

Draft guidance on best available techniques and best environmental practices for the production and use of hexabromocyclododecane listed with specific exemptions under the Stockholm Convention

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The designations employed and the presentations in this publication are possible options, based on expert judgment, for the purpose of assisting countries in their actions to reduce or eliminate releases of hexabromocyclododecane (HBCD) listed with specific exemptions in the Stockholm Convention. UN Environment or contributory organizations cannot be liable for misuse of the information contained in this publication.

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Preface

This document has been developed by the experts on Best Available Techniques (BAT) and Best Environmental Practices (BEP) nominated by parties and others in accordance with the process for the review and update of the guidelines and guidance on BAT and BEP. It contains most up-to-date information and knowledge as evaluated and integrated in the draft guidance by the BAT and BEP experts. The expert input provided by the BAT and BEP group of experts is highly acknowledged. The experts nominated by Parties and others to be consulted in the process for review and update of the guidelines and guidance on BAT and BEP are part of the joint Toolkit and BAT and BEP expert roster (UNEP/POPS/COP.8/INF/14).

1. Introduction

At its sixth meeting held from 28 April to 10 May 2013, the Conference of the Parties to the Stockholm Convention adopted an amendment to Annex A to the Convention to list hexabromocyclododecane (HBCD) with specific exemptions for production as allowed for the Parties listed in the Register of Specific Exemptions and for use in expanded polystyrene (EPS) and extruded polystyrene (XPS) in buildings (decision SC-6/13). The listing covers hexabromocyclododecane (CAS No: 25637-99-4), 1,2,5,6,9,10-hexabromocyclododecane (CAS No: 3194-55-6) and its main diastereoisomers: alpha-hexabromocyclododecane (CAS No: 134237-50-6); beta-hexabromocyclododecane (CAS No: 134237-51-7); and gamma-hexabromocyclododecane (CAS No: 134237-52-8). A more detailed description of the characteristics of HBCD can be found in UNEP (2015a).

According to Part VII of Annex A to the Convention, each Party that has registered for the exemption pursuant to Article 4 shall take necessary measures to ensure that EPS and XPS containing HBCD can be easily identified by labeling or other means throughout its life cycle.

1.1. Purpose

This document has been developed to provide guidance to Parties in their actions to prevent and/or reduce releases of HBCD from production and use under specific exemptions under the Stockholm Convention. It compiles available information relevant to Best Available Techniques (BAT) and Best Environmental Practices (BEP) for HBCD within the scope of the Convention. Further relevant guidance has been developed in the past and is available under the Basel and Stockholm Conventions to address certain aspects of environmentally sound management of chemicals that are applicable to HBCD; these guidance documents are referred to in the relevant sections/chapters in this document. The present document should therefore be considered in conjunction with other relevant guidance material as noted in the specific sections/chapters.

1.2. Structure and use of this document

Chapter 1 provides background information on HBCD and outlines the purpose and structure of this document. Chapter 2 includes information on past and current production and use of HBCD. Chapter 3 provides an overview of the main sources and pathways of releases of HBCD into the environment. Chapter 4 provides information on alternatives to the use of HBCD for the specific exemptions under the Convention, including chemical alternatives to HBCD as well as non-chemical, functional alternatives. Chapter 5 describes the BAT and BEP to consider in the production and use of HBCD for the specific exemptions under the Convention. Chapter 6 provides summary considerations for identification of the chemical in accordance to Part VII of Annex A to the Convention. Chapter 7 provides information for consideration in the environmentally sound management of wastes containing HBCD, and Chapter 8 addresses the issue of contaminated sites.

2. Background information on HBCD

2.1. Production of HBCD

2.1.1. Production volumes

HBCD has been on the world market since the late 1960s and is still being produced for use in EPS and XPS in buildings. It has been produced mainly in China, the European Union (EU), and the United States of America. The total production of HBCD was estimated at around 31,000 tonnes in 2011, of which about 13,000 tonnes were produced in EU countries and in the United States, and 18,000 tonnes in China (UNEP/POPS/POPRC.7/19/Add.1, UNEP/POPS/POPRC.8/16/Add.3). For comparison, in 2001, the demand for HBCD was 9,500-16,500 tonnes in Europe, 3,900 tonnes in Asia and 2,800 tonnes in North and South America (additional production and use data are available in UNEP/POPS/POPRC.7/19/Add.1 and UNEP/POPS/POPRC.8/16/Add.3). As of the second quarter of 2016, HBCD is no longer produced in

Europe. Due to Convention obligations and alternatives for HBCD being available for EPS and XPS the future production and use volumes are expected to decrease in the future (UNEP 2015a, ECHA 2009).

2.1.2. Production method

The production of HBCD is a batch-process. Elementary bromine is added to cyclododecatriene in the presence of a solvent. The process temperature is 20 to 70 °C, and the reaction takes place in closed systems. The suspension obtained is filtered, the solvent is removed with water, and the product is dried, stored in a silo and packed. According to one producer, production and transportation of the material to silo and the packaging are done in a closed system. The product is delivered as powder or pellets (European Commission 2008).

The production method as described in general terms in the IUCLID Data Sheet is as follows:

- Loading of raw materials
- Bromination
- Filtering
- Drying
- Storage in silo
- Packaging

2.1.3. Micronising (grinding to smaller particles)

The HBCD particles in some applications (e.g. for past use in textile back-coating) need to be very small. Therefore some quantities of HBCD were micronised in a grinding process (UNRP 2015a, European Commission 2008).

2.2. Uses of HBCD

The table below summarizes the uses of HBCD (UNEP 2015a, ECHA 2009):

Material	Use/Function	End-products (Examples)
Expanded Polystyrene (EPS)	Insulation	<ul style="list-style-type: none"> • Insulation boards (against cold or warm) of transport vehicles e.g. lorries and caravans • Insulation boards in building constructions e.g. houses walls, cellars and indoor ceilings and “inverted roof” (outdoor) • Insulation boards against frost heaves of road and railway embankments • Packaging material (non-food packaging, and very minor use and not intended in food packaging)
Extruded Polystyrene (XPS)	Insulation	<ul style="list-style-type: none"> • Insulation boards (against cold or warm) of transport vehicles e.g. lorries and caravans • Insulation boards in building constructions e.g. houses walls, cellars and indoor ceilings and “inverted roof” (outdoor) • Insulation boards against frost heaves of road and railway embankments
High Impact Polystyrene (HIPS) --use no longer allowed under the Convention--	Electrical and electronic parts	<ul style="list-style-type: none"> • Electric housings for VCR • Electrical and electronic equipment e.g. distribution boxes for electrical lines • Video cassette housings
Polymer dispersion for textiles -- use no longer allowed under the Convention --	Textile coating agent	<ul style="list-style-type: none"> • Upholstery fabric • Bed mattress ticking • Flat and pile upholstered furniture (residential and commercial furniture) • Upholstery seating in transportation • Automobile interior textiles • Draperies, and wall coverings

- | | | |
|--|--|--|
| | | <ul style="list-style-type: none"> • Interior textiles e.g. roller blinds |
|--|--|--|

2.2.1. Expandable Polystyrene (EPS)

Formulation of EPS compound

Expandable polystyrene is produced in a batch process, i.e. discontinuously, by suspension polymerization of styrene in water. Styrene is dispersed in water in the form of small droplets. Prior to combining the water with the organic phase, additives are introduced. Typically these include suspension agents, free-radical forming initiators and HBCD flame-retardant. HBCD-powder, most often delivered in paper bags with a plastic liner, with typically a content of 25 kg, is suspended at low temperatures in styrene prior to the addition of the water phase.

Normally the bags are emptied into an intermediate storage container from where the HBCD is transported via pipes and a weighing station prior the addition to the styrene. In the reactor, styrene forms the disperse phase as small monomer droplets in the continuous water phase. Final droplet size (0.01 to 0.5 mm) is determined by the ratio of disperse to continuous phase (typically 50:50) and by stirrer speed. The suspension agents prevent coalescence.

Within the monomer droplets (bulk), polymerization occurs while the reactor content is heated up and held at its reaction temperature. During this free-radical polymerization an expansion agent (e.g. pentane) is added to the reactor under pressure, where it is absorbed in the polymer droplets. In the final EPS beads, HBCD is incorporated as an integral and encapsulated component within the polymer matrix with uniform concentration throughout the bead.

After complete conversion of the styrene monomer to EPS-beads, the reactor is cooled down and the beads are separated from the water by centrifugation. The decanted water, which could contain dissolved and dispersed HBCD, is reused and exchanged on an annual basis or less frequently. The EPS beads are dried, and thereafter classified into various size fractions and surface coated. These different grades are packed in bins, bags, or transported in bulk trucks to the EPS-converters. The typical concentration of HBCD in EPS beads is assumed to be 0.7%, and the maximum concentration 1.0% (European Commission 2008, BC TG).

Industrial use of EPS compound

EPS foam is produced from EPS beads via pre-expansion of the beads with dry saturated steam, drying with warm air and shaping in shape moulds or in a continuous moulding machine. First, the raw material beads are pre-expanded in loose form with the help of dry saturated steam in pre-expanders. The raw materials are transported via pipes or tubes from the packaging containers to these stirred vessels. After expansion the beads are partly dried in fluid bed driers with warm air.

The beads are subsequently stored in large permeable silos to “mature” for several hours up to 24 hours. During this stage the beads dry further and reach equilibrium with the ambient atmosphere around them. In the third phase the beads are transported/blown, via pipes/tubes into block or shape moulds or in a continuous moulding machine in which the product gets its shape. The foam can then be further formed by cutting, sawing or other machine operations (European Commission 2008).

Professional and private use of EPS containing HBCD

EPS containing HBCD is used in end-products such as:

- insulation panels/boards in the construction sector
- rigid packaging material for fragile equipment (minor use)
- packaging material such as “chips” and shaped EPS-boards (minor use)

HBCD-containing EPS can also be used in props for theatre, film and also for exhibitions. Secondary process activities of the EPS foam products, especially block foam, can be cutting, sawing and machining to manufacture shaped products such as interlocking boards. The cuttings and sawdust can be recycled in the moulding process within the plant. The EPS foam products, e.g. insulation boards, are normally transported shrink-wrapped, or packed in cartons.

Nearly all EPS foam containing HBCD is used in the building and construction industry. The use of these flame-retarded products is often required to comply with the existing fire standards and/or building regulations and codes.

EPS used in packaging does normally not contain any flame retardant additive. According to information from 2008, only in some cases, e.g. when requested by customers to minimize for instance the effect of fires, flame retarded EPS-material is used for non-food packaging applications (European Commission 2008).

2.2.2. Extruded Polystyrene (XPS)

At the production of XPS-material the formulation stage can take place either at a separate site or at the same site as the following stage of industrial use.

Formulation of XPS compound

The HBCD is supplied either in powder or in low-dust granulated form in either 25 kg bags or in 1 ton supersacks or “big bags”. The supersacks are emptied into hoppers designed to minimize dust emissions. The HBCD is then carried to the point of mixing with screw or air driven metering equipment. The compounded polystyrene is extruded and cut into granules, and packaged. The extrudate is either air-cooled or cooled by running in a water bath. According to industry information the masterbatch can contain approx. 40 % (w/w) of HBCD (European Commission 2008).

Industrial use of XPS- compound (masterbatch) / HBCD powder/granules at the manufacture of XPS

The manufacture of XPS materials is carried out in the following way:

- The polystyrene, the additives such as processing aids, flame retardant in the form of a compound, powder or granules, dye and blowing agent are fed continuously to an extruder.
- The polymer is melted; the blowing agent is mixed with the melted polymer and a “foamable gel” is formed.
- The gel is then cooled before it exits through an orifice called a die, where the dissolved blowing agent volatilizes, causing the plastic to assume a foam structure. The blowing agent reduces the density of the product by the formation of a myriad of closed cells within its structure.
- The foam is then trimmed to desired shape. The boards are packed into shrink-wrapped bundles and palleted. The pallets are stored for curing and are then ready for shipment.
- The trimmed foam accounts for about 15-25 % of the feed material and is recycled back to the extruder. This material is mainly shavings from the side-profile and “skin” from the surface. The recycled material is compacted or pelletized; in the latter case the strands comes in contact with water during cooling.

One technology, which is not commonly used, known as the UCI technology, uses a vacuum in addition to blowing agents to produce the lighter (i.e., lower density) foams. In this technology, the product comes into contact with water in a water pond directly after the extrusion.

Insulation panels made from XPS contain 0.8 to 2.5 % (w/w) HBCD (European Commission 2008).

Professional and private use of XPS

XPS containing HBCD is mainly used in end-products such as insulation panels/boards in the construction sector. The XPS product is transported usually to a main distributor’s warehouse, perhaps from there to a local distributor/dealer and hence to a building site on the orders of the building contractor. There is a small amount (5 %) of “do it yourself”-business” via “do it yourself”-stores/building material suppliers. Clearly for major building sites the building contractor can have material delivered directly from the plant to the building site.

XPS has been officially approved for single- and double-layer use in inverted roofs. It may also be used with a water-proofing membrane to insulate parking decks and green roofs. XPS may also be used as perimeter insulation.

Similarly as in the case of EPS, the use of flame retarded polystyrene for prevention of frost damages on roads and in railway embankments is regulated through national fire standards and regulations mainly to prevent fire during transport and storage. It is assumed that, when flame retardant is used, the concentration of HBCD in XPS is 0.8-2.5 % (European Commission 2008).

2.2.3. High Impact Polystyrene (HIPS)

Formulation of polystyrene compound for the production of HIPS

High Impact Polystyrene is produced either in a batch or continuous polymerization process. The final raw material is homogenized and extruded into HIPS pellets either strand- or face-out. These pellets are the starting material for the production of flame-retarded HIPS. Different flame retardant additives are used of which HBCD was used only a small part¹. In the feeding hopper all ingredients together with the HIPS pellets are metered in the extruder for further mixing, homogenization and granulation into pellets.

An alternative route for HIPS production is via an intermediate-compounding route. First a masterbatch of general-purpose polystyrene pellets and HBCD at a high concentration is prepared, followed by compounding this masterbatch with virgin HIPS material in a conversion step. The process of preparing the HBCD masterbatch is similar to that of the HIPS production but at higher HBCD concentrations.

After the molten mass at the end of the extruder is pressed through a plate with holes (die/plate), different granulation processes take place, for example:

- face cutting in air; a rotating knife directly after the plate cut the extruded “strands” into pellets cooled by air.
- under water face cutting; a rotating knife directly after the plate in a water bath cuts the extruded strands in pellets cooled by water.
- strand cutting; the molten strands are passed through a water bath to solidify and cool and are cut in a granulator

After the granulation process the HIPS pellets are dried and packed, either in bulk silos/containers or 25 kg bags, ready for conversion into HIPS products. The HBCD masterbatch process normally uses the strand-cutting route.

Industrial use of HIPS-compound

HIPS materials can be converted into HIPS products using various extrusion techniques and injection moulding. HIPS products can also be manufactured via a compounding route, i.e. mixing virgin HIPS raw material with a HBCD masterbatch during the extrusion or injection moulding process.

Professional and private use of HIPS

Most of the flame retarded HIPS products are used in electrical and electronic appliances. HBCD in HIPS has been used in e.g.:

- audio visual equipment cabinets (video and stereo equipment)
- distribution boxes for electrical lines in the construction sector
- refrigerator lining

2.2.4. Textile coatings

Flame retardant systems are used in textile application to comply with flame retardant standards. HBCD was formulated to polymer-based dispersions (e.g. acrylic or latex) of variable viscosity in the polymer industry². The dispersions are then processed in the textile finishing industry. The HBCD particles used for textile back-coating needed to be very small. Therefore micronising was performed before the formulation step.

¹ According to the provisions of the Convention, HBCD is no longer in use in this application.

² According to the provisions of the Convention, HBCD is no longer in use in this application.

Formulation of polymer dispersion for textiles

Textile formulators prepare flame retarded formulations, which are water-based dispersions and can contain a binder system and HBCD as well as up to 20 other ingredients. These flame retarded formulations, mostly custom tailored, are supplied as dispersion to back-coaters. In this scenario, formulation is carried out in an open batch system. HBCD was added to a dispersion containing water, a polymer e.g. synthetic latex, acrylates or PVC, thickener and dispersion agent. The chemical preparation can also contain other brominated flame-retardants such as decabromodiphenyl ether. In addition, synergists such as antimony trioxide and antimony pentoxide could also be included in the end-product. According to industry information, the concentration of HBCD in the dispersion may range from 5 to 48 %. However, additional product information indicates that a likely concentration of HBCD in the coated layer may be about 25 % corresponding to 10 - 15 % in the final dilution of the dispersion. Water and solvents will leave the preparation when dried and concentrations of flame-retardants in the coating layer will be higher than in the preparation. Preparations with the highest concentration of HBCD are assumed to be diluted before use.

The water based dispersion used by the backcoaters; both paste as well as foam, need to be stable (no precipitation and no viscosity change) and should not contain particles to prevent clogging the system. This is why the particle size of the solids is so important. Too fine particles act as thickener, where too coarse material will lead to a non-stable dispersion (precipitation) and to an applied coated film with a non-acceptable rough surface.

Industrial use of textile back-coating agent

Applying a back-coating to textile can be carried out in the following ways:

- as paste where a layer is “glued” to the textile and a scratch knife defines the final thickness depending on the flame retardant standard, the textile used and the flame retardant concentration in the dispersion or
- as foam, where a foam layer is pressed on the textile through a rotating screen. Once applied the foam cells will break resulting in a thin coating film.

The coating is dried and fixated in an oven at temperatures between 140 till 180 °C. The formulated product is used on technical textile and furniture fabric, on cotton fabrics and cotton polyester blends. HBCD was usually applied with antimony trioxide as a backcoating in a mass ratio of 2,1 (i.e. about 6-15 % HBCD and 4-10 % antimony oxide by weight) (National Research Council, 2000).

Professional and private use of textiles with back-coating containing HBCD

The textiles with the back-coating containing HBCD can be used for e.g. flat and pile upholstered furniture (residential and commercial furniture), upholstery seating in transportation, draperies, and wall coverings, bed mattress ticking, interior textiles e.g. roller blinds, automobile interior textiles and car cushions.

3. Sources of releases

3.1. Production sites

The main part of HBCD is emitted from industrial point sources according to the EU risk assessment (European Commission 2008). Potential emissions to the environment can occur at all stages of the production process: transport and storage, opening and emptying of packaging, and the disposal of that packaging at the end of the production process. Efficient pollution prevention techniques at industrial sites producing and/or using HBCD should be implemented. Based on the physical-chemical properties of HBCD, a reduction of emissions to air and waste water at industrial sites can be expected to be achieved by enhancing the capacity of the pollution prevention systems already in place and/or improving their effectiveness.

The best available pollution abatement and prevention techniques are described for polymer industry and textiles industry by European Commission (2003 and 2007) in the "Reference Documents on Best Available Techniques" (BREFs). In the BREF for polymer industry, brominated flame retardants are mentioned separately, whereas in the BREF for textiles industry, they are not but belong to the "non biodegradable" substances. It is noted, that both BREFs do not cover downstream industrial uses, such as the use of EPS and XPS containing HBCD at construction sites.

According to Norden (2007), the releases from industrial sites to municipal wastewater treatment systems are in a model treatment plant trapped to sludge at a rate of ca. 80% of initial mass, whereas the remaining part is released with effluent. Even in treatment plants having optimal anaerobic degradation conditions, the removal by degradation would remain below 30% of the initial load and emission to aquatic environment would be ca 7% of the initial load. Measures enhancing the removal rate of particulate matter at treatment plants would lead to the increased trapping of HBCD to sludge (see the Voluntary Emissions Control Action Programme; recommendations for the disposal of sludge: <http://www.vecap.info/>). In order to reduce the overall release to the environment, anaerobic fermentation and/or incineration of sludge as an ultimate measure would be needed.

3.2. Accumulation of HBCD – stockpiling

HBCD has been on the world market since the 1960s. The wider use of HBCD in insulation boards started in the 1980s (European Commission 2008). The amount of HBCD in the society is accumulating, forming a stockpile, since the service life of HBCD-containing end-products are estimated to be generally longer than 1 year. They vary between 1 year and more than 50 years and in some cases more than 100 years.

Life expectancy of plastics

Applications	Service Life (years)
Building and construction	>50 for PS foams
Electronic	0 to 5
Electrical	10 to 20
Furniture	5 to 10
House wares	0 to 5
Packaging	2

Data from OECD (2004), the Fraunhofer Information Center for Planning and Building (2014), and BBSR (2011)

3.3. Import and export of articles containing HBCD

HBCD is often transported, including trans-border shipments, as powder/granules or pellets, as masterbatches of EPS beads and HIPS pellets downstream in the production chain for the conversion into end-products for further professional use or sales to consumers. Data on import and export of HBCD is currently limited as Parties to the Convention are expected to report this information in their fourth national reports to be submitted in 2018. Prior to the listing of HBCD in Annex A to the Convention, several country-specific imports of HBCD as a pure compound or in products have been reported in the 2010 Risk profile on HBCD developed by the POPs Review Committee: Canada (100-1,000 tonnes), Australia (<100 tonnes), Poland (500 tonnes), Romania (185 tonnes) (UNEP/POPS/POPRC.6/13/Add.2).

EPS and XPS for the construction industry are not likely to be transported over long distances due to the bulkiness of the material. Furthermore, the extrusion and expansion processes are relatively straightforward industrial processes, which allow them to be carried out in the region where the products are needed. Transport of compounded polystyrene (PS) with HBCD (granules, masterbatches or beads) over longer distances cannot be excluded, but information is lacking (European Commission 2008).

Packaging material containing HBCD (e.g. EPS) to protect sensitive equipment is likely to be shipped worldwide. High impact polystyrene (HIPS) containing HBCD is likely to be imported in certain countries in electrical and electronic equipment. Textile that is back-coated with an HBCD containing layer is likewise likely to be imported (European Commission 2008).

3.4. Losses of HBCD from end-products

The polymers are various kinds of polystyrene (EPS, XPS, HIPS), latex, acrylics etc. HBCD is added to the polymer matrix, it is not chemically bound, and does not seem to be degraded in the matrix. The concentration in the polymer varies between 0.7 (EPS) and 25 % (textile backcoating).

The release of HBCD from end-products will depend on chemical and physical processes. Physical processes determining loss of HBCD from the polymer matrix are (1) migration of HBCD in the polymer, (2) the loss of HBCD from the surface and (3) emission of particles lost at processing of the material or because of weathering and abrasion. The migration rate depends on the diffusion rate (concentration and mobility) and the solubility of the substance in the polymer. The loss from the surface will depend on the volatility and/or physical conditions e.g. temperature and the solubility of HBCD in a contacting media (PlasticsEurope, Exiba (Cefic) and Efra, 2016).

For quantitative estimation of the release from an end-product, the relative surface area of the product will have to be taken into account.

The rate-limiting step of the release of HBCD from end-products could be the migration rate in the polymer or the rate of loss from the surface depending on parameters such as:

- concentration of HBCD in the polymer
- nature of the polymer
- nature of the surrounding media

The surrounding media are air (most uses), water (outdoor uses e.g. inverted roofs flushed by precipitation) and soil (buried construction material).

In a study by Li et al. (2016), modeling results are given for the long-term emissions of HBCD in China. For the period 2000-2100 they show that the bulk of HBCD will enter pedosphere (59%), followed by atmosphere (25%) and hydrosphere (16%). The greatest share of soil emissions comes from the uncontrolled backfill or open dumping of construction and demolition waste. The uncontrolled disposal of construction and demolition waste is a practice in most parts of China and in other developing regions.

In another study by Håøya and Haagensen (2011) the following was concluded with respect to the HBCD content of EPS and soil samples taken from bridge sites where EPS blocks were used as fill material in “super lightweight” bridge embankments in Norway:

- The content of HBCD in the EPS blocks was at a level as expected based on product information;
- The content of HBCD in soil below the EPS blocks was below the limit of detection (0,2 mg/kg dry mass);
- The risk of exposure for humans and the environment to HBCD from the EPS blocks is considered low.

3.5. Disposal and material recovery

Waste containing HBCD is generated at each life cycle step. In some cases the waste material, so called pre-consumer waste, could be recycled into the process. Wasted end-products (post-consumer waste) are incinerated, put on landfill, recycled or eventually left in the environment.

According to the Stockholm Convention provisions, the recycling of articles/products containing HBCD above the low POP limit is not exempted. However, this may happen in case of countries which are not Parties to the Convention or have not ratified the HBCD amendment (UNEP 2015a). In the EU, the recycling of articles containing HBCD is allowed provided that that the concentrations in the final product are below 100 mg/kg.

In the European packaging sector, EPS does not usually contain HBCD, and is either incinerated or recycled. In other countries, however, packaging, mainly from electrical and electronic equipment, may contain HBCD. If some of the packaging in the country contains HBCD then it could be separated before recycling. Technologies for separation could be XRF screening (similar to the approach described for WEEE plastic in the UNEP 2015b). XRF analysis is limited to the detection solely of bromine in products, without

any capability to identify the type of BFR compound. For identification of HBCD in PS foams see Schlummer et al. (2015). At this time, incineration is therefore the most eco-efficient methodology to fully destroy HBCD in PS foams used in buildings (Mark et al. 2015).

The industry has developed processes which may recycle EPS into polystyrene and achieve bromine recovery whilst destroying HBCD³. In the example of HBCD containing polystyrene foam, such processes allow the recovery of approximately >99.5% of the used flame-retardant additive⁴. It has to be noted that these processes available for commercial use, but currently not yet implemented on an industrial scale⁵.

UNEP (2015a) lists the following sources of releases of and exposure to HBCD and its by-products to the environment in the life cycle:

Source	Released media	Waste types	Contaminants
1. HBCD Manufacture			
1.1. Production process	Solid waste, off-gas, waste water	Dusts, products residues, wastewater treatment sludge, waste products, discarded waste filter cloth, wastes from filtration	HBCD
1.2. Products and packaging process	Solid waste (Dust) particles	Waste products, packaging wastes	HBCD
2. HBCD use (Process)			
2.1. Building materials production	Waste gas, waste water and solid waste	Dust, production residue, wastewater sludge, waste products, packaging wastes	HBCD
2.2. Furniture manufacturing	Waste gas, waste water and solid waste	Dust, production residue, wastewater sludge, waste products and packaging wastes	HBCD
2.3. Textile production	Waste gas, waste water and solid waste	Dust, production residue, wastewater sludge, waste products and packaging wastes clothing	HBCD
2.4. Production of High Impact Polystyrene (HIPS)	Waste gas, waste water and solid waste	Dust, waste residue and sludge, waste products and packaging wastes	HBCD
3. Consumer Use			
3.1. Leaching and evaporation from products	Waste gas, waste water and solid waste	Dust/particles, waste residue	HBCD
3.2. Fires	Waste gas, waste water and solid waste	Waste residues, contaminated soil, hot spot	HBCD and PBDD/PBDF
4. Waste recycling and disposal			
4.1. Building material waste recycling	solid waste	HBCD containing EPS and XPS; wastes from recycling or from separation of HBCD from polymer	HBCD and other chemicals
4.2. Waste plastic recycling	solid waste	Waste HIPS, and other plastics Electrical and electronic plastic shells, circuit boards, wire and polyurethane foams which will not be recycled after dismantling	HBCD and other chemicals
4.3. Incineration	Exhaust, Solid Waste, Wastewater	Solid residues(ash, flue gas cleaning residues); Exhaust gas	HBCD and PBDD/PBDF*
4.4. Landfill	Solid waste and Leachate; air releases (fires)	Leachates; fumes from open burning	HBCD and other chemicals; PBDD/PBDF

³ <http://www.eumeps.construction/show.php?ID=5001&psid=sokmcvspm19d1e5nk4m4uv1em0>

⁴ <http://www.creacycle.de/en/the-process.html>; http://www.synbra.com/en/39/187/raw_materials.aspx

⁵ <http://www.creacycle.de/en/projects/recycling-of-expanded-poly-styrene-eps/polystyrene-loop-2016.html>; www.epc.com

* The quality of incineration determines the levels of PBDD/PBDF with low levels in state of art incinerators (Mark et al. 2015; Weber and Kuch 2003).

4. Alternatives to the use of HBCD for the specific exemptions under the Stockholm Convention

Alternative flame retardants as well as alternatives to EPS and XPS are available. These are mineral insulation materials, which do not need flame retardant and rigid polyurethane foam, for which alternative flame retardants are available. A mechanical alternative for HBCD would be an encasing of EPS or XPS into fireproof casings, but this solution could be used only in a limited amount of applications (UNEP 2015a).

For the use of HBCD in textiles, alternative chemicals are commercially available. These are: reactive phosphorous constituents, ammonium polyphosphates and diammonium phosphate. For HBCD used in high impact polystyrene (HIPS), chemical alternatives are available. The most common alternatives are other brominated flame retardants in connection with antimony trioxide. A non-brominated alternative is for some uses a combination of copolymer of HIPS together with polyphenylene oxide (PPO) and a flame retardant. As flame retardant, triphenylphosphate can be applied in HIPS-PPO (UNEP 2015a).

4.1. Flame retardant substitution

4.1.1. EPS and XPS alternatives

Butadiene-styrene brominated copolymer

A butadiene-styrene brominated copolymer, currently named as BLUEEDGE™ Polymeric FR™ trademark of the Dow Chemical Company, is currently commercially available (available under the following commercial names: Emerald Innovation 3000, FR-122P and GreenCrest). It has been designed to provide flame retardant properties at low loadings to polystyrene foam to meet industry fire norms such as ignition resistance (Beach 2013). Based on DfE Analysis of Alternative criteria and guidance, the hazard profile of the butadiene-styrene brominated copolymer (CASRN 1195978-93-8) shows that this chemical is anticipated to be safer than HBCD for multiple endpoints. Due to its large size, lack of low molecular weight (MW) components, and un-reactive functional groups, human health and ecotoxicity hazard for this polymer are measured or predicted to be low, although experimental data were not available for all endpoints. In general the exposure potential to the butadiene-styrene brominated copolymer is expected to be lower than the other chemicals in this assessment because it is a large polymer and is unlikely to be released from the polystyrene. The hazard designations for this alternative are based upon high MW formulations of the polymer, where all components have a MW >1,000. For butadiene-styrene brominated copolymer, the MW is around 100,000 daltons.⁶ This product is replacing HBCD.

⁶ For more information, see:

Dow Global Technologies: Press Release 15 April 2014: <http://building.dow.com/media/news/2014/20140415a.htm>

BASF: Press Release 25 November 2014: <https://www.basf.com/documents/corp/en/news-and-media/news-releases/2014/11/P407e-flame-retardant.pdf>

ICL-IP: FR-122P Press Release February 2016: <http://www.globes.co.il/en/article-icl-albemarle-agree-flame-retardant-supply-cooperation-1001106014>

Chemtura: Emerald Innovation 3000 Press Release April 2013:

<http://www.businesswire.com/news/home/20130422006889/en/Great-Lakes-Solutions-Sees-Continued-Success-Flame>

Comments to ECHA public consultation on alternatives to HBCDD

<http://echa.europa.eu/addressing-chemicals-of-concern/authorisation/applications-for-authorisation/comments-public-consultation-0013-01>

UNEP POP-RC Webinar on “Alternatives to HBCD – state of play” Recording and presentations from producers and users of alternatives to HBCD

<http://chm.pops.int/Implementation/TechnicalAssistance/Webinars/tabid/1529/Default.aspx?overlayId=ArtId-11407>

Non-flame retarded EPS and XPS in combination with thermal barriers (e.g. concrete)

Non-flame retarded EPS and XPS insulation foams in combination with other construction materials are used in some countries to protect the EPS and XPS from catching fire. For example, in Sweden and Norway, national regulations allow the use of non-flame retarded insulation materials, provided the total building element meets fire safety requirements. In these countries, EPS in combination with thermal barriers (non-combustible materials with high heat thermal capacity such as concrete) are used as alternatives to flame retarded EPS and XPS. Use of EPS in combination with thermal barriers reduces the need for flame retarded EPS without compromising fire safety performance in constructions (KLIF 2011). In the U.S. and Canada and most of Europe, where it appears that there are material requirements for insulation materials, EPS and XPS in building applications would most likely contain flame retardants (Blomqvist 2010).

4.1.2. HIPS alternatives

HIPS alternatives include: resorcinol bis (biphenyl phosphate), bisphenol A bis (biphenyl phosphate), diphenylcresylphosphate, triphenylphosphate and alloys of PPE/HIPS treated with halogen-free flame retardant alternatives. Specific information is not available to describe the performance of resorcinol bis (biphenyl phosphate), bisphenol A bis (biphenyl phosphate) and diphenylcresyl phosphate in HIPS. Nonetheless, in view of the fact that HBCD is not widely used in HIPS and these alternatives were preliminary identified to be technically feasible, it is possible that these substances are being used and that their performance attributes are similar to that of HBCD (Maag et al. 2010). And with respect to PPE/HIPS, major European manufactures of television sets appear to be using alloys including PPE/HIPS with non-halogenated flame retardant. This is an indication that alloys of PPE/HIPS with non-halogenated flame retardant also perform to required industry standards. Alloys of PPE/HIPS are known to have relatively higher inherent resistance to burning and spreading fire because they form an insulating char foam surface when heated. They also have higher impact strength and give similar design opportunities for parts with fine structural details. In addition, alloys of PPE/HIPS require fewer changes to the expensive molds and tooling used in the molding process (Maag et al. 2010).

4.1.3. Textile back coating alternatives

Intumescent systems have successfully shown their potential. Several intumescent systems for textile applications have been on the market for about 20 years (Posner et al. 2010). They are based on the formation of expanded coal tar, which partly acts as an insulating barrier against heat and as a smoke-fume trap. Intumescent systems for textile back coating require special handling in application to ensure that the systems work as intended. It is important that the best conditions and combinations of the 3 different components of the systems are in an evenly and well distributed dispersion in the textile application for the desired flame protection to be achieved (Posner 2004).

4.2. 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 the major insulation materials apart from the EPS/XPS are mineral wool, fibre glass wool and polyurethane rigid foams, but a number of other insulation materials are used to some extent.

Non-flame retarded EPS boards are used in some countries in combination with other construction materials which protect the EPS from catching fire. A widely applied construction is as ground or floor insulation below a concrete layer, but also walls and other more open constructions may be made with regular EPS boards which are not flame retarded if thermal barriers are applied.

4.2.1. 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.

After the furnace, droplets of the vitreous melt are spun into fibres. Droplets fall onto rapidly rotating flywheels or the mixture is drawn through tiny holes in rapidly rotating spinners which shapes it into fibres. Small quantities of binding agents are added to the fibres for adhesion. 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.

4.2.2. 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.

The raw materials are melted in a furnace at very high temperatures, typically 1300 to 1500 °C. In insulation fibre glass borates act as a powerful flux in the melt as it lowers glass batch melting temperatures (Floyd et al., 2008). After the furnace, droplets of the vitreous melt fall onto rapidly rotating flywheels or the mixture is drawn through tiny holes in rapidly rotating spinners which shapes it into fibres for adhesion. Small quantities of binding agents are added to the fibres. Glass wool products usually contain 95% to 96% inorganic material (Eurima 2011).

4.2.3. Phenolic foams

Phenolic foam insulation is made by combining phenol-formaldehyde resin with a foaming agent. When hardener is added to the mix and rapidly stirred, the exothermic reaction of the resin, in combination with the action of the foaming agent, causes foaming of the resin. This is followed by rapid setting of the foamed material (Greenspec 2011). 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. Compared to the EPS/XPS and PUR/PIR, the market share of the phenolic foams seems to be small due to higher prices.

4.2.4. 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.

4.2.5. Other natural fibre-based insulation materials

As mentioned, a number of the other natural fibre-based insulation materials have been considered as alternatives to flame retarded EPS, but not further assessed due to limitations of the study.

4.3. Specialty and Emerging Alternative Materials

The insulation materials presented in this section may be functional alternatives to EPS and XPS, but are not considered to be currently viable for large scale building applications, and so are constrained to specialty applications or limited geographic areas. This information is intended to provide context in case changes in manufacturing processes or economies of scale allow these products to become viable in the future. A range of insulation products exist to cover the various characteristics for different applications. Specific insulation products are generally not suitable for all applications.

Aerogel is available as a rigid board, roll, or loose-fill; and is used to insulate underfloors, rainscreens, roofing, cathedral ceilings, and interior walls (Madonik 2011). It is made from silica gel, polyethylene terephthalate (PET), fiberglass, and magnesium hydroxide (COWI 2011). Aerogel is lightweight and has a very high R-value of 10, but is costly.

Carbon foam is a type of rigid board foam made from calcined coke. It is manufactured in limited quantities and is used primarily as a specialty insulation in the aeronautic, marine, and energy industries (Madonik 2011).

Foamglas is a rigid board insulation made from sand, limestone, and soda ash that is primarily used for high-temperature industrial applications where extreme heat resistance is required but can be used to as insulation in roofs, walls, and below-grade.

Phenolic foam is a type of rigid foam and foamed-in-place insulation that may be used in roofing, wall cavities, external walls, and floors (COWI 2011). Currently, only foamed-in place phenolic insulation is available in the U.S (U.S. Department of Energy 2011). Rigid phenolic foams are no longer produced in the U.S. after corrosive breakdown products caused construction issues in the early 1990s, although they may be imported from Europe and Asia (Smith et al. 1993; Schroer et al. 2012).

Reflective insulation is a foil-faced insulation material that incorporates a radiant barrier (normally highly reflective aluminum) with a kraft paper, plastic film, polyethylene bubble, or cardboard backing (U.S. Department of Energy 2012). Reflective insulation is used to reduce radiant heat flow across an open space, most usefully for downward radiant heat flow, and is typically used between roof rafters, floor joists (or reflective insulation), and wall studs (U.S. Department of Energy 2008). The rest of the insulations described here are designed to reduce thermal heat conduction through solid surfaces in any direction. For this reason, reflective insulation is not an alternative for EPS and XPS, but rather works best in complement with other forms of insulation.

Agrifiber insulation is manufactured from agricultural waste (e.g., rice hulls, fungal mycelia, wheat or rice straw) and is available as board insulation (Healthy Building Network 2011; Wilson 2011). Agrifiber typically uses borate as a flame retardant (Sustainable Sources 2011). New agrifiber insulations under development using mycelium as a binder are reported to have obtained a Class 1 fire rating without use of added chemical flame retardants (Wilson 2011). Agrifiber insulation has an R-value ranging from 3.0 to 3.5 and is not water resistant; it is currently available only in limited SIPs applications (Healthy Building Network 2011; Madonik 2011).

5. Techniques to consider in the determination of BAT for production and use of HBCD

This chapter sets out techniques considered generally to have potential for achieving a high level of environmental protection in the industries within the scope of this document. Management systems, process-integrated techniques and end-of-pipe measures are included, but a certain amount of overlap exists between these three when seeking the optimum results. Prevention, control, minimization and recycling procedures are considered as well as the re-use of materials and energy (European Commission 2007).

5.1. Generic techniques

The BREF for the polymer industry considers that in general for each polymer installation, the combination of the generic BAT together with the polymer type specific BAT (i.e. for polystyrene - EPS and XPS) represents a starting point for the process of determining appropriate local techniques and conditions. The practical aim is the local optimization in the circumstances of the installation and other local factors.

5.1.1. Environmental management tools

The best environmental performance (BEP) is usually achieved by the installation of the best technology and its operation in the most effective and efficient manner. 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.

An environmental management system (EMS) can contain the following components:

- Definition of an environmental policy for installation by top management (its commitment is regarded as a precondition for a successful application of other features of the EMS).
- Planning and establishing of the necessary procedures.
- Implementation of the procedures, paying particular attention to:
 - Structure and responsibility;
 - Training, awareness and competence;
 - Communication;
 - Employee involvement;
 - Documentation;
 - Efficient process control;
 - Maintenance programme;
 - Emergency preparedness and response;
 - Safeguarding compliance with environmental legislation.
- Checking of performance and taking of corrective action, paying particular attention to:
 - Monitoring and measurement;
 - Corrective and preventive action;
 - Maintenance of records.
- Perform independent (where feasible) internal auditing to determine whether or not the EMS conforms to planned arrangements and has been properly implemented and maintained.

Four additional features are considered as supporting measures:

- Examination and validation of the management system and audit procedure by an accredited certification body or an external EMS verifier.
- Preparation and publication (and possibly external validation) of a regular environmental statement describing all the significant environmental aspects of the installation, allowing for year-by-year comparison against environmental objectives and targets as well as with sector benchmarks as appropriate.
- Consideration of applicable industry-specific standards, when available.
- Implementation and adherence to an internationally accepted EMS.

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.

5.1.2. Equipment design

The process vessels are equipped with vents to prevent pressure build up by inert gases. These vents are also used to de-pressurize and flush equipment during emergencies and prior to maintenance. Usually, vents are connected to air pollution control equipment, except major relief vents which, due to large flows, would overload the treatment system.

To prevent leaks from relief vents, rupture disks can be used in combination with safety valves, possibly with a previous 'safety risk analysis'. The pressure between the rupture disc and the safety valve is monitored to detect any leaks. If the safety valves are connected to an incinerator, rupture disks may not be necessary.

Technical provisions to prevent and minimize fugitive emissions of air pollutants include:

- use of valves with bellow or double packing seals or equally efficient equipment. Bellow valves are especially recommended for highly toxic services;
- magnetically driven or canned pumps, or pumps with double seals and a liquid barrier;
- magnetically driven or canned compressors, or compressors using double seals and a liquid barrier;
- magnetically driven or canned agitators, or agitators with double seals and a liquid barrier;
- minimization of the number of flanges (connectors) ;

- effective gaskets;
- closed sampling systems;
- drainage of contaminated effluents in closed systems;
- collection of vents.

5.1.3. Fugitive loss assessment and measurement

A good fugitive loss measurement and repair programme requires an accurate calculation of components and the establishment of a database. In the database, components are classified in terms of type, service and process conditions to identify those elements with the highest potential for fugitive losses and to facilitate the application of industry standard leak factors.

Experience has shown that an estimate derived by applying these standard factors can lead to an overestimation of overall fugitive emissions from the plant. A more accurate estimate is obtained if accessible components are screened by an established technique (e.g. USEPA 21), which identifies sources as 'leak', or 'no leak' according to a given threshold level. The percentage of leaking versus non-leaking components is applied to improve the overall validity of the fugitive loss estimates.

Accurate results can also be obtained when specific correlations are applied which have been developed from a set of comparable plants.

5.1.4. Equipment monitoring and maintenance

The established component and service database provides the basis for a routine monitoring and maintenance (M&M) programme or leak detection and repair (LDAR) programme. Components leak rates are checked on a regular basis using an organic vapor analyzer. Leaking components are identified for repair and future monitoring. Over time, it is possible to build up a picture of priority areas and persistent critical components enabling effective targeting of maintenance work and/or improvement in design.

5.1.5. Reduction of dust emissions

Air used for pneumatically conveying pellets and operating pellet de-dusting units contains dust and floss particles. Generally, the density of the polymer influences dust and floss formation, and a higher polymer density will lead to more dust formation, while a lower polymer density will increase the susceptibility for floss formation. Dust is potentially emitted, while floss ends up in the product or is collected as waste polymer. The following techniques and good operating practices to reduce dust emission are to be considered in the determination of BAT:

- dense conveying is more efficient to prevent dust emissions than dilute phase conveying, although upgrading to the dense phase conveying is not always possible due to design pressure constraints;
- reduction of velocities in dilute phase conveying systems to as low as possible;
- reduction of dust generation in conveying lines through surface treatment and proper alignment of pipes;
- use of cyclones and/or filters in the air exhausts of dedusting units. The use of fabric filter systems is more effective, especially for fine dust;
- use of wet scrubbers.

5.1.6. Minimization of plant stops and start-ups

Through improved operation stability (assisted by computer monitoring and control systems) and equipment reliability, the need for plant stops and start-ups is reduced to a minimum. Emergency stops can be avoided by timely identification of deviating conditions followed by the application of a controlled shut down process.

5.1.7. Containment systems

Emissions occurring during plant start ups, shut downs and emergency stops are sent to a containment system to avoid their emission to the environment. The contained material, which can be unreacted

monomers, solvents, polymers, etc. are recycled if possible or used as fuel, e.g. in the case of polymers of undefined quality.

5.1.8. Water pollution prevention

Process effluent and drainage or sewerage systems within the plant are made from corrosion resistant materials and designed to prevent leaks to reduce the risk of loss from underground pipelines. To facilitate inspection and repair, effluent water collection systems at new plants and retrofitted systems are either:

- pipes and pumps placed above ground;
- pipes placed in ducts accessible for inspection and repair;
- measures for water pollution prevention 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.

5.1.9. Waste water treatment

Various techniques exist to treat waste water: biotreatment, denitrification, dephosphatation, sedimentation, flotation, etc. Depending on the waste water effluent and its composition, and the plant operation, the most appropriate techniques are selected to treat the waste water.

The main part of the WWTP is usually the aerobic biological activated sludge process. Around this central facility a complex of preparatory and subsequent separation operations is grouped. The facility may be a dedicated plant on the site of the polymer installation, a central facility in the site containing the polymer installation, or an external urban WWTP connected by dedicated pipeline or a sewer with little risk of storm overflow prior to the WWTP. The central wastewater plant is normally equipped with:

- buffer or equalization volumes, if not already provided by other upstream facilities;
- mixing station, where neutralization and flocculation chemicals are added and mixed (usually lime milk and/or mineral acids, ferrous sulphate); enclosed or covered if necessary to prevent releases of odorous substances, the captured exhaust air ducted to an abatement system;
- primary clarifier, where the floc is removed; enclosed or covered if necessary to prevent fugitive releases of odorous substances, the captured exhaust air ducted to an abatement system;
- activated sludge part, e.g.
 - aeration basin with nutrient feed at the entry, enclosed or covered if necessary with exhaust air ducts to an abatement system;
 - or closed reaction tank (e.g. tower biology) with gas duct, connected to a gas-abatement system;
 - nitri/denitrification stage (optionally) and phosphate elimination.
- optional intermediate clarifier, when a second aerobic biological stage is operated, with sludge recycling optional second activated sludge part, for low load biology;
- final clarifier with sludge recycling and transfer to sludge treatment; alternative sand filter, MF or UF equipment;
- optionally further special treatment facilities to eliminate the rest of remaining COD, e.g. UV treatment or stripping columns;
- optionally further treatment facilities after the final clarifier, e.g. air flotation;
- optionally sludge treatment facilities, such as:
 - digesters;
 - sludge thickeners;
 - sludge dewaterers;
 - sludge incinerators.
- and/or other equivalent waste water treatment technologies.

5.2. Specific techniques

Additionally to the generic BAT (previous section), for the production of polystyrene, the following BAT are to be taken into account (European Commission 2007).

5.2.1. Minimization and control of emissions from storage

BAT is to use one or more of the following techniques:

- minimization of level variation;
- gas balance lines;
- floating roofs (large tanks only) ;
- installed condensers;
- vent recovery to treatment.

5.2.2. Recovery of all purge streams and reactor vents

Purge streams are used as fuel oils or treated with thermal oxidizers which can be used for heat recovery and steam production.

5.2.3. Collection and treatment of exhaust air from pelletising

Usually, the air sucked off the pelletising section is treated together with reactor vents and purge streams (GPPS and HIPS processes).

5.2.4. Emission reduction from the dissolving system in HIPS processes

BAT is to use one or more of the following or equivalent techniques:

- cyclones to separate conveying air;
- high concentration pumping systems;
- continuous dissolving systems;
- vapor balance lines;
- vent recovery to further treatment;
- condensers.

5.2.5. Emission reduction from EPS process-specific techniques

BAT is to use one or more of the following or equivalent techniques:

- vapor balance lines;
- condensers;
- vent recovery to further treatment.

European Commission (2007) lists the following EPS process-specific techniques:

Emissions	Available techniques	Cost	Efficiency
Gas			
Storage	Minimize level variation	L	M
	Gas balance lines	M	M
	Floating roofs	H	H
	Condensers installed	H	H
	Vent recovery to treatment	H	H
Preparation of organic reactor charges	Vapor balance lines	L	H
	Vent recovery to external treatment (regenerative thermal oxidizer)	M	H
Pentane emission after polymerization	Adsorption/desorption systems/flare	H	H
Liquid			
Purge	Recovered to be used with fuel oil or incinerated	M	H
Wastewater	Biological treatment*	L	H
Solid waste**			
Hazardous and non-	Minimize the volume by good segregation	L	M

hazardous waste	Collect to external treatment	M	H
Management techniques		M	H

*existing treatment plant

**only insignificant quantities

L: Low; M: Medium; H: High

5.3. Industry voluntary measures

Industry has implemented a voluntary emission control programme, VECAP (<http://www.vecap.info>) which is run under the principles of Responsible Care[®]. VECAP was established in 2004 by the three main producers of flame retardants, together with the UK Textile Finishers association. It ensures the environmentally responsible management of chemicals in all elements of the value chain, by reducing the potential for emissions of chemicals during the production and manufacturing process. The VECAP annual reports demonstrate a continuous decrease of potential emissions of HBCD to the environment (VECAP 2014).

In the past, the voluntary emission control and reduction programme on HBCD was formerly known as SECURE (Self Enforced Control of Use to Reduce Emissions); it is now taken up under VECAP and is subscribed to by HBCD producers and the EPS bead/XPS foam manufacturers.

6. Considerations for identification

According to part VII of Annex A to the Stockholm Convention, Parties having registered for the exemption for the production and use of HBCD for EPS and XPS in buildings shall take necessary measures to ensure that EPS and XPS containing HBCD can be easily identified by labeling or other means throughout its life cycle. The guidance on labeling of products or articles that contain POPs (UNEP 2012) provides Parties with some considerations on this matter.

7. Considerations for the environmentally sound management of wastes containing HBCD

Once buildings containing EPS/XPS insulation are demolished or articles containing HBCD treated textiles (e.g. vehicles, furniture), as well as plastic materials from electronics and others are discarded, they become wastes. Due to the long service-life of products where HBCD has mainly been used, when not managed in an environmentally sound manner, wastes may lead to a potentially increasing release of HBCD to the environment.

Wastes containing HBCD include production wastes, insulation boards, building and renovation wastes, and wastes from other applications such as WEEE plastics, textiles and transport vehicles. Insulation boards represent the majority of HBCD containing waste in particular for those countries using insulation for houses. The life span of polystyrene insulation foam in buildings is reported to be >50 years (OECD, 2004; the Fraunhofer Information Center for Planning and Building, 2014; BBSR, 2011) and could exceed 100 years. The use of HBCD in insulation boards has been increasing since the 1980s and it is likely that releases from EPS/XPS waste materials will be more significant in the future; particularly from about 2025 onwards, as increasing number of buildings containing HBCD will be refurbished or demolished (UNEP/POPS/POPRC.6/13/Add.2). Most of this material might go to landfill or incineration (Li et al. 2016; UBA 2015).

The knowledge of end-of-life pathways is essential to the better understanding of target wastes identification and for appropriate environmentally sound management (ESM) of these wastes. Technical guidelines for the environmentally sound management of wastes consisting of, containing or contaminated with hexabromocyclododecane have been developed in the frame of the Basel Convention (UNEP 2015d). Article 6, paragraph 2 of the Stockholm Convention sets the basis for close cooperation with the Basel Convention on common issues of relevance such as POPs wastes listed in Annexes I and VIII

of the Basel Convention. Relevant guidance is also available under the Stockholm Convention to assist parties in their actions for the environmentally sound management of wastes containing HBCD (the PBDE BAT/BEP guidance (UNEP 2015b) can be used as a supplemental reference).

Recovery of EPS / XPS

According to the Stockholm Convention’s provisions, the recycling of articles/products containing HBCD above the low POP limit is not exempted. Only EPS and XPS which contains HBCD below the low POP limit can be recycled. UNEP (2015a) notes that recycling beyond the Convention’s provisions may happen in countries which are not Parties to the Convention or have not ratified the HBCD amendment.

One option to recycle the polymer might be the separation of HBCD from the polymer by applying dissolution as a pre-treatment technique – separating HBCD from plastic, followed by the destruction of HBCD by pyrolysis with recovery of bromine.

The industry has developed processes which may recycle EPS into polystyrene and achieve bromine recovery whilst destroying HBCD⁷. In the example of HBCD containing polystyrene foam, such processes allow the recovery of approximately >99.5% of the used flame-retardant additive⁸. It has to be noted that these processes are available for commercial use, but currently not yet implemented on an industrial scale⁹.

Construction and deconstruction

Solid waste containing HBCD generated at construction and deconstruction sites may be scrap materials generated during processing or shredding operations with related particulate releases. Due to the presence of regulated blowing agents, shredding should be done under controlled conditions. Particles might be also released through aging and wear of end products, and the disposal of products at the end of their service life.

In deconstruction, there is a need for separation of HBCD containing materials. Technologies for the related identification could be XRF screening (similar to the approach described for WEEE plastic in the UNEP 2015b). To be noted that XRF analysis is limited to the detection solely of bromine in products, without any capability to identify the type of BFR compound. For the identification of HBCD in EPS see Schlummer et al. (2015) (see also section 3.5 above).

Thermal destruction

Releases of HBCD and by-products such as polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/PBDF) are low for state-of-art incinerators, however they might be high for other incinerators and open burning (Mark et al. 2015; Takigami et al. 2014; Weber and Kuch 2003). See the guidance provided in UNEP (2015b,c,d).

Landfilling

For landfilling of wastes containing or contaminated with HBCD, refer to Chapter 8 in UNEP 2015b.

8. Contaminated sites

In accordance with the provisions of Article 6(1)(e), Parties shall endeavour to develop appropriate strategies for identifying sites contaminated by chemicals listed in Annex A, B or C. UNEP (2015a) provides a list of potential HBCD-contaminated sites or hot spots as indicated in the table below:

Life cycle stage; Sector	Activities	Locations
HBCD production	(Former) Production	Production site

⁷ <http://www.eumeps.construction/show.php?ID=5001&psid=sokmcvspm19d1e5nk4m4uv1em0>

⁸ <http://www.creacycle.de/en/the-process.html>; http://www.synbra.com/en/39/187/raw_materials.aspx

⁹ <http://www.creacycle.de/en/projects/recycling-of-expanded-poly-styrene-eps/polystyrene-loop-2016.html>; www.epc.com

	(Former) Destruction of production waste	Sites where production waste has been destroyed
	Disposal of waste from production	Landfills related to waste from production
	Former water discharge	River sediment and banks related to releases from production site
Sites where EPS and XPS have been used in production	EPS/XPS industry (formerly) using HBCD	Site of production; Landfill site of related wastes; Impacted surface waters (sediment and flood plains)
	Textile industry and other industries (formerly) using HBCD	Site of production; Landfill site of related wastes; Impacted surface waters (sediment and flood plains)
	Factories micronising HBCD	Site of production; Landfill site of related wastes; Impacted surface waters (sediment and flood plains)
Use of HBCD	Sites where EPS and XPS is used	Soil impacted from buildings/city ¹⁰
	Accidental fire in building	Soil/environment around fire accidents with HBCD XPS/EPS
End-of-life treatment	Recycling area of HBCD containing materials	Recycling areas and landfills with deposited wastes
	Deposition of HBCD-containing waste	Landfill and surrounding from leachate from HBCD- containing wastes
	Open burning or non-BAT incineration of HBCD-containing waste ¹¹	Related sites and sites were residues/ashes are disposed
	Application sites of HBCD impacted sewage sludge	Agriculture land

Guidance for POPs-contaminated site investigation and management was developed by the United Nations Industrial Development Organization (UNIDO) Expert Group on POPs and is available on the Stockholm Convention website (see UNIDO 2010). The UNIDO Toolkit for POPs-contaminated site investigation and management includes information specific to the POPs initially listed in the Stockholm Convention, but also contains generic guidance elements for the development of suitable technologies for land remediation in accordance with BAT and BEP.

9. References

Albemarle Corporation. (2000). Saytex 9006L Flame Retardant. Baton Rouge. Louisiana: Albemarle Corporation. 2 pp.

Albemarle Corporation. (2005). Albemarle to raise prices of SAYTEX, ANTIBLAZE flame retardant for construction materials and furnishings. May 17, 2005.
<http://investors.albemarle.com/phoenix.zhtml?c=117031&p=irol-newsArticle&ID=710907&highlight=>

BBSR. (2011). Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem Nachhaltiges Bauen (BNB). 3 March 2011

¹⁰ The comparison of HBCD in soils in UK cities compared to rural environment revealed higher levels in cities with some peak concentration in city soil (Harrad et al. 2010). See also Li et al. (2016) and Håøya and Haagensen (2011) referred to in section 3.4.

¹¹ The combustion of HBCD-containing waste in state of art incinerators does not lead to relevant releases of HBCD or PBDD/F (Mark et al. 2015; Weber et al. 2003).

- The Fraunhofer Information Center for Planning and Building. (2014). "Rückbau, Recycling und Wiederverwertung von WDVS". April 2014.
http://www.irbnet.de/daten/baufo/20148036054/F_2932_WDVS_Recycling_Langbericht.pdf
- Li et al. (2016). Long-term emissions of hexabromocyclododecane as a chemical of concern in products in China. *Environment International* 91 (2016) 291–300.
- Maag J, Brandt UK, Mikkelsen SH, Lassen C. (2010). Inclusion of HBCDD, DEHP, BBP, DBP and additive use of TBBPA in annex IV of the Commission's recast proposal of the RoHS Directive. Danish Environmental Protection.
- Madonik A. (2011). Should Green Buildings Contain Fire Retardants? Design for the Environment Kick-Off Meeting, Crystal City, VA.
- Mark FE, Vehlow J, Dresch H, Dima B, Grüttner W, Horn J. (2015). Destruction of the flame retardant hexabromocyclododecane in a full-scale municipal solid waste incinerator. *Waste Management & Research* 33, 165–174.
- National Research Council. (2000). Toxicological risks of selected flame-retardant chemicals. National Academy Press.
- Nordic Council of Ministers Norden (2007). Hexabromocyclododecane as a possible global POP, Copenhagen 2007. TemaNord 2008:520
- OECD. (2004). Emission Scenario Document on Plastics Additives. OECD Series on Emission Scenario Documents No. 3. 2004
- PlasticsEurope, Exiba (Cefic), and Efra. (2016). HBCD in Polystyrene Foams Product Safety Assessment. <http://www.basel.int/Implementation/POPsWastes/AdditionalResources/tabid/4740/Default.aspx>
- Posner S. (2004). Survey and technical assessment of alternatives to decabromodiphenyl ether (decaBDE) in textile applications. Kemi Nr 5/04.
- Posner S, Roos S, Olsson E. (2010). Exploration of management options for HBCDD. Swerea Report 10/11. http://www.unece.org/fileadmin/DAM/env/lrtap/TaskForce/popsxg/2010/Updated%20documentns_June2010/Exploration%20of%20management%20options%20for%20HBCD.pdf
- Rani M, Shim WJ, Han GM, Jang M, Song YK, Hong SH. (2014). Hexabromocyclododecane in polystyrene based consumer products: an evidence of unregulated use. *Chemosphere*. 110, 111-119.
- Remberger M, Sternbeck J, Palm A, Kaj L, Strömberg K, Brorström-Lundén E. (2004). The environmental occurrence of hexabromocyclododecane in Sweden. *Chemosphere* 54, 9-21.
- Schlummer et al. (2015): Rapid Identification of HBCD in PS foams in *Waste Management & Research*. doi:10.1177/0734242X15589783
- Schroer D, Hudack M et al. (2012). Rigid Polymeric Foam Boardstock Technical Assessment.
- Smith TL, Carlson JD et al. (1993). Steel Deck Corrosion Associated with Phenolic Roof Insulation: Problem Causes, Prevention, Damage Assessment and Corrective Action. 10th Conference on Roofing Technology. Gaithersburg, MD.
- Smock D. (2011). The Molding Blog: BASF Supports New Polymeric Flame Retardant, posted on April 5, 2011. <http://www.themoldingblog.com/?p=173>
- Sustainable Sources. (2011). "Insulation." Retrieved June 8, 2011, from <http://insulation.sustainable-sources.com/>
- Swedish Chemicals Agency (Kemi). (2005). Survey and Technical Assessment of Alternatives to Decabromodiphenyl Ether (decaBDE) in Plastics. http://www.kemi.se/Documents/Publikationer/Trycksaker/Rapporter/Rapport1_05.pdf

Swedish Chemicals Agency (KEMI) (2006). Survey and Technical Assessment of Alternatives to TBBPA and HBCDD.1/2006. https://www.kemi.se/Documents/Publikationer/Trycksaker/PM/PM1_06.pdf

Takigami H, Watanabe M, Kajiwara N. (2014). Destruction behavior of hexabromocyclododecanes during incineration of solid waste containing expanded and extruded polystyrene insulation foams. *Chemosphere* 116, 24–33.

UBA. (2015). 'Identification of potentially POP-containing Wastes and Recyclates – Derivation of Limit Values.

https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_35_2015_identification_of_potentially_pop-containing_wastes.pdf

UNEP/POPS/POPRC.6/13/Add.2 Risk profile on hexabromocyclododecane.

<http://chm.pops.int/TheConvention/POPsReviewCommittee/Meetings/POPRC6/POPRC6ReportandDecisions/tabid/1312/Default.aspx>

UNEP/POPS/POPRC.7/19/Add.1 Hexabromocyclododecane Risk Management

Evaluation. <http://chm.pops.int/Convention/POPsReviewCommittee/POPRCMeetings/POPRC7/POPRC7ReportandDecisions/tabid/2472/Default.aspx>

UNEP/POPS/POPRC.8/16/Add.3 Addendum to the risk management evaluation on

hexabromocyclododecane. <http://chm.pops.int/Convention/POPsReviewCommittee/LatestMeeting/POPRC8/POPRC8ReportandDecisions/tabid/2950/Default.aspx>

UNEP. (2012). Guidance on labeling of products or articles that contain POPs. Secretariat of the Stockholm Convention. <http://chm.pops.int/Implementation/NIPs/Guidance/Labelingofproductsorarticles/tabid/3174/Default.aspx>

UNEP. (2015a). Guidance for the inventory, identification and substitution of Hexabromocyclododecane (HBCD). Draft, April 2015. Secretariat of the Stockholm Convention.

<http://chm.pops.int/Implementation/NIPs/Guidance/tabid/2882/Default.aspx>

UNEP. (2015b). Guidance on best available techniques and best environmental practices for the recycling and disposal of articles containing polybrominated diphenyl ethers (PBDEs) listed under the Stockholm Convention on Persistent Organic Pollutants. Secretariat of the Stockholm Convention.

UNEP/POPS/COP.7/INF/22.

<http://chm.pops.int/Implementation/NIPs/Guidance/GuidanceonBATBEPfortherecyclingofPBDEs/tabid/3172/Default.aspx>

UNEP. (2015c). General technical guidelines on the environmentally sound management of wastes of wastes consisting of, containing or contaminated with persistent organic pollutants. Secretariat of the Basel Convention. UNEP/CHW.12/5/Add.2/Rev.1.

<http://www.basel.int/Implementation/POPsWastes/TechnicalGuidelines/tabid/5052/Default.aspx>

UNEP. (2015d). Technical guidelines for the environmentally sound management of wastes consisting of, containing or contaminated with hexabromocyclododecane. Secretariat of the Basel Convention.

UNEP/CHW.12/5/Add.7/Rev.1.

<http://www.basel.int/Implementation/POPsWastes/TechnicalGuidelines/tabid/5052/Default.aspx>

UNIDO. (2010). Persistent Organic Pollutants: Contaminated Site Investigation and Management Toolkit.

<http://chm.pops.int/Implementation/BATandBEP/AdditionalResources/tabid/1493/Default.aspx>

U.S. Department of Energy. (2008). Insulation Fact Sheet.

U.S. Department of Energy. (2011). Types of Insulation. Retrieved June 9, 2011, from

http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm?mytopic=11510

VECAP. (2014). European Progress Report 2014 https://issuu.com/burson-marsteller-emea/docs/vecap_2015_bro_light

Weber R, Kuch B. (2003). Relevance of BFRs and thermal conditions on the formation pathways of brominated and brominated-chlorinated dibenzodioxins and dibenzofurans. *Environment International* 29, 699-710.

Wilson A. (2011). Greensulate – A fungus-based insulation material that's grown rather than manufactured. <http://greenspec.buildinggreen.com/blogs/greensulate-fungus-based-insulation-material-thats-grown-rather-manufactured>