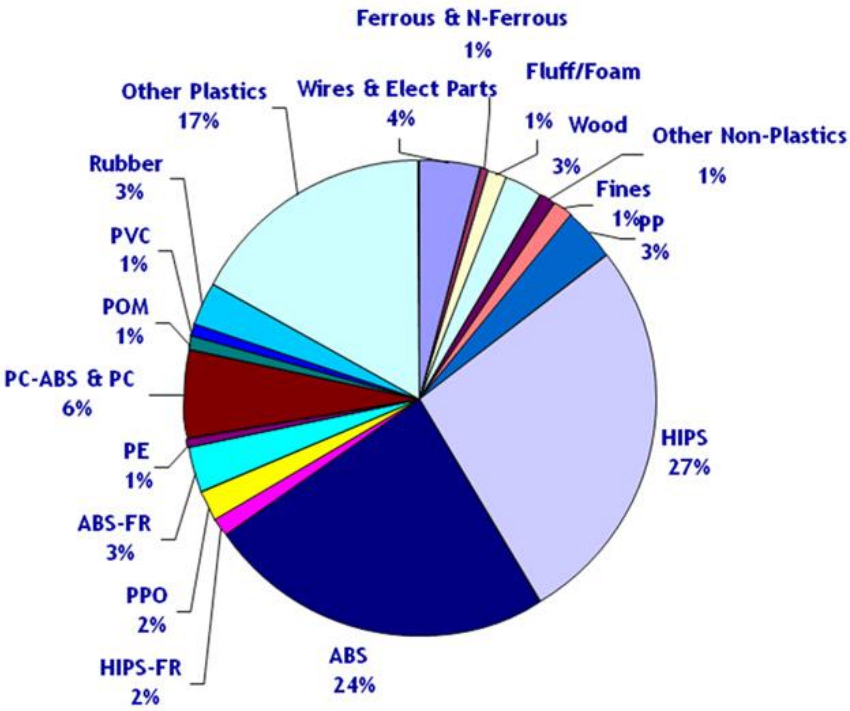
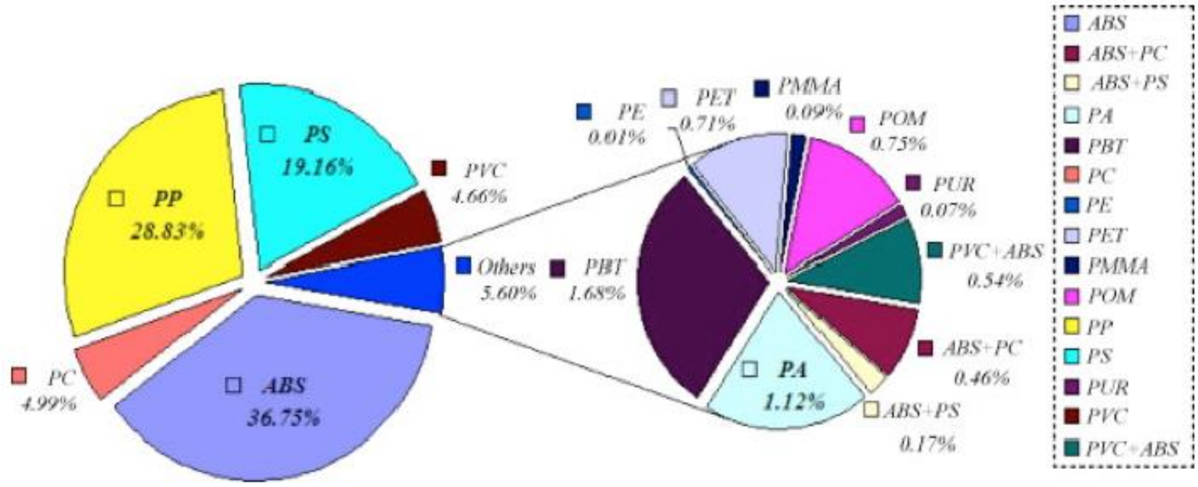
[8] Normally no/low POP-PBDE or PBB.

[9] https://ec.europa.eu/environment/waste/weee/standards_en.htm



(Slijkhuis/MBA polymers 2011)

**Figure 5-1:** Composition of the polymer rich mixture after metal recovery from e-Waste shredding



(Dimitrakakis et al. 2009)

**Figure 5-2:** Polymer types identified in small WEEE polymer samples (%, w/w).

Some of the plastics used in WEEE equipment are high-value engineered thermopolymers that can be repeatedly remelted by heat and hardened by cooling. If these thermoplastics can be recovered in a usable condition they can be sold for a profit.

TV sets (CRT and flat screen items) and computer monitors provide two of the richest sources of plastics: the plastic content in these two product groups varies between 10 wt % and 40 wt %. The major plastic part of a monitor is the rear part of the housing; this is separated for recovery and to gain access to the cathode ray tube. These plastic parts are normally removed by hand in the facilities and this gives a clean polymer fraction consisting mainly of ABS and HIPS, which then have to be disposed of safely to destroy BFR (e.g. in case of BFR containing housings from CRT appliances) or can be recycled (only in case they are BFR free). To maximize resale value, polymers must then be sorted by polymer type (e.g.

HIPS, ABS thermoplastic), and by colour. In addition, the blend PC/ABS is a valuable target material in such waste streams.

A large-scale study to determine the levels of PBBs and PBDEs in visual display units concluded that about 15% of plastic waste from TV casings and about 47% plastic waste from PC-CRT casings show significantly higher levels of PBDEs than 0.1% (Aldrian et al. 2014). In a similar screening study in Nigeria 32.9% of the sampled TV CRT and 66.1% of computer CRT casings contained bromine at a concentration above 1% considered to be flame retarded with BFRs with average plastic also exceeding 0.1% PBDEs (Sindiku et al. 2014). An Australian study (Bentley et al. 2013) shows a non-destructive testing strategy to rapidly identify imported consumer products by using hand-held XRF device followed by a swipe test. The authors concluded that the procedure can be used to identify key BFR and specifically to estimate c-octaBDE content in consumer products.

After the plastic has been cleaned and sorted into a specific type, it will need to be compacted for storage and transportation (see Annex 1), or further processing (see below). This can be done by hand tools such as scissors, shears, etc., or, better, by baling, shredding and size grading. Some mechanized operations combine heating, rapid cooling and cutting into grain. These smaller pieces are then typically heated and extruded through a die to form strings and pellets for final sale as raw materials. This polymer fraction is normally traded at prices that only allow a limited number of treatment steps, especially when the cost of incineration of residual PBDE-containing plastics has to be covered. Therefore, the disposal of residual contaminated plastics needs to be covered by the revenue from WEEE recycling (e.g. copper, steel, noble metals), by waste management fees or by legal implementation of the extended producer responsibility (e.g. European WEEE or Chinese WEEE regulations).

While initial collection and handling of unbroken plastic parts and cases should not involve exposures of concern to hazardous substances, all subsequent processing involves higher exposure risks. Plastic particles, additives and brominated flame retardants may be released, causing exposures to workers (UNEP 2010a, b). Size reduction and granulation can also generate heat and, if not properly managed, open smoke and fire. After granulation, the plastic will be moulded under elevated pressure and temperature with risks of exposure to substances contained in the plastic and new substances such as halogenated dioxins and furans (Ota et al. 2009).

### 5.1.3. Technologies to separate PBDE-containing plastic

Separation technologies are designed to collect PBDE-free plastics out of WEEE plastics with the aim of recovering valuable and marketable products, the sale of which generates much of the process revenues. Thus, development and running and combining these technologies is driven mainly by economy of the overall process chain. That means that separation of PBDEs is only a part of the overall strategy to produce valuable products with a reasonably high yield and a quality accepted by producers of new products (see Table 5-1).

WEEE plastics may be transformed into valuable plastic for recycling by a chain of optimized processes sometimes performed by more than one company. The process is only economically feasible if the cumulative cost of processing is lower than the revenues for the recycled product (see Figure 4-3). Therefore, separation of PBDE-containing plastic needs to be effectively integrated with the main driving forces of a recycling plant: the technologies used for shredding of WEEE and separation of polymers for polymer material recycling and for metal recycling.

The following techniques could be used in combination at a plant recycling plastics from WEEE as BAT/BEP (see Table 5-1):

- Manual dismantling approaches or shredding technologies.
- Sorting technologies to separate possibly PBDE-containing bulk and shredded plastics (see Table 5-1).

- Combinations of technologies to optimize the separation process (see Table 5-2).
- Full-scale plants to separate WEEE and PBDE-containing plastics (see Table 5-3)

### *Manual dismantling approaches*

Recycling companies handling CRT monitor housings often manage these plastics separately based on their experience of the specific type of polymers and type of flame retardant, thus keeping these streams "cleaner".

In Europe, only a minor share of plastics from manual dismantling of WEEE is checked for the Br content (European Commission 2019).

In Sweden, Retegan et al. (2010) describe the current principal method used in the Swedish recycling industry for the separation of plastics from TVs and computer monitors containing PBDEs. The listed items are removed manually from the waste stream. Training and experience in manually sorting WEEE plastics and parts containing PBDEs is needed to effectively sort polymers and remove those components. Even experienced manual sorting operatives cannot, however, determine which types of flame retardants are incorporated in the polymers. Thus, it is recommended that manual sorting be supervised by spot-checks using XRF measurements for bromine screening.

The effectiveness of manual separation needs to be evaluated as the composition of PBDEs in the different WEEE categories is likely to be different in different countries or regions before a BEP recommendation can be given.

Pure manual separation without instrumental help/Br screening has to be developed base on statistical analysis of the results, considering the complexity of the different electronics (different types, different producers and different series from the same type and producer) and the uncertainty of producers that have used a certain PBDE type. Manual separation is challenging considering the complexity of the different electronics (different types, different producers and different series from the same type and producer) and the uncertainty of producers that have used a certain PBDE type. Manually disassembling and removing plastics that contain brominated flame retardants is especially suitable for a producer responsibility system in which only the products manufactured by a specific producer or producers are pre-treated. In that case, there is usually more detailed information on the composition of the original products available in the scrap processing chain which has been provided by the manufacturer. Separation based only on the workers' experience on the flame retardants contained by individual parts is vulnerable to errors, in which case plastic containing POPs may end up in material streams considered suitable for recycling. Therefore, separation must be complemented by measuring the bromine content of the plastics, such as XRF screening and post separation checks. Manual separation does carry the risk of the workers being exposed to brominated flame retardants, therefore, attention must be paid to the occupational safety and health of the workers (Finnish Ministry of Environment 2016).

Table 5-1: Possible separation technologies and methods.

| Possible processes | Separation principle | Capable to remove or eliminate BFR |
|---|---|---|
| **Manual XRF** | X-ray fluorescence | Yes |
| **Manual NIR/MIR** | Polymer separation based on IR spectra | Not those regulated by RoHS and Stockholm Convention |
| **Manual sorting** | Knowledge and polymer labelling | (Yes) |
| **Grinding and removal of foreign materials** | Magnetic and eddy current separation | No |
| **Airstream sorting** | Specific weight | No |
| **Sink and float** | Density | Yes |

| | | |
|---|---|---|
| **NIR sorting** | Polymer separation based on NIR spectra | Not those regulated by RoHS and Stockholm Convention |
| **Laser sorting** | Polymer separation based on laser spectroscopy | Not yet approved |
| **XRT** | X-ray transmission | Yes |
| **Compounding and melt filtration** | Sieving | No |
| **Upgrade** | Addition of additives | No |

### *Screening techniques to separate PBDE-containing bulk and shredded plastics*

A range of technologies can be applied for screening bromine in materials like plastics. XRF and sliding spark technologies are available and relatively simple and robust methods (UNEP 2017b). They appear appropriate for use in developing countries (UNEP 2010a,b, 2017b). Both methods are labour intensive.

Information on various screening techniques is provided below.

**Sliding spark spectroscopy**

The lowest detection limit for bromine with the sliding spark spectroscopy technology is 0.1%. For practical reasons the recyclers normally set the system at 1% bromine to screen out PBDE/BFR-containing plastics, which normally contain between 3% and 20% PBDEs/BFR (Seidel et al. 1993; Seidel 2010, 2012).

Sliding spark spectroscopy using handheld instruments is used in WEEE dismantling plants and other fields for screening halogens in plastic. It allows operators to distinguish between BFR-containing (halogen-containing) and almost BFR (halogen) free components. The scanning time is quick and takes only a few seconds. Also the instrument needs a direct contact to the material surface and coated materials need to be specifically addressed by scratching the coating.

With dual-function equipment including near-infrared (NIR), this method can also distinguish different polymer types. Instruments with this integrated function therefore have the potential for practical separation not only of PBDE/BFR and non-PBDE/BFR plastic but also for polymer types at e-waste dismantling and recycling facilities at the dismantling stage. As mentioned above, NIR has difficulties with recognizing black plastic.

The sliding spark technology for the detection of halogens (Seidel et al. 1993; IoSys 2010; Seidel 2012) costs around US$6,000. A German producer of sliding spark technology has confirmed that equipment has been supplied to China and South Africa (Seidel 2010), thus indicating it is already used in developing countries.[10] Such handheld sliding spark equipment is available with additional detectors (near infrared; NIR) for determination of the polymer type (at a cost of approximately US$33,000) and could be used for producing clean polymer fractions with associated higher market values. The manual determination of polymer type to produce clean polymer fractions could be an attractive option for recovery of high-quality polymer from developing countries and could be combined with the separation of PBDE/BFR containing plastic.

**Near Infrared (NIR) Spectroscopy**

NIR spectroscopy (700-2500 nm spectral range) is one of the most widely used identification method for automated plastic sorting. The infra-red irradiation is absorbed by overtone and combination vibrations that are characteristic of particular functional groups, such as O-H, N-H and CH. Different polymers can be readily identified provided that the objects do not contain additives such as carbon

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[10] The tasks for which the equipment is used in South Africa and China are not documented.

black, which cause excessive absorption of the radiation. Advantages of NIR compared to mid infrared spectroscopy include shorter response times, improved detection ability of the NIR photodetectors (germanium, indium arsenide or indium gallium arsenide) and the ability to use inexpensive quartz fibre optics with low attenuation. NIR can be used to identify the type of plastic and separate the plastic most likely to contain POPs (PUR, ABS and HIPS plastics) from the plastics that contain bromine (Krummenacher et al. 1998).

**FT-IR technology**

Fourier-Transform Infrared (FT-IR) spectroscopy identifies chemical bonds in a molecule by producing an infrared absorption spectrum. On the other hand, the FT-IR allows quantifying specific compounds using calibration spectra of known concentration. It might be useful for screening PBDE-containing materials. According to application note by supplier, the FT-IR technique makes this determination possible and molecular Bromine-contents of more than 5% can be non-destructively analyzed (Bruker 2009). The handheld FT-IR instrument recently developed has also the possibility of applicability as a detection and separation tool in the field of dismantling and sorting process of PBDE-containing product.

**Raman spectroscopy**

Raman spectroscopy equipment in combination with sorting to separate PBDE-containing polymers has been developed in Japan (Tsuchida et al. 2009; Kawazumi et al. 2011). The pilot equipment can sort 400 kg of plastic shredder/hour. Practical performance of the equipment need to be further verified before recommendations can be given.

**XRF technology**

WEEE may contain components that originate from previous recycling of PBDE-containing polymers. These may contain mixtures of different BFRs, including c-octaBDE, but exhibit bromine levels in the range of 100-1000 ppm (Bantelmann et al. 2010; Chen et al., 2009, 2010; Sindiku et al. 2011). XRF is sensitive enough to trace these materials, detecting the total bromine content.

XRF can be used for detection and separation of PBDE-containing plastic with a bromine detection limit of 10 to 100 ppm. In practice the use of XRF measurement technology can only be used for 1000 ppm of bromine as element, as the only validated test method using XRF is validated for 1000 ppm (EN 62321-3-1). The time requirement for a measurement when applying handheld items is only a few seconds. With a cost of approximately US$20,000 to US$50,000, its use in small size enterprises may be limited. Additional costs for software are of around US$ 3,000. Since the handheld XRF instrument needs a direct contact to the material surface, it is not applicable for use in automated sorting systems but is used in the dismantling stage. Coated materials need to be specifically addressed by scratching the coating.

XRF technology is applied for instance by Austrian dismantlers since the Austrian Waste Treatment Obligation Ordinance requires the monitoring of plastics from WEEE if plastic wastes are subject to material recycling (Aldrian et al. 2014). A limit value of 2000 mg bromine /kg d.s. is set in the Ordinance on the basis of TS 50625-3-1[11]. If less than 2000 ppm total bromine are determined, the material is considered to be below the POP-threshold levels (remark: no POP-limit value has been yet fixed for DecaBDE) (Figure 5-3).

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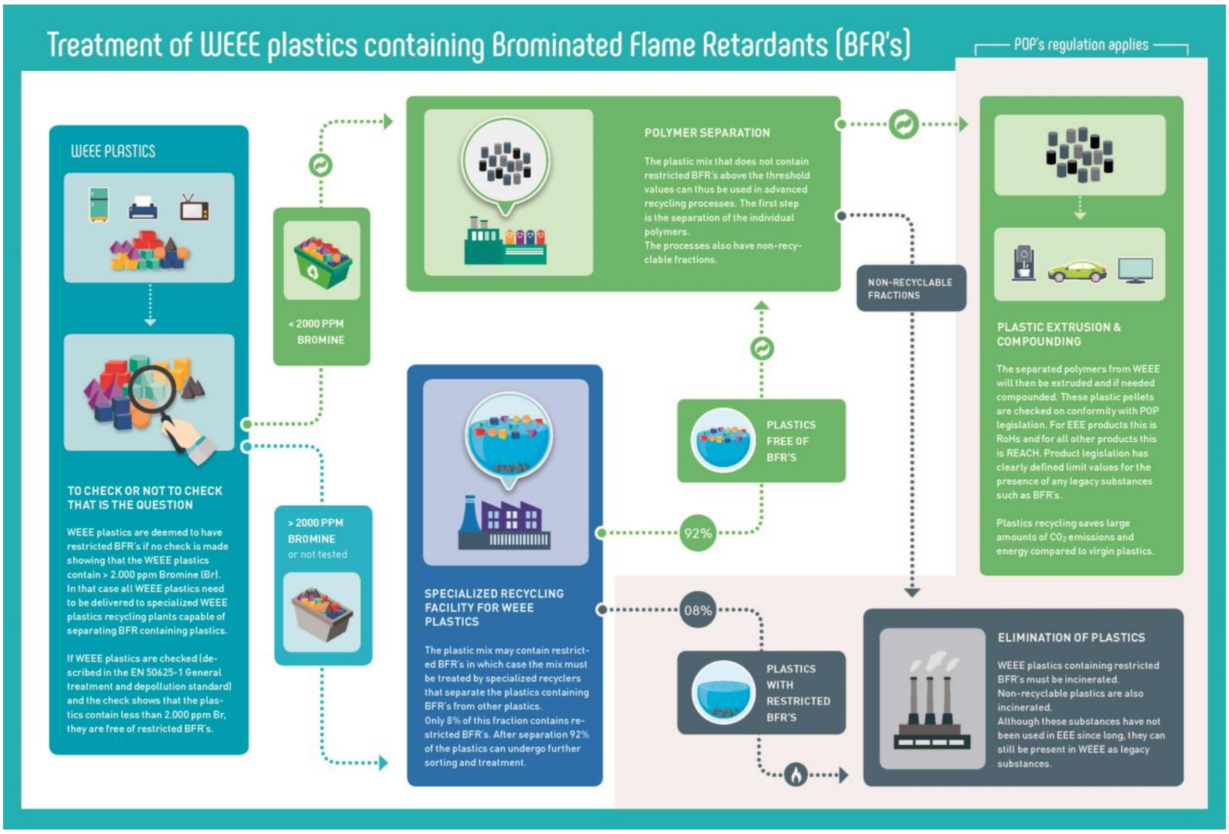
[11] TS 50625-3-1 requests the separation of plastics with a certain bromine content (2000 mg/kg) based on a proof that plastics for recycling are below this threshold. It applies to flat panel displays and CRT screens. According to https://www.weeelabex.org/operators-list/ (the list of operators certified according to these standard) there are currently about 25 operators in the EU with a certificate for treatment of CRT appliances.



**Treatment of WEEE plastics containing Brominated Flame Retardants (BFR's)**

**TO CHECK OR NOT TO CHECK THAT IS THE QUESTION**

WEEE plastics are deemed to have restricted BFR's if no check is made showing that the WEEE plastics contain > 2.000 ppm Bromine (Br). In that case all WEEE plastics need to be delivered to specialized WEEE plastics recycling plants capable of separating BFR containing plastics.

If WEEE plastics are checked (described in the EN 50625-1 General treatment and depollution standard) and the check shows that the plastics contain less than 2.000 ppm Br, they are free of restricted BFR's.

**POLYMER SEPARATION**

The plastic mix that does not contain restricted BFR's above the threshold values can thus be used in advanced recycling processes. The first step is the separation of the individual polymers.
The processes also have non-recyclable fractions.

**SPECIALIZED RECYCLING FACILITY FOR WEEE PLASTICS**

The plastic mix may contain restricted BFR's in which case the mix must be treated by specialized recyclers that separate the plastics containing BFR's from other plastics.
Only 8% of this fraction contains restricted BFR's. After separation 92% of the plastics can undergo further sorting and treatment.

**PLASTIC EXTRUSION & COMPOUNDING**

The separated polymers from WEEE will then be extruded and if needed compounded. These plastic pellets are checked on conformity with POP legislation. For EEE products this is RoHs and for all other products this is REACH. Product legislation has clearly defined limit values for the presence of any legacy substances such as BFR's.

Plastics recycling saves large amounts of $CO_2$ emissions and energy compared to virgin plastics.

**ELIMINATION OF PLASTICS**

WEEE plastics containing restricted BFR's must be incinerated.
Non-recyclable plastics are also incinerated.
Although these substances have not been used in EEE since long, they can still be present in WEEE as legacy substances.

**Figure 5-3:** WEEE Plastic Recycling and separation of BFRs in the EU (https://www.eera-recyclers.com)

According to the Austrian study, handheld XRF was proven as an effective tool and allowed fast monitoring of large volumes of waste plastics limited time. Handheld XRF are quite expensive, but the maintenance costs are manageable. The use of stationary XRF requires some measures of reconstruction in order to comply with radiation protection requirements and is therefore much more expensive. However, the use of handheld XRF items requires knowledge on X-rays and specific protection shields in order to avoid human exposure due to back reflection of X-rays.

### XRT technology

The X-ray transmission (XRT) has been developed to separate materials with different optical densities. XRT is in contrast to the handheld screening instrument (XRF) normally applied in dismantling plants to sort scrap automatically. Industrial machines sort up to 1 tonne of scrap per hour. The technology is used to separate PBDE/BFR-containing plastics from BFR free types in Switzerland. It may, therefore, play a role in WEEE plastic recycling plants particularly if combined with NIR.

One of the companies claims its system is able to clean and separate alumina fractions, CRT glass fractions (Pb vs non-Pb), and RDF fractions from metals, glass and PVC, and to remove halogen-containing materials (Schlummer 2011). Limited information, however, exists on the separation success with mixed WEEE plastic scrap, the waste fraction containing the majority of WEEE plastics.

XRT is not a stand-alone technique as the produced bromine-reduced fractions require further treatment with respect to producing marketable recycled polymer. Sorting machines based on X-ray transmission are available at an industrial scale (for example one of the existing systems costs approximately €400,000).

### Sink and float technologies

Polymer types exhibit different specific weights, and therefore liquid media with appropriate densities allow for separation of different thermoplastics into density groups. The salinity, and hence the density, of the liquid media can be changed by adding different salts. If water is being used, for example, the density can be raised 15% by the addition of magnesium sulphate. BFR additives increase the density of the ABS and HIPS materials significantly, when added at typical concentrations (> 3%). If treated in an appropriate liquid medium, bromine-free polystyrene will float while bromine-containing polystyrene will sink, thus separating the polymers containing bromine from other polymers (Schlummer and Maeurer 2006).

A simple two-stage separation has been described in a German collaborative project (SpectroDense; InnoNet 2009). At first the mixture is treated in a liquid with a density of around 1,100 kg/m$^3$. The float fraction will mainly consist of PP, PE and BFR free PS, and ABS; whereas BFR- containing styrenics, but also PPO/PS and PC/ABS (both flame retarded with phosphate based FR) and highly filled PP items will sink. The float fraction is further treated with water (density 1,000 kg/m$^3$) to separate HIPS and ABS from PP and PE.[12] Valuable polymers as PC/ABS and PPO/PS (normally free of PBDEs) could be separated from the heavy fraction by downstream NIR techniques, as these materials are grey in many cases.

For selected input fractions, the sink and float technology produces very clean and qualitatively good products in respect to separation of BFR-containing materials. TV housings are mainly HIPS. Since about 30%[13] of the casings in Europe contain BFR, sink and float (S/F) is a good way to separate them, and the high yields of BFR free materials suggest the process is economic (Schlummer 2011). In Africa this share seems higher (Sindiku et al. 2009).

With respect to BFRs, and especially PBDEs, S/F has been reported to effectively separate BFR-containing materials from non-BFR types of ABS and/or HIPS (Schlummer and Maeurer 2006). S/F has been reported used in separation of BFR rich fractions of TV/PC from low BFR fraction intended for recycling purposes in Sweden (Retegan et al. 2010). One challenge of the S/F technology is that the fractions of HIPS/PPO (1,150 kg/m$^3$) and PC/ABS (1,180 kg/m$^3$) are present containing phosphorus flame retardants and must be considered in the overall separation strategy (see below).

With respect to plastics from small electronic equipment and mixed WEEE, S/F can produce almost bromine-free plastic fractions, consisting largely of ABS, PS (incl. HIPS) and polyolefins. Despite a large share of black plastics in these low-bromine fractions, which inhibit a downstream NIR separation, it is possible to produce polymers with reasonable qualities a good market price as useful output. Therefore, ABS and PS with densities between 1 and 1.1 are separated by electrostatic, polyolefines are recovered in a density fraction below 1.0 kg/L. The yield of these techniques only allows economic recovery of polymers, if the yield of ABS, PS and PP is higher than 60-65%, depending on variability of market prices. This is especially true for waste plastic from small domestic appliances (SDA) and information and communication technologies (ICT). Thus, S/F has become a well-accepted treatment approach in North, Mid and South Europe (e.g. Stena (Sweden), Coolrec (The Netherlands), Bage plastics (Germany) and Galea (Spain) (Table 5-2). For the EU it has to be taken in mind, that the recycling targets for WEEE set in the WEEE Directive (Directive 2012/19/EU), require recycling of plastic fractions, otherwise the targets cannot be achieved. Thus, due to obligatory EPR for WEEE in the EU, the costs for end-of-life management have to be borne by the producers and are not a justification for not recycling plastics from small WEEE.

### *Combinations of technologies for producing marketable products*

None of the individual techniques described above has the ability to separate mixed plastic from WEEE: to ensure that the plastic is separated into marketable polymer fractions and that, at the same time,

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[12] These two binary mixtures could further be separated by NIR or electrostatic separation.

[13] The content of BFR will depend on the region and the legislation for flammability standards - in the United States/Canada most of the casings contain flame retardants.

PBDE/BFR-containing plastics are separated. Therefore, combinations of the techniques need to be used in practice.

In addition, no technique achieves a 100% separation, leading to residual PBDE levels in the intended bromine-free fraction. In the case of handheld sorting this is due to errors by the operatives. For automated systems, the sorting efficiency with blowing bars has its limits and the purity of sorted fractions is normally below 95%.

This section describes process chains, which include steps suitable (in principle) for the separation of PBDEs/BFRs followed by technologies focusing on polymer separation and upgrade of fractions. The process combinations are based only on technical considerations and do not take into account the economic feasibility, which may vary significantly in different countries. Local costs and revenues therefore need to be calculated for the different combinations of technologies.

**Dismantling, NIR, and sink and float (followed by electrostatic separation for dark density fraction separation)**

In the dismantling process of various appliances, large plastic fragments such as housings, which are in most cases built by PS, ABS or blends of these polymers with polycarbonate (PC/ABS) or polyphenylene oxide (PPO/PS) are generated.

After a coarse crashing process, the material waste plastics can be separated into the following polymer fractions by online NIR: light PS, light ABS, light PC/ABS, light PP, light PPO/PS and dark materials that cannot be identified with NIR.

The light PS and light ABS, as well as the dark fraction, are most likely containing higher amounts of BFR, which can be separated by the sink and float technology when performing two separation runs in density media of 1,000 and around 1,100 kg/m$^3$. The sink and float technology is based on the fact that BFR rich ABS and PS exhibit significantly higher densities compared to non-BFR ABS and PS.

As the dark density fraction 1,000-1,100 kg/m$^3$ is intended to contain both ABS and PS, a subsequent separation of both materials is preferred and can be performed by electrostatic separation. The latter technique is available on an industrial scale and works best for binary and well dried plastic mixtures. In this process, the plastic mixture is fed via a vibrating conveyor into a so-called tribo-electric charging unit. Different plastics are charged here selectively and specifically according to the material, taking on a positive or negative charge. After charging has taken place, the plastic mixture reaches a high tension field where the components are separated electrostatically into pure sorted fractions according to their charges: positive particles are attracted by a negative electrode, while negative particles are rejected and vice versa.

**Dismantling and sink and float (followed by electrostatic separation for dark density fraction separation)**

Dismantling sites usually recover CRT glass from TV sets. As TVs typically include large plastic housings predominately composed of PS and only rarely by ABS or PP, dismantling personnel can easily produce a polymer fraction from these items. Recent research has shown that it is possible to reduce the amount of non-BFR-ABS in this fraction to a minimum by appropriate training. This is important, since TVs contain dark plastics unsuitable for NIR sorting. After a grinding process, the PS rich fraction is separated in a BFR rich and almost BFR free fraction by S/F. As the dark density fraction 1,000-1,100 kg/m$^3$ contains both ABS and PS, a subsequent separation of both materials is preferred and can be performed by electrostatic separation. The latter technique is available on an industrial scale and works best for binary and well dried plastic mixtures (Andersson et al. 2019; Bage Plastics, Stena, Galea, Coolrec see Table 4-1 and 4-2). Care should be taken with respect of the accuracy of the marking/labelling of BFR-ABS and non BFR ABS.

**Dismantling and manual sorting**

The most elaborative approach is manual sorting, preferably assisted by handheld NIR and a handheld bromine identification tool (such as XRF). In addition to these tools, sorting personnel should check casing for materials stamps indicating the type of material. By using these techniques, trained personnel may be able to collect a high share of (almost) BFR free materials from plastic streams. Subsequently NIR technologies will enable production of fractions of defined polymer types for further processing. A disadvantage of this approach may be that large items like housing of printers, monitors and TVs with high levels of BFRs are side products requiring a sound waste treatment. In contrast, plastics parts from non-BFR or low BFR equipment are normally smaller and not often dismantled and treated by shredder techniques.

**Shredder, sink and float and electrostatic separation**

Shredded plastics from mixed WEEE (especially small WEEE appliances) have to pass removal steps for ferrous and non-ferrous metals and dust before they may be treated by a two-step sink and float process in density media of around 1,100 kg/m³ and 1,000 kg/m³. The fraction lighter than 1,000 kg/m³ is intended to be rich in PP and minor amounts of PE. The intermediate density fraction is considered to contain BFR free ABS and PS as well filled PP types. These three fractions may be subsequently separated by electrostatic separation (Hamos 2012; Wersag 2012; see Table 5-1).

**Shredder, XRT and spectroscopy**

From mixed WEEE fraction, a plastic fraction is recovered in state of the art WEEE treatment plants by a set of smashing, grinding and mechanical separation processes. Since this fraction has a typical particle size below 20 mm, automated online rather than manual separation processes are required for further upgrading this fraction for polymer recovery.

Bromine and chlorine may be removed by online XRT technology producing a low-bromine fraction of mixed plastics composed of up to 16 polymer types. The main polymer types (PS, ABS, and PP) may be recovered subsequently by online NIR; however, this technique is limited to the fraction of light materials, which is unfortunately not the major fraction of WEEE plastics.

Fraunhofer IVV (Freising, Germany) and Unisensor (Karlsruhe, Germany) tested and optimized a new automated sorting technique based on laser spectroscopy. Results indicate that this technique is able to separate several polymer types out of a mixed input stream of shredded plastics automatically with high throughput rates (~1 tonne per hour). Laser spectroscopy (in contrast to NIR) can identify black and dark plastics and might therefore become a key technology to transform BFR free plastic shred from WEEE into marketable sorted polymer type fractions (Arends 2014).

### *Comparison of technologies to separate polymer streams*

Some practical combinations of technologies used for separation of polymers for different input materials are listed in Table 5-2. Also the possible product output, the status of development and the economy or available commercial systems are mentioned.

Table 5-2: Combinations of separation techniques, input materials, products, status of development and remarks on related economy.

| Combination | Suitable input | BFR free products | Status of development | Remarks | Reference |
|---|---|---|---|---|---|
| **Dismantling, NIR, sink and float (Electrostatic separation)** | Plastics from dismantled WEEE items | ABS, PS | Approved for use in commercial setting | Economy depends on the yield of BFR free products | Schlummer (2011) |
| **Dismantling, Sink and float** | TV casings | HIPS | Approved for use in | Approved | Schlummer (2011) |

| | | | | | |
|---|---|---|---|---|---|
| **(Electrostatic separation)** | | | commercial setting | | |
| **Dismantling, manual sorting** | Plastics from dismantled WEEE items | ABS, PS, PC-ABS | Approved for use in commercial setting | Not approved in industrial countries | |
| **Shredder, Sink and float (Electrostatic separation)** | Mixed WEEE (small appliances) | ABS, PS, PP | Approved for use in commercial setting | System run successfully at Bage plastics, Stena, Galea and Coolrec | NONTOX 2020; Bage Plastic GmbH; CloseWEEE (2017) Coolrec |
| **Shredder, XRT and spectroscopy** | Mixed WEEE | BFR and PVC “free” plastic mix | Approved for use in commercial setting | No information | Schlummer (2011) Unisensor (2012) |

### *Full-scale plants to separate WEEE and PBDE-containing plastics*

Table 5-3 lists some of the WEEE treatment plants in operation and their potential to separate PBDE-containing plastics.

Table 5-3: Full-scale WEEE/WEEE-plastic treatment plants and their potential to separate PBDE-containing plastics.

| WEEE input (country) | Separation techniques | Polymers Separated | Quality of separated polymers | PBDE/BFR Elimination<br>(RoHS compliant) | Development Stage* | Reference |
|---|---|---|---|---|---|---|
| **Mixed plastic from WEEE (Austria, China)** | Not disclosed | Low-BFR types of ABS, HIPS and PP | Good (Customer specified) | Yes<br>BFR rich fraction incinerated | Industrial scale | MBA Polymers (2012) and MGG Polymers (2018) |
| **Small EEE, White goods (Switzerland)** | Includes XRT | BFR and PVC free polymers | Good | Yes | Industrial scale | RUAG Technology (2012) |
| **WEEE plastics (UK)** | Undisclosed | Low-BFR types of ABS and HIPS | Good | Yes | Industrial scale | Morton (2007) |
| **WEEE plastics (Austria, Germany)** | Undisclosed (incl. S/F and Electrostatic) | Low-BFR types of PP, ABS, HIPS | Good | Yes | Industrial scale | Bage Plastics GmbH (2012, 2020) |
| **WEEE plastics (The Netherlands)** | Undisclosed (incl. S/F and Electrostatic) | Low-BFR types of PP, ABS, HIPS | Good | Yes | Industrial scale | CloseWEEE (2017) Coolrec |
| **WEEE plastics (Sweden)** | Undisclosed (incl. S/F and Electrostatic) | Low-BFR types of PP, ABS, HIPS | Good | Yes | Industrial scale | NONTOX (2020) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **WEEE plastics (Galea)** | Undisclosed (incl. S/F and Electrostatic) | Low-BFR types of PP, ABS, HIPS | Good | Yes | Industrial scale | NONTOX (2020) |
| **Mixed plastic from WEEE (Germany)** | Successive Grinding and XRT | BFR and PVC free polymers | Not yet approved | Yes | Industrial scale | ReToVal GmbH (2018) |

(UNEP 2010a, updated as of 2020)

### 5.1.4. Processing technologies using PBDE-containing plastic

The exemptions listed in Part IV and V of Annex A to the Convention allow the recycling of PBDE-containing materials if a country has registered for such exemption. The following BAT/BEP should be further considered for processing technologies of PBDE-containing plastic:

#### *Minimization of exposure / releases in the processing stage*

A range of processing technologies are used to convert plastic from recycling (and virgin polymers) into the required shape of the final product. The processing step itself is mainly a physical transformation step using different technologies (European Commission 2007) such as:

- extrusion (for pipes, profiles, sheets and cable insulation and granules)
- injection moulding (for products of different, often very complex shapes like machine parts, electrical plugs and medical equipment such as syringes; thermoplastics and thermosets)
- pultrusion for rods, tubes, etc.
- blown film for thermoplastics
- cast film for thermoplastics
- pressing (for resins)
- spinning (for fibres)

Environmental and health concerns of moulding or extruding recycled plastics are emissions of volatile/semi-volatile organic compounds including PBDEs. In some cases wastewaters with the potential for high loads of organic compounds, spent solvents and non-recyclable waste are generated. Wastewater should always be connected to a waste water treatment plant. Contaminated sludge should be incinerated.

During extrusion and moulding fumes are generated which contain volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) possibly including PBDEs and other POP-BFRs. The fume production is influenced by (UK Health and Safety Executive 2013):

- the material being processed, including recommended temperature ranges and residence/ dwell times;
- operating procedures, including purging;
- the reliability of temperature control; and
- machine/screw maintenance.

A major task is the reduction of VOC/SVOC (European Commission 2007). Dedicated documents to control the releases have also been developed from governments (e.g. UK Health and Safety Executive 2013) and industry (e.g. Du Pont 2013).

**Techniques to reduce VOC/SVOC emission in process design**

Techniques to reduce emissions can be considered during the process design and the plant design. Process design conditions (e.g. temperature, pressure, vapour pressure of materials/chemicals) can influence the levels of VOC and SVOC emissions.

Techniques to reduce VOC and SVOC emissions resulting from process design include (European Commission 2007):

- To optimise the reactor design and physical parameters to minimize (VOC) releases (homogeneous recycled plastic mixtures, optimum temperature, appropriate suction systems)
- Minimize the use of volatile compounds and use of materials with low vapour pressure
- To treat wastewater streams which contains VOCs by stripping, rectification or extraction in order to remove solvents which could contribute to VOC emissions in further treatment operations
- To carry out solid-liquid separation in a way to minimize VOC emission (e.g. using centrifuges, keeping the system closed)

**Techniques to reduce VOC/SVOC emission in plant design**

The selection of plant components and the way they are configured can greatly influence the extent of fugitive emissions. These should consider:

A) Limiting the number of potential emission points

Design piping layout appropriately by minimizing pipe length and reducing the number of connectors and valves. Also welded fittings and pipe can help to reduce emissions.

B) Maximize inherent process containment features

To enclose effluent drainage systems and tanks used for effluent storage/treatment

C) Collecting and treating emissions/fumes

D) Selecting appropriate material for equipment, selecting equipment that is appropriate for the process, and to select appropriate material to avoid corrosion by lining or coating equipment

E) Facilitating monitoring and maintenance activities by good access to critical components

F) Select high quality equipment (e.g. appropriate valves; fitting high-integrity gaskets for critical applications; pumps, compressors and agitators fitted with mechanical seals)

The treatment of emissions/fumes is described in dedicated documents available in internet (e.g. UK Health and Safety Executive 2013; Du Pont 2013). An effective way to control these emissions is to “capture” them at the point of release and remove them by exhaust ventilation before they are dispersed into the air of the workplace atmosphere. This “capture” technique is called local exhaust ventilation (LEV) (Du Pont 2013). The LEV system is made up of an exhaust fan, which pulls air and contaminants into the exhaust hood and through the ducting and an air cleaner to remove PBDEs and other contaminants, before exhausting air outdoors. The hood should be shaped to enclose the source as far as is practical yet still allow access to the equipment for normal operation (Du Pont 2013). The air velocity (speed) at the point where contaminants are released and captured “capture velocity” should usually be at least 0.5 meters per second (Du Pont 2013). A simple check of its effectiveness can be made by using a ventilation “smoke tube” to produce a stream of dense white chemical “smoke” at the location where contaminants are released. The smoke will follow the air flow and should be rapidly captured (within 1-2 seconds) by the exhaust air and swept into the hood (see illustration: Ventilation “Smoke Tube”) (Du Pont 2013). If smoke escapes the hood and moves into the surrounding air, then some adjustment of hood location and/or air velocity will be needed.

Activities where a LEV system is likely to be required are:

- recycling mixed grades of polymer at pelletiser units;
- bag making at sealing heads where film regularly sticks and overheats;
- blown film lines with internal bubble cooling where the fume-laden air needs to be ducted outside;
- burning out blocked dies and nozzles;
- older machines where process controls are less reliable.

It is important to obtain professional assistance in designing a LEV system to ensure that it will meet the expectations for performance, maintenance, noise level and compliance with local workplace and environmental regulations or permits (Du Pont 2013).

Economic considerations: While the reduction of emissions might need some monetary investment they also provide opportunities for saving raw materials. In countries with economic incentives for low emissions, the releases also have economic implications.

**Controls checklist**

The UK Health and Safety Executive has developed a factsheet which includes a control checklist to minimise the risk of fume being produced in plastics processing and related exposure.

Main points for the control checklist are (UK Health and Safety Executive 2013):

- Information on the material including safety data sheet (SDS) from the supplier/distributor for the particular formulation to select the correct processing temperature, information on degradation products and additives and their possible effects on fume production.
- Information on operation: That all virgin and regrind materials are clearly marked so that the wrong material/grade can’t be used. That the machine operators are trained and have all the relevant processing data (temperature, residence time, changes from previous formulation).
- Cleaning: That machines and barrels are kept clean.
- Ventilation: Ensure processes are well ventilated in all cases. Provide local exhaust ventilation (LEV) wherever material manufacturers recommend it and your own assessment confirms it is required.
- Maintaining control measures: Once control measures are in place they need to maintain using daily and monthly checks, so they continue to provide good control all the time. Regular inspection procedures should be taking place.
- Procedures: Set out clearly in writing the procedures to be adopted. This will help to ensure the actions are understood correctly and carried out exactly as intended.
    - Train operators to work according to the procedures, and make sure supervisors regularly check for compliance.
    - Provide emergency procedures when processing heat-sensitive materials (e.g. acetals and PVC).
    - Make sure any emergency procedures are clearly explained and practised by all who may need to use them. Emergency procedures and rehearsals should include evacuation of the area(s) likely to be affected.

### *Type of articles produced from such WEEE plastic fractions.*

In the past, PBDE-containing materials have been recycled into sensitive uses such as children toys and food contact materials (Chen et al. 2009, Ionas et al. 2014; Puype et al. 2015; Samsonek and Puype 2013).

Due to exposure risk to PBDE, PBDEs containing materials (Chen et al. 2009; Ionas et al. 2016; Liu et al. 2016, 2017) should not be used for sensitive uses such as:

- toys and other plastic goods with exposure risk to babies and children;
- food packaging; food containers and other food contact materials;
- silos, storage and piping for food and animal feed;
- kitchen equipment;
- refrigerator interior; freezer interior;[14]
- water tanks and water pipes, in particular tanks used for drinking water pipes;

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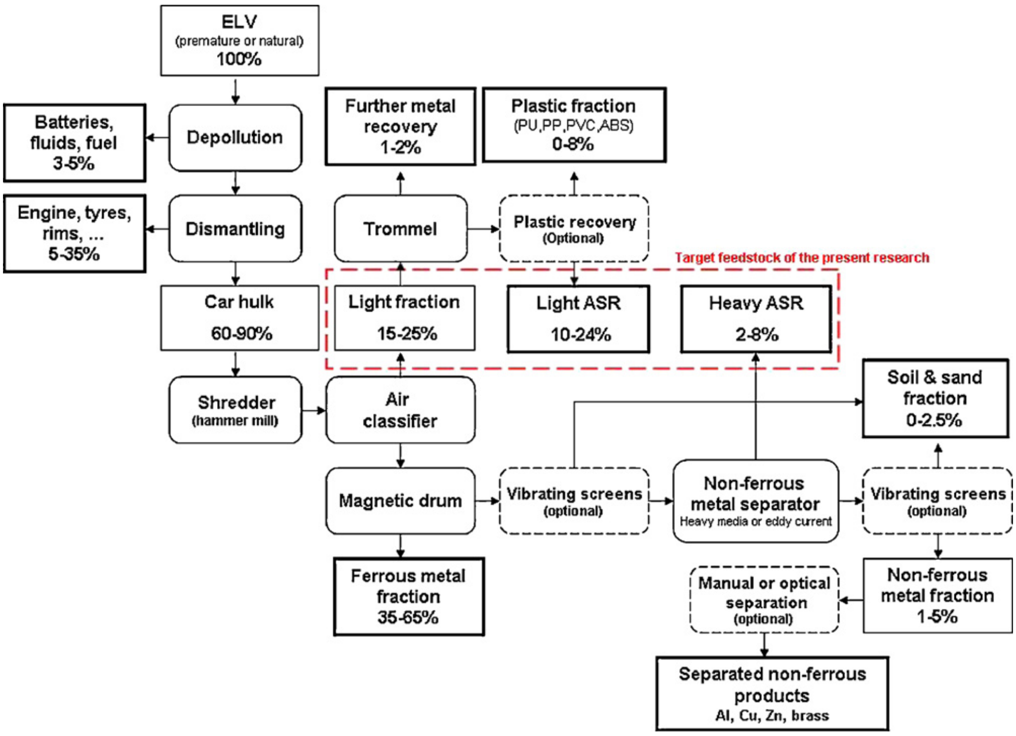
[14] The recycling of polymers from WEEE polymers containing no critical chemicals is encouraged following cradle-to-cradle principle e.g. polymers from refrigerators/fridges to refrigerators/fridges.

- plastic parts with direct contact such as furniture, handles of tools and doors;
- medical devices.

## 5.2. Vehicles in the transport sector

The transport sector can be considered as a large stock and reuse/recycling flow for PBDEs because of the relatively long lifetime of vehicles (in particular in developing countries) and high reuse and export rate. POP contaminants in end-of-life vehicles (ELVs) or their treatment fractions could also include polychlorinated biphenyls (PCBs)[15] and PCDD/PCDF (*Stockholm Convention BAT/BEP Guidelines* (UNEP 2007/2019); Vermeulen et al. 2011). Other hazardous substances found in ELVs are heavy metals, such as mercury (in switches) and lead (in lead acid batteries), which need to be separated before shredding, and as copper, cadmium, chromium VI, lead, nickel and zinc, which also need to be considered for proper assessment of final waste management of ASR. Due to these contaminants, some countries have classified ASR as hazardous waste and have established legislative controls.



(Vermeulen et al. 2011)

**Figure 5-4**: Schematic of the processing of an end-of-life vehicle

### 5.2.1. Reuse of vehicles

Repair and reuse of vehicles are the preferred options for vehicles prior to end-of-life management when considering the waste management hierarchy. The same is true for the preparation for reuse of used spare parts from end-of-life vehicles. Reuse saves energy from new manufacturing and avoids the environmental impact of the production of new raw materials, which is particularly important for such resource intensive material flows. It should be noted that while the use of c-pentaBDE and c-octaBDE in vehicles has ceased long time ago, there is a high relevance of decaBDE use (and subsequently in waste and recyclate) due to long lifetimes.

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[15] The data available indicate that polychlorinated biphenyls released from shredder plants are from industrial/intentional polychlorinated biphenyl production and have been introduced with the oils and dielectric fluids, etc., contained in the vehicles or more probably in consumer goods which are shredded in particular white goods (*Stockholm Convention BAT/BEP Guidelines;* UNEP 2007/2019).

### 5.2.2. Recycling of end-of-life vehicles

ELVs contain valuable materials (in particular metals) and therefore their recycling rate of ELVs has always been about 80-85% in industrial countries (Cossu and Lai 2015). The environmental impact of the non-recycled fraction of an ELV should nevertheless not be overlooked, as it often exhibits hazardous characteristics due to the presence of spent oils and lubricants, heavy metals, fluorinated ODS and fluorinated GHGs and POPs (Vermeulen et al. 2011; Babayemi et al. 2016). Many ELVs today also have air conditioners containing ozone-depleting substances (ODS) and/or greenhouse gases (GHG). Thus the dismantling and depollution step is of crucial importance for environmentally sound management of ELVs (see below). In parallel to the depollution of fluids and hazardous substances, the dismantling of used spare parts (for reuse) and recyclable materials takes place (e.g. catalytic converters, steel and aluminium parts, partially also vehicle glass, vehicle electronics and large plastic parts).

Many components of vehicles are made of non-ferrous materials, such as copper, aluminium and zinc. In the shredding process, magnetic separation is used to remove the magnetic ferrous fraction from other materials. The non-ferrous metals, such as copper and aluminium, are normally sorted out at a later stage by separation techniques such as density, induction, colour separation, etc. The remainder is called automotive shredder residue (ASR), which is estimated at between 15% and 30% of the weight of ELVs (UNEP 2007/2019; Vermeulen et al. 2011). ASR consists of glass, fibre, rubber, automobile liquids, plastic, PUR foam and dirt (Figure 5-6) and is normally further separated into the “light fraction” (containing PUR foam, most of the textile and plastic) and a “heavy fraction” (see Figure 4-5). Normally the materials containing PBDEs end up in the light ASR fraction when processing ELVs (see Figure 4-5).

The light shredder residues from ELVs are normally not recycled but subject to thermal destruction/energy recovery (see Chapter 6) or disposal in landfills (see UNEP 2019g) unless legal requirements require increased recycling of materials - in addition to the main metals.

Some countries have introduced legislation requiring recycling quotas for ELVs (and other materials) (Sakai e al. 2014), e.g. the Japanese Government introduced the Law on Recycling of ELVs (ELV Recycling Law) in 2002, which requires manufacturers to retrieve CFCs, airbags, and ASR from ELVs and to properly recycle the remaining materials. The EU had introduced the ELV Directive 2000/53/EC requiring in its current version reuse and recovery to a minimum of 95% and a reuse and recycling to minimum of 85% from 2015 onwards. More recently, some facilities recycle the polymer fractions as described below. Given these targets and the increasing plastic shares of vehicles increased recycling of contaminant-free plastics derived from ELV is inevitable.

#### *Dismantling and depollution of the vehicle*

ELVs must be pre-treated in a way that ensures that any harm or hazard to health or the environment from the operations is prevented. In pre-treatment, the parts suitable for reuse must be removed and stored appropriately. The parts and materials not suitable for reuse must be sent out for recycling or other recovery as far as possible. During pre-treatment, the hazardous parts and materials must be removed and sorted so that they do not contaminate the waste created when the ELVs are shredded.

If plastics from ELVs containing brominated flame retardants are not isolated from the shredded material, all fractions created during shredding that contain plastic must be treated as POP waste (Finnish Ministry of Environment 2016, Oeko-Institut 2018).

Before dismantling, the potentially hazardous and toxic parts need to be removed from the ELV. Fluids, like brake fluid, petrol, steering fluid, motor oil, coolants (ODS and GHG) and transmission fluid, should generally be removed from the ELVs or other devices before shredding. This is especially applicable in the case of PCBs, which should be identified and removed from any device to be shredded. Specific attention should be given to transformers and condensers. More detailed measures are described in the Stockholm Convention’s BAT/BEP guidelines for Annex C chemicals (UNEP 2007/2019).

Annex I(3) to the EU ELV Directive gives the following details for treatment operations for depollution of end-of-life vehicles:

- removal of batteries and liquefied gas tanks,
- removal or neutralisation of potential explosive components, (e.g. air bags),
- removal and separate collection and storage of fuel, motor oil, transmission oil, gearbox oil, hydraulic oil, cooling liquids, antifreeze, brake fluids, air-conditioning system fluids and any other fluid contained in the end-of-life vehicle, unless they are necessary for the re-use of the parts concerned,
- removal, as far as feasible, of all components identified as containing mercury.

This depollution step offers the option to remove PBDE-containing materials for further treatment. These materials could be separated using bromine screening technologies (see section 4.1.3), particularly if the non-impacted polymers are further considered for material recycling. It should be noted, however, that if no information for individual vehicles is available and no list of parts suspected to contain PBDEs is in force, the dismantlers have no means to target components for separation (Oeko-Institut 2018).

Exposure to pollutants (including PBDEs) should be minimised by appropriate procedures (e.g. with low dust generation) and the use of appropriate personal protection equipment.

Table 5-4: Parts that can be recycled from ELVs.

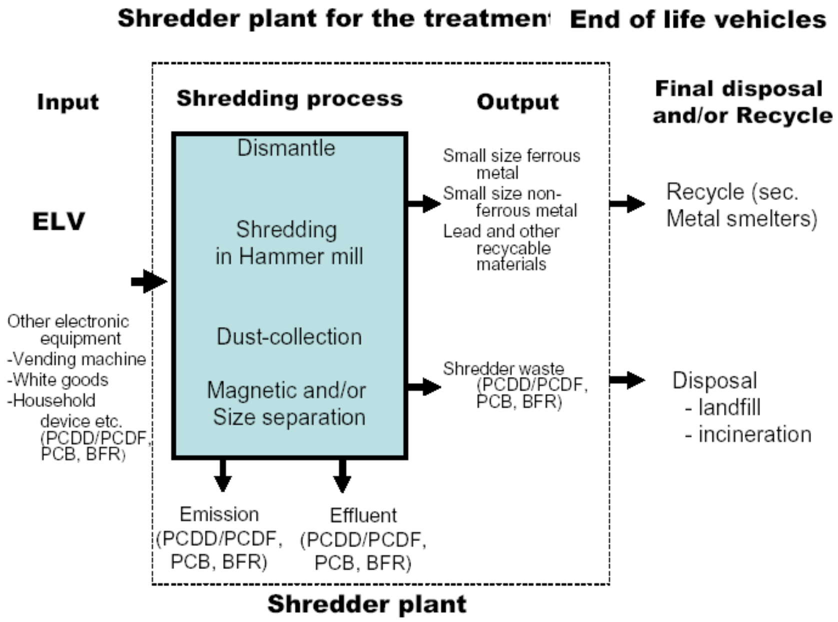
| Part | Material | Recycled as |
|---|---|---|
| **Window** | Glass | Tiles |
| **Body, trunk, hood and door** | Steel | Car parts and general steel products |
| **Wire harness** | Cu | Cu and engines products (cast Al reinforcement) |
| **Bumper** | Resin | Bumper, interior parts, toolbox, etc. |
| **Radiators** | Cu and Al | Gun metal ingots and Al products |
| **Coolant, engine and gear oil** | Oil | Alternative fuel for boilers and incinerators |
| **Engine transmission, suspension and wheel** | Steel and Al | General steel and Al products |
| **Catalytic converter** | Precious metals | Catalytic converters or precious metal (e.g. platinum) recycling |
| **Tire** | Rubber | Raw material and energy recovery (e.g. cement kilns) |

(Zameri and Saman 2006; Vermeulen et al. 2011)

A precondition for the treatment of PBDE-containing ELVs is the strict enforcement of best management practices for the operation of shredders. This precondition not only applies to address releases of PBDEs from the treatment of ELVs but also in order to avoid emissions of PCDD/PCDF during deflagration and fire caused by halogenated substances, e.g. from WEEE in input materials.

### *Shredder plants*

Shredder plants for the treatment of ELVs are listed in Annex C of the Stockholm Convention as a source that has the potential to form and release unintentionally produced POPs; they are therefore described in the Stockholm Convention BAT/BEP guidelines (UNEP 2007/2019, Part III Source category (k)). An overview of the process is shown in Figure 5-5.



(UNEP 2007/2019)

Figure 5-5: Overview of the shredder process

Furthermore, shredder plants are also described in the BREF and BAT conclusions for waste treatment (European Commission 2018). The BAT conclusions for the mechanical treatment in shredders of metal waste are the following:

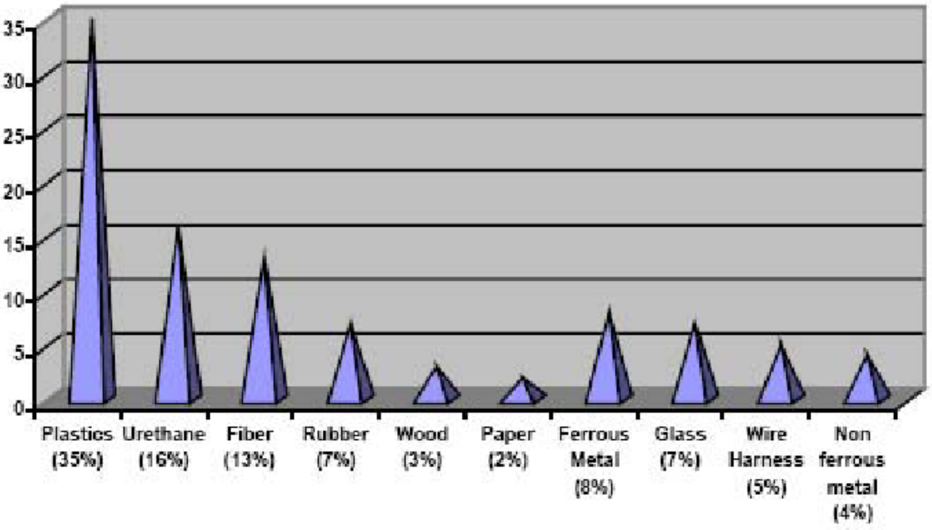
- According to BAT 8 brominated flame retardants, but also PCDD/F – when identified as relevant in the waste gas stream - have to be monitored at least once every year.
- The following reduction techniques for dust and particulate-bound metals, PCDD/F and dioxin-like PCBs are given (BAT 25):
    - Cyclone
    - Fabric filter (may not be applicable to exhaust air ducts directly connected to the shredder when the effects of deflagration on the fabric filter cannot be mitigated)
    - Wet scrubbing
    - Water injection into the shredder (only applicable within the constraints associated with local conditions (e.g. low temperatures, draught)
- The BAT associated emission value for PCDD/PCDF for dust is 2 – 5 mg/Nm$^3$ as average over the sampling period. If fabric filters are not applicable, the upper end of the range is 10 mg/Nm$^3$.

According to the BAT 26 (European Commission 2018) the following further measures apply to mechanical treatment in shredders of metal waste:

- Implementation of a detailed inspection procedure for baled waste before shredding
- Removal of dangerous items from the input stream and their safe disposal (e.g. gas cylinders, non-depolluted ELVs, non-depolluted WEEE, items contaminated with PCBs or mercury, radioactive items
- Treatment of containers only when accompanied by declaration of cleanliness

Since shredder plants can generate dust and other releases (including the above-mentioned pollutants) collective and technical measures such as suction and ventilation systems should be implemented to control the safety and health hazards. Also appropriate personal protective equipment should be used.

In organising the operation of shredding and cutting up facilities, special attention must be paid to managing POP emissions, especially emissions into the air and dust control. Dust control should be taken into account for both the shredding process itself as well as in the transport and storage of shredder residue. The shredding process and the shredder residue conveyor belts should be equipped with sufficient protective covers and dust collectors to prevent the dust from spreading (Finnish Ministry of Environment 2016). Oeko-Institut (2018) concluded that in the context of treatment of ELVs and WEEE in shredders and considering the PBDE content in such materials, it is crucial to be in line with most recent BAT. However, during other than normal operating conditions (e.g. deflagration), a very relevant amount of dust containing PBDE might be released. Therefore, it might be relevant to establish a maximum number of deflagrations in a given time.



(UNEP 2007/2019)

Figure 5-6: Composition of shredder waste

### *Post-shredding techniques*

A significant share of materials from ELVs can be recycled. The possible PBDE-containing materials (PUR foam and plastic/textiles from the interior) are normally not listed as materials being recycled (see Table 5-4). Due to the increased pressure on material recycling, however a higher share of the polymer fraction will need to be recycled in future.

The PUR foam (considered to contain the main PBDE fraction)[16] is approximately 5%, and up to 15%, of the ASR fraction (in average approximately 16 kg PUR foam/car); however, it makes up over 30% of its volume (Hoffman 2008).

Three options for separating and treating fractions that contain POPs on an industrial scale can be specified:

- Manually disassembling and removing plastics that contain brominated flame retardants from vehicles, and treating the separate fraction as POP waste;
- Separating plastics that contain brominated flame retardants from shredded material and treating the separate fraction as POP waste;
- Further treatment of the whole fraction created during shredding as POP waste without separating the plastic that contains brominated flame retardants.

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[16] In the United States, the main PUR-foam applications in transport (seat, arm/head rest) were treated with approximately 1% c-pentaBDE to meet MVSS 302 (Luedeka 2011).

The most appropriate treatment option should be selected, taking account of the functionality of the whole producer responsibility chain (Finnish Ministry of Environment 2016).

Shredding in combination with post-shredding technologies (PST) can produce different fractions of bromine and expected PBDE concentrations in different output fractions (Oeko-Institut 2018). The most common PST are:

- Classification (size separation);
- Metals separation: Magnetic separation of ferrous metals, Eddy current separation of nonferrous metals, All-metal separators (for negative sorting of e.g. plastics);
- Density separation: Air classification, Ballistic separation, Sink-float devices, Air tables; and
- Sensor-based sorting for separation of different metals and alloys.

Further technologies might be applied as well:

- Sensor-based sorting: NIR-Spectroscopy

NIR-S (near-infrared spectroscopy) can be used to identify the type of plastic and separate the plastic most likely to contain POPs (PUR, ABS and HIPS plastics) from the plastics that contain bromine; is suitable as a continuously operating measurement method on a separation line; is not yet well suited to identifying black plastic.

Regarding PBDE content of the different fractions from the treatment of ELVs in shredders and PST installations, the following should be noted (Oeko-Institut 2018):

- Shredder sand is apparently well below 1 000 mg/kg bromine with an average of 211 mg/kg.
- Fluff contains on average 729 mg/kg bromine but for a relevant number of samples the bromine content exceeds 1000 mg/kg. This fraction can be used in feedstock recycling processes. If low Br-concentration can be guaranteed (analysed) it also may be subject to material recycling.
- Bromine content of the light granulate fraction < 1.1 g/cm$^3$ is on average 202 mg/kg bromine; very few samples exceed 1000 mg/kg. Therefore, it may be used in material recycling processes. All analyses indicate concentrations of decaBDE well below 100 mg/kg.
- The granulate fractions with medium density (>1.1 and <1.3 g/cm$^3$) and high density (>1.3 g/cm$^3$) reveal higher concentrations of bromine (on average 2277 and 2749 mg/kg bromine respectively). A few analyses indicate that these PST outputs might exceed the decaBDE concentrations of 1 000 mf/kg and thus are not applicable in material recycling processes.
- The fraction with medium density (>1.1 and <1.3 g/cm$^3$) could be used in blast furnaces for feedstock recycling.
- The granulate fractions revealing a high density (>1.3 g/cm$^3$) contain normally high concentrations of PVC and are not accepted by blast furnace for feedstock recycling; they may be processed further on in chemical treatment processes to recover PVC or go to a waste incineration plant.
- The detected differences for the bromine content in different fractions explain some outliers in the literature, since such outliers refer to PST output fractions suspected to contain high concentrations.
- Detection technologies like XRF supporting sorting or hyper spectral imaging (HSI) are considered emerging techniques and offer promising opportunities to achieve high quality sorting results. Since the techniques are used for other purposes in the sector as well, R&D will continue and possibly generate windfall benefits for sorting hard plastic fractions from PST.

## 5.3. Polyurethane foam

Flexible polyurethane foam (FPF) is a manufactured article with a multitude of end uses (Luedeka 2011; UNEP 2010b). The main uses of FPF products are in:

- Residential and commercial upholstered furniture (coach, chairs)
- Residential and institutional mattresses and top-of-bed products including pillows and mattress pads
- Vehicles (cars, trucks, trains, ships, planes) as interiors for seating, upholstered trim and acoustic panels
- Military and defence applications to help prevent fuel-related flash fires in vehicles, vessels and aircraft

Minor use volumes are in:

- Protective packaging applications
- Healthcare for restraining, support, pressure-relief, fluid absorption and wound care applications
- Air and fluid filtration
- Laboratories and testing instruments as absorption medium
- Apparel padding and insulation
- Cushion underlayment for residential carpet installation, particularly in the United States

While FPF may appear to be a generic commodity product, it is, in fact, often a technical article with specific performance attributes created through proprietary formulations and fabrication processes. Many FPF manufacturers produce more than 150 different FPF products, each having unique characteristics appropriate for specific end uses (Luedeka 2011).

The FPF industry uses two basic production methods: slabstock (outside the United States, referred to as “block foam”) and moulding. Each method requires unique product formulations using a number of raw materials including, but not limited to, a polyol, diisocyanate, surfactant, catalyst, auxiliary blowing agent and numerous optional specialty additives including, in some instances, fire retardant products (Luedeka 2011). Formulations for slabstock and moulded products may require adjustment prior to or during production to respond to ambient production conditions including humidity, temperature and barometric pressure. Such formulation adjustments may include variations in concentration and/or changes in the selection of various raw materials including additives such as optional fire retardants (Luedeka 2011).

The use of PBDEs is particularly relevant for recycling considerations of PUR foam for regions possibly impacted by those markets because of vehicle or furniture export/imports.

### 5.3.1. Reuse of furniture and mattresses

The reuse of FPF-containing furniture (e.g. couch, (arm)chair), mattresses or textiles is the preferred end-of-life management when considering the waste management hierarchy, if they do not contain POPs. Reuse saves energy of new manufacturing and avoids the environmental impacts of production of new raw materials.

Markets with flammability standards for furniture at the time of production of c-pentaBDE (before 2005) are the United States and the United Kingdom. Mattresses for private consumers were not significantly treated with c-pentaBDE, which was mainly used for those from public/governmental institutions like prisons, military facilities or hospitals (Luedeka 2011).

For most other countries, no specific flammability standards have been established in the past for furniture. These countries/regions, therefore, are not, or only to a minor extent, impacted by c-pentaBDE in PUR foam applications depending on the import of such articles from countries with specific flammability standards (United States and United Kingdom). Thus the reuse sector for furniture and mattresses is likely not (significantly) impacted by PBDEs in most countries/regions. In the EU, according to the amended POP Regulation No. 2019/2021, the destruction of PBDEs in wastes with higher contents than 0.1% PBDEs is required, and therefore not allowing placing on the market of these items for re-use.

If an aged couch, pillow or vehicle, however, contains c-pentaBDE, human exposure to PBDEs could be relevant (Betts 2003; Imm et al. 2009; Stapleton et al. 2008; UNEP 2010b) and the reuse would not be recommended.

The assumption that most regions are not impacted by PBDEs in these use areas requires some confirmation before the unrestricted reuse of these articles can be considered as BEP. Parties discovering relevant c-pentaBDE in such articles in use or reuse might need to assess if further steps for the protection of human health are necessary.

### 5.3.2. Recycling/recovery of PUR foam

Recycling of articles containing PUR foam such as furniture, vehicles, mattresses, scrapped refrigerators and construction needs management considerations such as the geographic origin and the production years of the articles. The use of flame retardants and the type of flame retardants used highly depend on the region and country. It is assumed that more than 90% of c-pentaBDE in PUR foam, and also most hexabromobiphenyl (HxBB), has been produced/used in the United States and is largely either already deposited in landfills, in use or recycled in carpet rebond (UNEP 2010a,b). Therefore it can also be assumed that most other regions and countries (excluding United States/North America) have a low content of c-pentaBDE and HxBB in their current PUR foam.

In all facilities dealing with recycling or end-of-life of PUR foam, the general BAT/BEP considerations (Chapter 3; Annex 1) should be taken into account. Considering the finding of high c-pentaBDE blood levels in workers at a US PUR foam recycling facility (Stapleton et al. 2008), occupational safety measures, such as elimination of contaminated PUR foam before processing foams should be considered in facilities known to process c-pentaBDE-containing PUR foam. Furthermore collective protection measures (ventilation; closed shredding system possibly with explosion protection) and the use of appropriate personal protective equipment should be considered.

For flexible PUR foam categories known to partly contain PBDE impacted material, such material could be screened for bromine (see Chapter 5.1) to separate the PBDE-containing materials. Such separation can either be at the state of collection or in the facility recycling PUR foam.

While the separation of PBDE/BFR-containing polymers by separation of BFR-containing fractions has been developed to full scale for WEEE plastics (see Chapter 5.1), there is no information on such separation for other PBDE/BFR-containing materials including PUR foam. For larger polyurethane foam items like mattresses or furniture, the same screening methods used for WEEE plastics items could be applied with handheld XRF or sliding spark spectroscopy. A screening study, possibly supported by government, could reveal if such an approach was needed in a country.

In the EU, according to the amended POP Regulation No. 2019/2021, landfilling of these PUR-wastes will not be allowed any more if the wastes show higher contents than 0.1% PBDEs.

#### *Rebond: Recycling PUR foam with phase-out of c-pentaBDE*

Rebonding is the process whereby scrap PUR foam is shredded into small pieces and then reconstituted with a polyurethane prepolyol binder to produce an aggregated polyurethane foam product (USEPA 1996). The main use is in the production of carpet cushions (Eaves 2004). The vast majority of carpet cushion is used in English-speaking countries, specifically the United States, United Kingdom and Australia. Little carpet cushion is yet used in the rest of the world (Luedeka 2011). Other uses of rebond include school bus seats (USEPA 1996) and floor mats for gymnasia (Zia et al. 2007). Other recycling uses for foams that are not reused in the refurbishment of mattresses or for rebond include pet bedding, stuffed animals and insulation (UNEP 2010b).

Relevant exposure of PUR recycling and carpet installers to PBDEs has been demonstrated in a first study from the United States (Stapleton et al. 2008) and there are obvious risks of further exposure of consumers.

#### *Material recovery from mattresses*

Mainly mattresses in specific institutions (e.g. prison, hospital, military) are flame retarded, even in countries with specific flammability standards. Such specific sources could be monitored for bromine/PBDE for an overview of the presence of PBDEs/BFRs. If PBDEs are detected in these uses, they could be excluded from recycling or be screened (e.g. XRF) and separated.

### 5.4. Other materials possibly impacted by PBDEs

Some other uses of PBDEs applied in the past:

- Textiles (e.g. back-coated textiles in vehicles)
- Rubber (e.g. for conveyer belts)
- Coatings/lacquers

Although no specific BAT/BEP has been developed for these minor uses: the same basic approach as described for PUR foam could be considered:

- Country/region survey of the presence of PBDEs in these sectors
- Assessment of recycling activities of these materials
- Exclusion of specific impacted streams from recycling
- Screening and separation by bromine screening approaches in the recycling
- Recycling of PBDE free material flows
- Energy recovery of PBDE-containing material streams (see Chapter 6)

If the above listed options are not available in a country, the material might be stored (see Chapter 3; Annex 1) until appropriate treatment technologies are available or it is disposed of in sanitary landfills, which is the least preferred option (see UNEP 2019g).

# 6. Energy/material recovery from PBDE-containing material

This Chapter briefly summarizes BAT/BEP for energy/material recovery processes using PBDE-containing material. Further details are available in the Best Available Techniques Reference Documents (BREFs) developed for the respective industrial processes (https://eippcb.jrc.ec.europa.eu/reference/), in the Stockholm Convention BAT/BEP Guideline document with emphasis on reduction of unintentionally produced POPs (UNEP 2007/2019), and in the Basel Convention technical guidelines (UNEP 2019c,d). However, PBDE-containing materials are not specifically addressed in these documents. Therefore, if such materials are present in the process, Annex 2 to this document should be consulted. It provides relevant information regarding corrosion issues, formation and monitoring of PBDD/Fs and PXDD/Fs etc. as well as information regarding the suitability of industrial installations for treatment of PBDE-containing material.

## 6.1. Incinerators

BAT/BEP for waste incineration is specified in Section V for Source category A of the Stockholm Convention BAT/BEP guidelines (UNEP 2007/2019). The Basel Convention general technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with persistent organic pollutants (UNEP 2019d) provide the complete overview of technologies for the destruction and irreversible transformation of POPs in wastes.

Further details are also described in the EU Waste Incineration BREF (European Commission 2019) and the EU BAT conclusions on Waste Incineration (Commission Implementing Decision of 12.11.2019). The Commission Implementing Decision of 12.11.2019 describes the best available techniques for waste incineration and includes BAT associated emission values. Competent authorities shall set emission limit values that ensure, that under normal operating conditions, emissions do not exceed the BAT-AEL in the BAT conclusions (Art 15(3) IED Industrial emission directive (2010/75/EU). Guidance relevant to the recovery processes in incinerators is available in:

- Basel Convention general technical guidelines [http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx]
- Stockholm Convention BAT/BEP guidelines: V.A Waste incinerators [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]
- EU WI BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118637_WI_Bref_2019_published_0.pdf]

## 6.2. Cement kilns

Cement kilns are increasingly used in waste management schemes in both industrial and developing countries (Holcim and GTZ 2006; Reijnders 2007). Major PBDE-containing materials like WEEE plastic, ASR and potentially other PBDE/BFR-containing materials are also partly treated. BAT/BEP considerations for cement kilns are described in Section V for Source category 2B of the Stockholm Convention BAT/BEP guidelines (UNEP 2007/2019). Further details are described in the EU BAT Reference document “Production of Cement, Lime and Magnesium Oxide” (European Commission 2013a) and the Basel Convention Technical guidelines on the environmentally sound co-processing of hazardous wastes in cement kilns (UNEP 2011b). Annex 2 to this document provides more specific information on the proper management and monitoring of PBDE wastes in cement kilns.

General BAT BEP guidance relevant to recovery processes in cement kilns is available in:

- Basel Convention technical guidelines on the environmentally sound co-processing of hazardous wastes in cement kilns [http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx]

- Stockholm Convention BAT/BEP guidelines: V.B Cement kilns firing hazardous waste [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]

- EU CLM BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf]

## 6.3. Metal industries

### *Copper smelters and integrated smelters-refineries*

Category 2D "Thermal processes in the metallurgical industry" in Section V of the Stockholm Convention BAT/BEP Guidelines (UNEP 2007/2019) describes some key BAT/BEP issues for secondary copper production). In particular, BAT/BEP of reducing unintentionally produced POPs emissions in that document would be considered. BAT/BEP details on the technologies are described in the EU BREF document on non-ferrous metal industries (European Commission, 2017). BAT conclusion for non-ferrous metals have been published in 2016 in the Journal of the European Union and are the reference for permitting conditions in the EU.

General BAT/BEP considerations and guidance on unintentional POPs release from copper smelters include:

- Stockholm Convention BAT/BEP guidelines: V.D Thermal processes in the metallurgical industry [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]

- EU NFM BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC107041_NFM_bref2017.pdf]

### *Electric arc furnaces*

Some key BAT/BEP measures to be considered for reduction of unintentional POP release from electric arc furnaces (EAFs) are described in Section VI Part III Source category (b) "Thermal processes in the metallurgical industry not mentioned in Annex C, Part II" of the Stockholm Convention BAT/BEP guidelines (UNEP 2007/2019). Details on the BAT technologies used are described in the EU BREF for the Iron and Steel Industry (European Commission 2013b).

Further detailed BAT BEP guidance relevant to recovery processes in EAFs is available in:

- Stockholm Convention BAT/BEP guidelines: V.D Thermal processes in the metallurgical industry not mentioned in Annex C, Part II [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]

- EU IS BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/IS_Adopted_03_2012.pdf]

### *Primary steel industry*

The Stockholm Convention BAT/BEP guidelines (UNEP 2007/2019) do not include BAT for blast furnace operations since they are not listed as a relevant source of UPOPs; however, blast furnaces are covered by the EU IS BREF (European Commission 2013b).

Further detailed BAT BEP guidance relevant to recovery processes in blast furnaces is available in:

- EU IS BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/IS_Adopted_03_2012.pdf]

### Secondary aluminium industries

Some key BAT/BEP recommendations to be considered for secondary aluminium production facilities focusing on UPOPs release reduction are described in Section V for Source category 2D “Thermal processes in the metallurgical industry” of the Stockholm Convention BAT/BEP guidelines (UNEP, 2019). Details on the technologies are described in the EU BREF documents on non-ferrous metal industries (European Commission 2017) and the associated BAT conclusions.

Further detailed BAT BEP guidance relevant to recovery processes in secondary aluminium production facilities is available in:

- Stockholm Convention BAT/BEP guidelines: V.D Thermal processes in the metallurgical industry [http://chm.pops.int/Implementation/BATBEP/BATBEPGuidelinesArticle5/tabid/187/Default.aspx]
- EU NFM BREF [https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC107041_NFM_bref2017.pdf]

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# Annex 1: General BAT/BEP considerations for specific sectors

## Crushing, shredding, sieving and washing operations

Within the management and treatment of PBDE-containing materials crushing, shredding and sieving operations are common.

BAT/BEP is to:

Perform crushing, shredding and sieving operations in areas fitted where needed with extractive vent systems linked to abatement equipment when handling materials that can generate emission to air (e.g. dust, VOCs, odours).

Perform washing processes considering:

a. identifying the washed components that may be present in the items to be washed (e.g. solvents, oil, refrigerants).

b. transferring washings to appropriate storage and then treating them in the same way as the waste from which they were derived.

c. using treated wastewater from the water treatment plant for washing instead of fresh water. The resultant wastewater can then be treated in the wastewater treatment plant or re-used in the installation.

## General BAT/BEP considerations in respect to air and water releases

### *Air emission treatment*

To prevent or control the emissions mainly of dust, VOC and odours and some inorganic compounds, BAT includes restricting the use of open topped tanks, vessels and pits by:

a. preventing direct venting or discharges to air by linking all the vents to suitable abatement systems when storing materials that can generate emissions to the air (e.g. VOCs, dust, odours).

b. keeping waste or materials under cover or in waterproof packaging.

Correctly operate and maintain the abatement equipment, including the handling and treatment/disposal of spent scrubber media. Have a scrubber system in place for the major inorganic gaseous releases from those unit operations which have a point discharge for process emissions.

Have leak detection and repair procedures in place in installations a) handling a large number of piping components and storage and b) compounds that may leak easily and create an environmental problem (e.g. fugitive emissions, soil contamination). This may be seen as an element of the EMS.

Air emissions should be reduced at least to the levels required by the respective national legislation. Facilities are encouraged to use BAT technologies to achieve BAT emission level.

Appropriate monitoring schemes should be in place to supervise the performance and document releases.

### *Wastewater treatment*

BAT/BEP is to reduce the usage and contamination of water by:

a. applying where necessary site waterproofing and storage retention methods

b. carrying out regular checks of storages, bunkers, pits and tanks

c. where appropriate applying separated water drainage according to the pollution load (roof water, road water, process water)

d. applying a security collection basin

e. performing regular water audits, with the aim of reducing water consumption and preventing water contamination

f. segregating process water from rainwater

Have procedures in place to ensure that the effluent specification is suitable for the on-site effluent treatment system or discharge

Avoid the effluent by-passing the treatment plant systems

Have in place and operate an enclosure system whereby rainwater falling on the processing areas is collected along with tanker washings, occasional spillages, drum washings, etc. and returned to the processing plant or collected in a combined interceptor

Segregate the water collecting systems for potentially more contaminated waters from less contaminated water

Have a full concrete base in the critical area, which falls to internal site drainage systems which lead to storage tanks or to interceptors that can collect rainwater and any spillage.

Collect the rainwater in a special basin for checking, treatment if contaminated and further use.

Maximise the re-use of treated wastewater and use of rainwater in the installation

Identify wastewater that may contain hazardous compounds. Segregate the previously identified wastewater streams on-site and specifically treat wastewater on-site or off-site.

Select and carry out the appropriate treatment technique for each type of wastewater.

Implement measures to increase the reliability with which the required control and abatement performance can be carried out (for example, optimising the precipitation of metals)

Identify the main chemical constituents of the treated effluent (including the make-up of the COD) and to then make an informed assessment of the fate of these chemicals in the environment

Only discharge the wastewater from its storage after the conclusion of all the treatment measures and a subsequent final inspection

Achieve the water emission values required by national legislation and/or competent authority before discharge. Facilities are encouraged to use BAT technologies to achieve low releases of pollutants to water.

### Prevention of soil contamination

To prevent soil contamination, BAT is:

- to provide and then maintain the surfaces of operational areas, including applying measures to prevent or quickly clear away leaks and spillages, and ensuring that maintenance of drainage systems and other subsurface structures is carried out
- to utilise an impermeable base and internal site drainage
- to reduce the installation site and minimise the use of underground vessels and pipe work
- to avoid the releases of wastewater discharge to soil
- to assure that only non-contaminated sludge from wastewater treatment are applied to soil

# Annex 2: BAT/BEP considerations for energy/material recovery

## General remarks

### *Corrosion caused by bromine/HBr*

Bromine/HBr has a high potential to cause corrosion, in particular of metal parts (Daniel and Rapp 1976). Thus corrosion effects need to be considered when larger amounts of PBDE/bromine-containing waste are thermally treated in facilities. The process needs to be closely observed and the economic benefits and drawbacks assessed, including the cost of maintenance and repairs (Rademakers et al. 2002).

### *Formation and monitoring of PBDD/Fs and PXDD/Fs*

Since PBDE-containing materials are flame retarded, their flammability is reduced, which can result in increased formation of products of incomplete combustion and unintentional POPs in facilities not equipped with optimally efficient combustion chambers (Weber and Kuch 2003), as specified in the BAT/BEP guidelines (UNEP 2007/2019). Since materials containing PBDE are excellent precursors of PBDF, the formation of the more toxic PBDF is also a crucial parameter to be considered and evaluated during thermal recovery and destruction operations of PBDE-containing waste (Sakai et al. 2001; Weber and Kuch 2003; UNEP 2010b). Because chlorine is normally present at relevant levels in PBDE-containing materials (e.g. WEEE plastic, ASR) (Schlummer et al. 2007), the formation of polybrominated-chlorinated dibenzo-*p*-dioxin and dibenzofurans (PXDD/PXDF) can comprise the highest share of dioxin-like compounds (Vehlow et al. 2002; Hunsinger et al. 2002; Zennegg et al. 2009). To overcome this dilemma of instrumental analysis of the complex mixed halogenated PXDD/PXDF, support of such monitoring by using accredited bio-assays measuring total dioxin-like toxicity like CALUX, DRCALUX or EROD is recommended (UNEP 2007/2019; Suzuki et al. 2016). In state-of-the-art waste incineration facilities equipped with dioxin abatement measures for compliance with stringent emission limit for PCDD/F (e.g. -< 0.1 nanogram/Nm$^3$; Table 5-1) it can be assumed that PBDD/PBDF and PXDD/PXDF are also adequately captured.

### *Removal of HBr and bromine in flue gas treatments*

For all thermal treatment technologies, the behaviour of bromine within the facility and the flue gas line need to be considered. Due to similar redox potential of bromine and oxygen (see Table 1), bromine is present in the flue gas partly as HBr and partly as elemental bromine. The ratio is influenced by, for example, the level of sulphur present (Vehlow et al. 2002).

HBr (together with HCl and other acid gases) can be removed by the usual removal technologies (dry/semi dry scrubbing with basic adsorbents, scrubbing with a NaOH solution, etc.). The technique to remove elementary bromine (and iodine) from the flue gas is a reductive wet scrubber stage with the addition of sulphite or bisulphite.

Table 1: Redox potential of halogens and boiling/melting point of potassium and sodium halogenides.

| | Fluorine | Chlorine | Bromine | Iodine |
|---|---|---|---|---|
| Boiling Point Potassium halogenides(ºC) | 1505 | 1500 | 1380 | 1330 |
| Boiling Point Sodium halogenides (ºC) | 1704 | 1465 | 1393 | 1304 |
| Melting point Potassium halogenides (ºC) | 858 | 790 | 732 | 686 |
| Melting point Sodium halogenides (ºC) | 995 | 801 | 755 | 662 |
| Redox potential (Standard potential $O_2$ +1.23) | +2.87 | +1.36 | +1.09 | +0.54 |

## Recovery in incinerators

To assure that BAT/BEP criteria are met and that long-term emissions of unintentional POP and POPs are low, continuous dioxin/UPOPs and respective POPs monitoring could be performed at least for some months (Reinmann et al. 2010; Weber 2007). Monitoring requirements include (European Commission 2019, BAT 4):

- PBDD/F: once every six months for the incineration of waste containing brominated flame retardants or for plants with continuous injection of bromine.
- PCDD/F: once every six months for short term sampling and once every six months for long term sampling. The monitoring for the long term sampling does not apply if the emission levels are proven to be sufficiently stable.
- Dioxin-like PCBs: once every six months for short term sampling and once every month for long term sampling. The monitoring for the long term sampling does not apply if the emission levels are proven to be sufficiently stable. The monitoring for dioxin-like PCBs does not apply where the emissions are proven the be less than 0.01 ng WHO-TEQ/Nm$^3$.

BAT for the reduction of channelled emissions to air of dust, metals and metalloids from the incineration of waste are the following (European Commission 2019, BAT 25):

- Bag filter
- Electrostatic precipitator
- Dry sorbent injection
- Wet scrubber
- Fixed- or moving-bed adsorption

BAT for the reduction of channelled emissions to air of organic compounds including PCDD/F and PCBs from the incineration of waste are the following (European Commission 2019, BAT 30):

- Optimisation of incineration process
- Control of waste feed
- On-line and off-line boiler cleaner
- Rapid flue-gas cooling to prevent de novo synthesis
- Dry sorbent injection by activated carbon or other reagents
- Fixed or moving bed adsorption
- SCR (Selective Catalytic Reduction) (where SCR is used of NOx abatement, the adequate surface of the SCR system also provides for the partial reduction of PCDD/F and PCB)
- Catalytic filter bags
- Carbon sorbent in a wet scrubber (PCDD/F and PCB are adsorbed by carbon sorbent added to the wet scrubber, either in the scrubbing liquor or in the form of impregnated packing elements. This technique is also used to prevent or reduce the re-emission of PCDD/F in the scrubber (the so called memory effect) occurring specially during shutdown and start-up periods).

The BAT associated emission levels for PCDD/F and PCDD/F and dioxin-like PCBs are shown in Table 2.

Table 2: BAT-associated emission levels (BAT-AELs) for channelled emissions to air of TVOC, PCDD/PCDF and dioxin-like PCB from the incineration of waste.

| Parameter | Unit | BAT-AEL | | Averaging period |
|---|---|---|---|---|
| | | New Plant | Existing plant | |
| TVOC | mg/Nm$^3$ | < 3-10 | < 3-10 | Daily average |

| | | | | |
|---|---|---|---|---|
| PCDD/PCDF[1] | ng I-TEQ/$Nm^3$ | < 0.01-0.04 | < 0.01-0.06 | Average over the sampling period |
| | | < 0.01-0.06 | < 0.01-0.08 | Long term sampling period[2] |
| PCDD/PCDF + dl-PCB[1] | ng WHO-TEQ/$Nm^3$ | < 0.01-0.06 | < 0.01-0.08 | Average over the sampling period |
| | | < 0.01-0.08 | < 0.01-0.1 | Long term sampling period[2] |
| [1]Either the BAT-AEL for PCDD/PCDF or BAT-AEL for PCDD/PCDF + dioxin-like PCB applies<br>[2]The BAT-AEL does not apply if the emission levels are proven to be sufficiently stable | | | | |

*(Commission Implementing Decision 12.11.2019, European Commission 2019)*

## Recovery in cement kilns

Stable molecules (and dioxin precursors) like PCB or POPs pesticides need to be fed at the "hot end" of the kiln into the burner flame with temperature up to 2000°C and residence time of more than 2 seconds which can guarantee a high destruction efficiency and related emissions. A properly configured test-burn, together with the establishment of the destruction efficiency, which incorporates an analysis of all emissions from the process including from products and the bypass stack, should always be carried out before any POPs waste is considered for routine disposal. Ideally POPs destruction projects are monitored continuously by long term sampling of unintentionally POPs and the POPs in the feeding material (Weber 2007, Umweltbundesamt 2017). Modification of cement kilns with post combustion have recently been added in some cement kilns in Austria. Also improved flue gas treatment systems has been established in some cement kiln with secondary fuel use and is described in the EU BAT Reference Document (European Commission 2013a).

Cement kilns with pre-heaters normally have PCDD/PCDF emission levels well below 0.1 ng TEQ/$Nm^3$ (Karstensen et al. 2006). In the BAT conclusions for cement, lime and magnesia the BAT-AEL for the emissions of PCDD/Fs from the flue-gases of the kiln firing processes is <0.05 – 0.1 ng PCDD/F I-TEQ/$Nm^3$, as the average over the sampling period (6 – 8 hours). The following BAT techniques are described in the BAT conclusions for cement, lime magnesia:

- Carefully selecting and controlling of kiln inputs (raw material and fuels), i.e. chlorine, copper and volatile compounds
- Limiting/avoiding the use of wastes which contain chlorinated organic materials
- Avoid feeding fuels with a high content of halogens in secondary firing
- Quick cooling of kiln flue gases to lower than 200°C and minimising residence time of flue gases and oxygen content in zones where the temperature range between 300 and 400°C
- Stop co-incinerating waste for operations such as start-ups and/or shutdowns

Options and limitations for the destruction of PBDEs in wastes (such as plastics from WEEE, automotive/transport shredder, polyurethane foam from furniture insulation or mattresses) in cement kilns need a detailed evaluation of the individual kiln to decide on the options and limits of recovery energy from PBDE/BFR-containing materials in such kilns. Such assessment should include comprehensive monitoring of the release of PBDEs and other unintentionally produced POPs and brominated and brominated-chlorinated toxic substances including PBDD/PBDF and PXDD/PXDF. Considering that the build-up of chloride (and most likely bromide too) within a cement kiln can take weeks, an assessment and appropriate monitoring of the fate of PBDE/BFR-containing materials on associated pollutant releases could best be performed through long-term monitoring (Reinmann et al. 2010) considering the recently developed CEN standard EN 1948-5 for long term PCDD/F sampling (DIN 2015; Reinmann 2015). The following measures are proposed (Umweltbundesamt 2017):

- Limitation of POP contaminated waste/residues in co-incineration plants and industrial plants. Representative sampling of individual batches of POP contaminated waste/residues is necessary before using them as input material.

- Avoid/prohibit highly contaminated waste/residues in co-incineration plants.
- Before treating POP contaminated waste/residues in industrial plants, test runs (including monitoring of POP emissions) have to be conducted.
- If POP contaminated waste/residues are used as input materials in industrial plants, regular/continuous monitoring of POP emissions is necessary. If a destruction of these POPs cannot be ensured in the industrial plant, the POP residues/waste must not be used as input material.
- If there are any changes in the process involving POP contaminated waste/residues, test runs (including monitoring of POP emissions) have to be conducted.

A properly configured test-burn, including the assessment of the destruction efficiency of the kiln, which incorporates an analysis of emissions (including sampling for PBDEs and PXDD/PXDF) from the process and the bypass stack together with the concentrations in clinker and cement kiln dust, should always be carried out before PBDE waste is considered for routine disposal. The routine disposal of PBDE-containing wastes can be supervised by long-term monitoring of unintentionally produced POPs and PBDD/PBDF or PBDE in stack emissions (Reinmann et al. 2010) for an appropriate control of releases over the time span of the POPs destruction project.

## Recovery in metal industries

### *Copper smelters and integrated smelters-refineries*

BAT techniques for the reduction of PCDD/F emissions in secondary copper production are the following (European Commission 2017):

- Select and feed the raw materials according to the furnace and the abatement technique used;
- Optimise combustion conditions to reduce the emissions of organic compounds;
- Use charging systems, for a semi-closed furnace, to give small additions of raw material;
- Thermal destruction of PCDD/PCDF in the furnace at high temperatures (> 850°);
- Use oxygen injection in the upper zone of the furnace;
- Internal burner system;
- Post-combustion chamber or afterburner or regenerative thermal oxidiser;
- Avoid exhaust systems with a high dust build-up for temperatures > 250°;
- Rapid quenching;
- Injection of adsorption agent in combination with an efficient dust collection system.

These techniques are also effective with regard to PBDE emissions.

General BAT/BEP considerations and guidance on unintentional POPs release from copper smelters include:

Table 1: Summary of primary and secondary measures for secondary copper smelters.

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| ***Primary measures*** | | | |
| Presorting of feed material | The presence of oils, plastics, organic materials and chlorine compounds in the feed material should be | Processes to consider include:<br>• Strict control over materials sources<br>• Oil removal from feed material<br>• Use of milling and grinding techniques with good dust extraction and abatement | Thermal decoating and de-oiling processes for oil removal should be |

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| | avoided to reduce the generation of PCDD/PCDF during incomplete combustion or by de novo synthesis | • Elimination of plastic by stripping cable insulation<br>• In order to increase the secondary recovery yields from scrap the following techniques can be used:<br>  • manual separation for the separation of large visible constituents<br>  • magnetic separation for the separation of ferric metals<br>  • optical or eddy current separation for the separation of aluminium<br>  • relative density separation for the separation of different metal and non-metallic constituents | followed by afterburning to destroy any organic material in the off-gas |
| Effective process control | Good combustion. Process control systems should be utilized to maintain process stability and operate at parameter levels that will contribute to minimizing generation of chemicals listed in Annex C | PCDD/PCDF emissions may be minimized by controlling other variables such as temperature, residence time, gas composition and fume collection damper controls after having established optimum operating conditions for the reduction of PCDD/PCDF | Continuous emissions sampling of PCDD/PCDF has been demonstrated for some sectors (for example, waste incineration), but research is still ongoing for applications to other sources |
| ***Secondary measures*** | | | |
| Fume and gas collection | Effective fume and off-gas collection should be implemented in all stages of the smelting process to capture PCDD/PCDF emissions | Measures to prevent or reduce diffuse emissions from pretreatment are:<br>  • enclosed conveyers or pneumatic transfer systems,<br>  • enclosed building,<br>  • dust suppression systems such as water cannons or water sprinklers,<br>  • enclosed equipment<br>  • extraction system such as a hood.<br>Measures to prevent or reduce diffuse emissions from charging, smelting and tapping operation are:<br>  • briquetting and pelletisation of raw materials,<br>  • enclosed charging system such as single jet burner, door sealing, closed conveyers or feeders ,<br>  • the operation of the furnace and gas route under negative pressure and a sufficient gas extraction rate,<br>  • capture hood/enclosures at charging and tapping points,<br>  • encapsulation of the furnace in extractable housing,<br>  • furnace sealing, | a gas extraction system and a dust and gas abatement system have to be connected |

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| | | • holding of the temperature in the furnace at the lowest required level,<br>• boosted suction systems,<br>• enclosed building in combination with other techniques to collect the diffuse emissions,<br>• double bell charging system,<br>• use of lids on throats of rotary anode furnace. | |
| High-efficiency dust removal | Dusts and metal compounds should be removed as this material possesses high surface area on which PCDD/PCDF easily adsorb. Removal of these dusts would contribute to the reduction of PCDD/PCDF emissions | Processes to consider include:<br>• Fabric filters (most effective method)<br>• Wet/dry scrubbers in combination with ESP<br>• ceramic filters | Dust removal is to be followed by afterburners and quenching. Collected dust must be treated in high-temperature furnaces to destroy PCDD/PCDF and recover metals |
| Afterburners or regenerative thermal oxidizer and quenching | Afterburners or regenerative thermal oxidizers should be used at temperatures >950 °C to ensure full combustion of organic compounds, followed by rapid quenching of hot gases to temperatures below 250 °C | Considerations include:<br>• PCDD/PCDF formation at 250–500 °C, and destruction > 850 °C with O2<br>• Requirement for sufficient O2 in the upper region of the furnace for complete combustion<br>• Need for proper design of cooling systems to minimize reformation time | De novo synthesis is still possible as the gases are cooled through the reformation window |
| Adsorption on activated carbon | Activated carbon treatment should be considered as this material possesses large surface area on which PCDD/PCDF can be adsorbed from smelter off-gases | Processes to consider include:<br>• Treatment with activated carbon using fixed or moving bed reactors<br>• Injection of adsorption agent (powdered carbon) into the gas stream followed by efficient dust collection system | Lime/carbon mixtures can also be used |
| ***Emerging research*** | | | |
| Catalytic oxidation | Catalytic oxidation is an emerging technology for sources in this sector (demonstrated technology for incinerator applications) which should be considered due to its high efficiency and lower energy consumption. | Considerations include:<br>• Process efficiency for the vapour phase of contaminants<br>• Hydrochloric acid treatment using scrubbers while water and CO2 are released to the air after cooling<br>• Complexity, sensitivity to flue gas conditions and high cost | Catalytic oxidation has been shown to destroy PCDD/PCDF with shorter residence times, lower energy consumption and > 99% efficiency. |

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| | Catalytic oxidation transforms organic compounds into water, CO2 and hydrochloric acid using a precious metal catalyst | | Particulate matter should be removed from exhaust gases prior to catalytic oxidation for optimum efficiency |

(UNEP 2007/2019 and European Commission 2017)

Performance levels in air emissions associated with BAT / BEP for secondary copper smelters are ≤ 0.1 mg I-TEQ/Nm$^3$ (at operating oxygen concentrations). Further details can be found in the Stockholm Convention BAT/BEP guidelines (UNEP 2007/2019) and in the EU NFM BREF (European Commission 2017).

### *Electric arc furnaces*

The major feedstock for the EAF is ferrous scrap, which may be comprised of scrap from inside the steelworks, cut-offs from steel product manufacturers (e.g. vehicle builders) and capital or post-consumer scrap (e.g. end-of-life products) (European Commission 2013b).

EAFs have not been considered to be facilities for recovery of PBDE/BFR-containing wastes. For a number of years it has been demonstrated that EAFs processing scrap metals can generate high levels of PCDD/PCDF in solid wastes and dust from flue gas cleaning (ENDS 1997). More recently, PBDE and PBDD/PBDF emissions from EAFs have been reported for China and Turkey (Du et al. 2010a,b; Odabasi et al. 2009; Wang et al. 2010). The levels from metallurgical processes were higher than from incinerators (Du et al, 2010a,b). This demonstrates that feedstock wastes containing PBDE is entering EAFs and needs to be addressed in the Stockholm Convention implementation. Since EAFs can facilitate the recovery of metals, such cases might fall into the category of recycling and recovery of materials containing PBDEs.

Specific BAT/BEP considerations to reduce or eliminate PBDEs and PXDD/PXDF release from EAFs include:

Table 2: Summary of primary and secondary measures for new and existing electric arc furnaces.

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| ***Primary measures*** | | | |
| General operating practices | An integral part of a facility's pollution prevention programme should include best environmental, operating and maintenance practices for all operations and aspects of the electric arc furnace steel-making process | Generally applicable; part of an integrated concept for pollution prevention | |
| Raw material quality | A review of feed materials and identification of alternative inputs and/or procedures to minimize unwanted inputs should be conducted. Documented procedures should be developed and implemented to carry out the appropriate changes | Generally applicable. Measures include changes in material specifications, improved quality control programmes, changes in the types of raw materials (such as controlling the use of oily scrap) and programmes to prevent the entry of contaminants | |

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| Electric arc furnace operation | Minimizing the duration of the roof being open for charging, reduction of air infiltration into the furnace, and avoiding or minimizing operational delays | Collateral benefit is reduced PCDD/PCDF | Other pollutants are reduced, including aromatic organohalogen compounds, carbon monoxide, hydrocarbons and greenhouse gases |
| Off-gas conditioning | Design and installation of an adequately sized gas conditioning system based on optimum system parameters should prevent or minimize formation of PCDD/PCDF in the gas conditioning system.<br>Development and implementation of documented operating and maintenance procedures should be developed to assist in optimizing the operation of the gas conditioning system | A reduction in de novo synthesis in the gas conditioning system has been linked to the rapid cooling of the furnace off-gases to below a range of 225 °C to 200 °C | |
| Continuous parameter monitoring | A continuous parameter monitoring system such as Continuous Opacity Monitors (COMs) or Bag Leak Detection (BLD) systems should be employed to ensure optimum operation.<br>Operators should prepare a site-specific monitoring plan for the continuous parameter monitoring system and keep records that document conformance with the plan | Correlations between parameter values and stack emissions (stable operation) should be established. Parameters are then continuously monitored in comparison to optimum values | System can be alarmed and corrective action taken when significant deviations occur |
| ***Secondary measures*** | | | |
| Off-gas collection | Primary and secondary emissions (incl. scrap preheating, charging, melting, tapping, ladle furnace and secondary metallurgy) should be collected as much as possible to achieve an efficient extraction of all emission sources, preferably at the source of origin and then abated..<br>Combination of direct off-gas extraction (4th hole or 2nd hole) and hood systems, direct gas extraction and dog house systems or direct gas extraction and total building evacuation are the preferred systems.<br>Dust collection efficiency of primary and secondary emissions from the electric arc furnace should be maximized. | combination of direct fume extraction and hood system is often used. This combination achieves a collection of about 98% of the primary emissions. Ventilation systems in the EAF melt shop should be appropriately sized to ensure capture of process emissions within the building and conveyance to the air pollution control system. | A combination of a direct extraction device and a furnace enclosure can achieve collection rates from 97-100% of the total dust emissions. 98% efficiency or more of dust collection is achievable |

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| Fabric filters | Bag filters are very effective in capturing all particle-bound pollutants, e.g. heavy metals as well as organochlorine pollutants such as PCDD/F particularly if adsorption agents are used.<br>Well-designed and maintained fabric filters achieve less than 5 mg dust/Nm$^3$ as daily average.<br>Procedures should be developed for the operation and maintenance of the fabric filter dust collector to optimize and improve collection performance, including optimization of fabric bag cleaning cycles, improved fabric bag material and preventive maintenance practices.<br>An important issue for a sound bag filter operation is to prevent incandescent particles from reaching the filtering medium and thus burning holes into it. For this purpose, spark arresting devices, such as cyclones are often installed in the raw gas ducts.<br>A continuous temperature monitoring and alarm system should be provided to monitor the off-gas inlet temperature to the emission control device.<br>A bag leak detection system should be provided with documented operating and maintenance procedures for responding to monitoring system alarms | There are correlations between PCDD/PCDF emissions and dust emissions. At various flue gas temperatures, PCDD/PCDF will be absorbed and adsorbed on the dust captured in the fabric filter. Modern baghouses that are appropriately sized, operated, maintained and monitored are capable of dust emissions < 5 mg/Nm$^3$. To achieve these emission levels it is important to avoid that parts of the bag filters are destroyed. Here good operation which consists of the continuous monitoring of dust emissions and consequent replacement of all destroyed bag filters are important. | Maintaining the off-gases in the baghouse to below 60 °C will reduce PCDD/PCDF evaporation and increase capture of PCDD/PCDF associated with the dust. The collected dust should be appropriately managed, considering the pollutants contained in the dust.<br>Enclosing the filter dust collection areas and transfer points minimizes diffuse dust.<br>The use of appropriately sized and operated ventilation systems will reduce facility workers to occupational exposure of pollutants. |
| Post-combustion of off-gas | Well optimised post-combustion in a combustion chamber reduces the emission of organic and organochlorine compounds such as PAH, PCB or PCDD/F. Post-combustion with the additional aim of minimising organic micropollutants needs an adequate retention time, turbulence and temperature. To prevent the de novo synthesis of PCDD/F, it is essential to have a rapid cooling (quenching) of the fumes as soon as possible after post-combustion to a temperature of below 250 °C at which all risk of de novo synthesis is excluded. | In general, with proper post-combustion followed by rapid cooling emission concentrations of PCDD/F of lower than 0.1 ng I-TEQ/Nm$^3$ can be achieved. | PCDD/PCDF that have been formed in the process undergo dechlorination reactions as the off-gas is burnt by the additional oxygen burners.<br>This technique with a rapid water quench has been an early PCDD/PCDF emission control technique applied to electric arc furnace steel making |

| Measure | Description | Considerations | Other comments |
|---|---|---|---|
| Adsorbent injection | In order to reduce POPs, especially PCDD/F in the total off-gas (primary and secondary emissions) adsorbents (e.g. activated carbon, pulverized activated lignite coke or mixtures of these with lime) can be dosed to the exhaust duct before the dust abatement device. Residual PCDD/F emission concentrations of 0.01-0.1 ng I-TEQ/Nm$^3$ are achievable.<br>Besides PCDD/F adsorption, activated carbon and pulverized activated lignite coke have shown high efficiency of separation of heavy metals and a certain efficiency in removing mercury from the gas phase.<br>The technique has been implemented in several European EAF plants since 1997. | | |
| Minimize solid waste generation | Electric arc furnace slag and filter dust should be recycled to the extent possible.<br>Filter dust from high-alloy steel production, where possible, may be treated to recover valuable metals.<br>Best management practices should be developed and implemented for hauling and handling dust-generating solid wastes.<br>Excess solid waste should be disposed of in an environmentally sound manner | | |
| Minimize wastewater | Closed-loop water-cooling systems for electric arc furnace components avoid wastewater being generated.<br>Recycle wastewater to the maximum extent possible.<br>Residual wastewater should be treated.<br>Semi-dry air pollution control systems can be designed to have zero discharge of excess wastewater.<br>Wastewater from wet gas cleaning systems should be treated before discharging to the environment | These measures would be primarily associated with general pollution prevention and control practices rather than being applied specifically, or only, for the purpose of PCDD/PCDF | No standards were found on PCDD/PCDF limits for treated wastewater discharged as final effluent from wet off-gas cleaning systems |

*(European Commission 2013b)*

A performance level associated with best available techniques for air emissions of PCDD/PCDF from secondary steel-making plants and iron and steel foundries is < 0.1 ng I-TEQ/Nm$^3$ (at operating oxygen concentrations) (European Commission 2013b).

### *Primary steel industry*

Plastic and possibly other polymers are used in the primary steel industry either i) directly in blast furnaces as coke substitutes or ii) as substitutes for coal in the production of coke (Japan National Institute for Environmental Studies 2010; European Commission 2013b). An LCA for PBDE-containing TV casings (Hirai et al. 2007) compared four scenarios: material recycling, feedstock recycling, incineration and landfilling. It concluded that feedstock recycling of PBDE-containing material in the primary steel industry could be preferable compared to the second best option of material recycling but noted that the capacity is limited because of the Br content of the plastics.

According to the European BAT reference document for iron and steel, shredder residue are feedstocks in primary steel production (European Commission 2013b), there are no data published for emissions from an operating blast furnace with explicit co-treatment of PBDE-containing materials. The BAT/BEP document, however, emphasizes that to assess the options and limitations of the feedstock use of such polymer rich fractions (from mixed electronics and/or automotive shredder) it is necessary to ascertain heavy metal content of the polymer feedstock[17] in order to assess its suitability and limitation for use[18] (European Commission 2013b). Hirai et al. (2007) found that bromine/halogen content was one factor limiting the extent of use in the primary steel industry[19] as the Japanese steel industry only accepts a halogen content of up to 0.5% (bromine or chlorine). In Europe the allowable halogen content appears higher.[20]

The conditions in a blast furnace are likely to destroy PBDEs and other halogenated organics in furnaces with high efficiency. Emissions of PBDEs and PBDD/PBDF, however, need to be assessed in detail to ensure compliance with the Stockholm Convention obligations.

### *Secondary aluminium industries*

Processes used in secondary aluminium smelting are dependent on feed material. Feed consists of process scrap, used beverage cans, foils, extrusions, commercial scraps, turnings and old rolled or cast metal. The use of chlorine and chlorides (as salt flux) provides a source of chlorine and hence the potential for the formation of PCDD/F in the combustion zone and in the cooling part of the off-gas treatment system (de novo synthesis). The use of modern regenerative burners can prevent or minimize de novo synthesis. Efficient dust filtration removes organic compounds and the PCDD/F that are associated with dust; carbon may be added to increase the cleaning efficiency. Afterburning of the off-gases may also be carried out to destroy organic compounds produced in the furnace or in pre-treatment stages (UNEP 2007/2019).

PBDD/PBDF and PXDD/PXDF have been detected in stack gas emissions from secondary aluminium smelters (Du et al. 2010a, b). Thus, secondary aluminium plants should be properly assessed for the release of PBDEs, PBDD/PBDF and PXDD/PXDF into the air and solid residue.

The BAT/BEP guidelines provide primary and secondary measures for secondary aluminium (UNEP 2007/2019). Primary measures include the pre-sorting of the feed material and the avoidance of bromine or chorine in the feed, the use of reverberatory furnace for organic scrap (internal afterburning system). Secondary measures are the adsorption on activated carbon or afterburning and rapid quenching.

PCDD/PCDF performance levels in air emissions associated with best available techniques and best environmental practices for secondary aluminium smelters are ≤ 0.1 ng I-TEQ/Nm$^3$ (at operating oxygen concentrations) (European Commission 2017, UNEP 2007/2019).

## References

See the list of references provided in Chapter 7 of this guidance document.

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[17] Particularly mercury, but also of cobalt, chromium, arsenic, lead, nickel, cadmium and zinc.

[18] The European IS BREF specifies the limits for cobalt, chromium, arsenic, lead, nickel, mercury, cadmium and zinc in plastic feedstock recycling in blast furnaces (European Commission 2013b).

[19] The bromine content of waste TV casings generated in Japan each year is 705 tons or nearly twice the 400 tonnes of total halogen that could be accepted/managed by plastic feedstock recycling in the Japanese primary steel industry. Consequently, a maximum of about 50% of the TV plastics could theoretically be recovered via this route for Japan (Hirai et al. 2007).

[20] In Europe chlorine content of up to 1.5% (Bremen/Germany) (Tukker 2002) and 2% (Linz/Austria) (European Commission 2017) is reportedly acceptable to the steel industry.