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Office of Chemical Safety and
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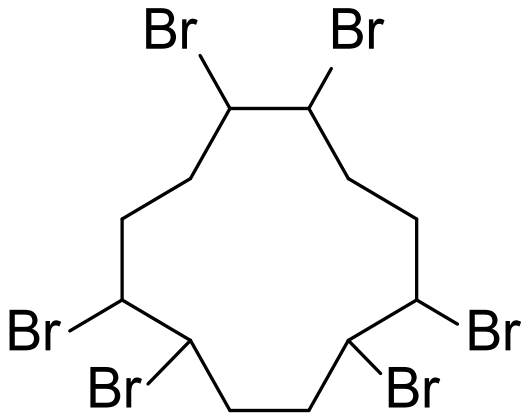
United States
Environmental Protection Agency

Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD)



CASRN	NAME
25637-99-4	Hexabromocyclododecane
3194-55-6	1,2,5,6,9,10-Hexabromocyclododecane
3194-57-8	1,2,5,6-Tetrabromocyclooctane

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Docket
Supporting information can be found in public docket: EPA-HQ-OPPT-2016-0735.

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ABBREVIATIONS

°C	Degrees Celsius
7Q10	lowest expected weekly flow over a ten-year period
atm	Atmosphere(s)
AAD	Acute Absorbed Dose
ACC	American Chemistry Council
ADC	Average Daily Concentration
ADME	Absorption, Distribution, Metabolism, and Excretion
ADR	Acute Dose Rate
AERMOD	AMS (American Meteorological Society)/EPA Regulatory Model
AF	Assessment Factor
AIC	Akaike Information Criterion
AIHA	American Industrial Hygiene Association
ALT	Atlanine Aminotransferase
APF	Assigned Protection Factors
ATSDR	Agency for Toxic Substances and Disease Registry
AUC	Area Under the Curve
BAF	Bioaccumulation Factor
BCF	Bioconcentration Factor
BDE209	3,3',4,4',5,5',6,6'-decabromodiphenyl ether
bdwt	Body Weight
BLS	Bureau of Labor Statistics
BMD	Benchmark Dose Modeling
BMDL	Lower Confidence limit on the BMD
BMR	Benchmark Response
$BW^{3/4}$	Body Weight Scaling to the ¾ Power
C&D	Construction and Demolition
CAA	Clean Air Act
CAD	Chronic Absorbed Dose
CASRN	Chemical Abstracts Service Registry Number
CBI	Confidential Business Information
CCL	Candidate Contaminant List
CDR	Chemical Data Reporting
CDT	1,5,9-cyclodecatriene
CEPA	The Center for European Policy Agency
CFR	Code of Federal Regulations
CHAD	Consolidated Human Activity Database
COC	Concentration of Concern
COU	Condition of Use
CPSC	Consumer Product Safety Commission
CSCL	Chemical Substance Control Law
CT	Central Tendency
DAF	Domestic Adjustment Factor

DBCD	9,10-dibromocyclododeca-1,5-diene
DEE	Data Extraction and Evaluation
DMF	dimethylformamide
DMSO	dimethyl sulfoxide
dwt	Dry weight
Dwt	Dry weight
EASE	Estimation and Assessment of Substance Exposure
EC	European Commission
EC50	Median Effective Concentration
ECB	European Chemicals bureau
ECHA	European Chemicals Agency
EC/HC	Environment Canada / Health Canada
ECOTOX	ECOTOXicology knowledgebase
E-FAST	Exposure and Fate Assessment Screening Tool
EINECS	European Inventory of Existing Commercial Substances
EPCRA	Emergency Planning and Community Right-to-Know Act
EPS	Expanded Polystyrene
EPS-IA	Expanded Polystyrene Industry Alliance
ER	Extra Risk
ESD	Emission Scenario Document
EU	European Union
EURAR	European Union Risk Assessment Report
FR	Federal Register
g	Gram(s)
GI tract	Gastrointestinal tract
GM	Geometric Mean
GS	Generic Scenario
GSH	Glutathione
GST	Glutathione-S-transferase
HAP	Hazardous Air Pollutant
HBCD/HBCDD	Hexabromocyclododecane
HED	Human Equivalent Dose
HERO	Health and Environmental Research Online
HE	High-End
HIPS	High Impact Polystyrene
HPLC	High Performance Liquid Chromatography
HQ	Headquarters
hr	Hour
IECCU	Indoor Environmental Concentrations in Buildings with Conditioned and Unconditioned Zones
IIOAC	Integrated Indoor-Outdoor Air Calculator
Ind	Industrial
KABAM	KOW(based) Aquatic BioAccumulation Model
KLH	Keyhole limpet Hemocyanin
kg	Kilogram(s)

Koa	Octanol:Air Partition Coefficient
L	Liter(s)
lb	Pound
LADC	Lifetime Average Daily Concentration
LCD	Liquid-Crystal Display
LC/MS	Liquid Chromatography-Mass Spectrometry
LOQ	Level of Quantitation
LOAEL	Lowest Observed Adverse Effect Level
LOEC	Lowest Observed Effect Concentration
Log Koc	Logarithmic Organic Carbon:Water Partition Coefficient
Log Kow	Logarithmic Octanol:Water Partition Coefficient
LPO	Lipid Peroxidation
m^3	Cubic Meter(s)
MATC	Maximum Acceptable Toxicant Concentration
MFG	Manufacture
MLD	Million Liters per Day
mmHg	Millimeter(s) of Mercury
MOA	Mode of Action
MOE	Margin of Exposure
MOEJ	Ministry of Environment Government in Japan
MSW	Municipal Solid Waste
MSWLF	Municipal Solid Waste Landfills
MT	Metric Tons
N/A	Not Applicable
NAICS	North American Industry Classification System
ND	No Data
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
NIOSH	National Institute of Occupational Safety and Health
NITE	National Institute of Technology and Evaluation
NOAEL	No observable Adverse Effect Level
NOEC	No Observed Effect Concentration
NR	Not Report
NRC	National Research Council
OARS	Occupational Alliance for Risk Science
OECD	Organisation for Economic Co-operation and Development
OEL	Occupational Exposure Limits
OES	Occupational Employment Statistics
ONU	Occupational Non-User
OPPT	Office of Pollution Prevention and Toxics
OSHA	Occupational Safety and Health Administration
P	Persistence
P&CB	Public and Commercial Buildings
PAPR	Power Air-Purifying Respirator
PBDE	Polybrominated Diphenyl Ether

PBPK/PD	Physiologically Based Pharmacokinetic / pharmacodynamic
PBZ	Personal Breathing Zone
PDM	Probabilistic Dilution Model
PEC	Predicted Environmental Concentration
PECO	Populations, Exposures, Comparators
PESO	Pathways and Processes, Exposure, setting or Scenario, and Outcomes
PESS	Potentially Exposed or Susceptible Subpopulations
PM	Particular Matter
PND	Post-Natal Day
PNOR	Particles Not Otherwise Regulated
POD	Point of Departure
POPs	Stockholm Convention on Persistent Organic Pollutant
POTW	Publicly Owned Treatment Works
ppm	Part(s) per Million
PQL	Practical Quantitation Limit
PTF	Post Fertilization
PV	Production Volume
QC	Quality Control
RAR	Risk Assessment Report
RCRA	Resource Conservation and Recovery Act
RD	Relative Deviation
REACH	European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals
RESO	Receptors, Exposures, Comparators, and Outcomes
ROS	Reactive Oxygen Species
SAR	Supplied-Air Respirator
SCBA	Self-Contained Breathing Apparatus
SCCH	Stockholm Convention Cleaning House
SD	Standard Deviation
SHGB	Sex Hormone Binding Globulin
SIAP	Screening Information Dataset Initial Assessment Profile
SIC	Standard Information Panels
SIDS	Screening Information dataset
SIPS	Structural Insulated Panels
site-yr	site-year
SNUN	Significant New Use Notice
SNUR	Significant New Use Rule
SOC	Standard Occupational Classification
SOD	Superoxide dismutase
SPF	Spray polyurethane foam
SUSB	Statistics of US Businesses
SVHC	Substance of Very High Concern
SWC	Surface Water Concentration
T	Toxicity
TBCD	5,6,9,10-tetrabromocyclododec-1-ene

TGD	Technical Guidance Document
TLV	Threshold Limit Value
TOC	Total Organic Carbon
TRI	Toxics Release Inventory
TSCA	Toxic Substances Control Act
TSH	Thyroid Stimulating Hormone
TURA	Toxics Use Reduction Act
TWA	Time-Weighted Average
UF	Uncertainty Factor
U.S.	United States
UNEP	United Nations Environment Programme
vB	very Bioaccumulative
VVWM-PSC	Variable Volume Water Model - Point Source Calculator
WEEE	Waste Electrical and Electronic Equipment
WEEL	Workplace Environmental Exposure Level
WSDE	Washington State Department of Ecology
WWT/WWTP	Wastewater Treatment Plant
XPS	Extruded Polystyrene (i.e., Extruded Polystyrene foam)
XPSA	Extruded Polystyrene Association
yr	year

EXECUTIVE SUMMARY

This draft risk evaluation for hexabromocyclododecane (HBCD) was performed under the auspices of the Frank R. Lautenberg Chemical Safety for the 21st Century Act and disseminated for public comment and peer review. The Frank R. Lautenberg Chemical Safety for the 21st Century Act amended the Toxic Substances Control Act, the Nation's primary chemicals management law, on June 22, 2016. As per EPA's final rule, *Procedures for Chemical Risk Evaluation Under the Amended Toxic Substances Control Act* (82 FR 33726), EPA is taking comment on, and will also obtain peer review on, this draft risk evaluation for HBCD. All conclusions, findings, and determinations in this document are subject to comment.

The Agency published the *Scope of the Risk Evaluation for HBCD* (U.S. EPA, 2017d) in June 2017, and the *Problem Formulation for Cyclic Aliphatic Bromide Cluster (HBCD)* in June 2018 (U.S. EPA, 2018f), which represented the analytical phase of risk evaluation in which "the purpose for the assessment is articulated, the problem is defined, and a plan for analyzing and characterizing risk is determined" as described in Section 2.2 of the *Framework for Human Health Risk Assessment to Inform Decision Making*. The EPA received comments on the published problem formulation for HBCD and has considered the comments specific to HBCD, as well as more general comments regarding the EPA's chemical risk evaluation approach for developing the draft risk evaluations for the first 10 chemicals the EPA is evaluating.

TSCA § 26(h) requires EPA to use scientific information, technical procedures, measures, methods, protocols, methodologies and models consistent with the best available science and base its decisions on the weight of the scientific evidence.). To meet the TSCA § 26(h) science standards, EPA used the TSCA systematic review process described in the *Application of Systematic Review for TSCA Risk Evaluations* document (U.S. EPA, 2018b). The process complements the risk evaluation process in that the data collection, data evaluation and data integration stages of the systematic review process are used to develop the exposure, fate and hazard assessments.

The cyclic aliphatic bromide cluster chemicals, including HBCD (Chemical Abstracts Service Registry Number [CASRN] 25637-99-4), 1,2,5,6,9,10-hexabromocyclododecane (1,2,5,6,9,10-HBCD; CASRN 3194-55-6 are flame retardants. Uses for 1,2,5,6-tetrabromocyclooctane have not been identified. For the purposes of this draft risk evaluation document, the use of "HBCD" refers to this cluster of chemicals. The primary use of HBCD is as a flame retardant in expanded polystyrene and extruded polystyrene; however EPA identified other uses including use as a component of solder and use in automobile replacement parts.

The manufacturing, importation, and use of HBCD has rapidly declined in the U.S. and globally over the past ten years due to international regulation and the availability of substitutes. Annual production volumes were consistently 10-50 million lbs. from 2007 to 2011. From 2012 to 2015, production fell to 1-10 million lbs./year (Chemical Data Reporting (CDR)). Additional communications with industry representatives indicate that, as of 2018, domestic manufacture of HBCD has ceased. Use of stockpiles and exportation from the United States was completed at the end of 2017 and is further discussed in Section 1.2.2 of this draft risk evaluation. Under the Stockholm Convention, 171 of the 188 Parties (countries) have agreed to ban the production, use, import, and export of HBCD, consistent with the obligations of that Convention (SCCH, 2018a, b). The United States is not a signatory to the Convention.

EPA believes that manufacturing by large manufacturers is no longer ongoing based on communication with industry and it is assumed that for small manufacturers, it would be cost prohibitive to produce HBCD in small quantities. Although HBCD is no longer manufactured in the U.S., it is still possible to import HBCD. Based on one third party source (Datamyne), HBCD was imported in 2016 and 2017, however, no import volume was reported for 2018. The 2016 CDR data only includes data through 2015 and therefore the more recent import volumes reported through Datamyne have not yet been reported to CDR. Importation of HBCD in small quantities of under 100,000 lbs. (CDR threshold for small businesses) is possible. Historically, the main use of HBCD was in EPS and XPS in construction insulation boards. According to EPS and XPS associations, the major processors of EPS and XPS have stopped using HBCD. It is possible, however, that smaller processors may still be using the chemical, although evidence of this has not been found and EPA has not received information that this is occuring. For these reasons, EPA concludes that the import of HBCD and processing of HBCD for use in EPS and XPS insulation is possible and therefore included in the scope of this risk evaluation.

EPA has also included in this draft risk evaluation the processing of HBCD to manufacture automobile replacement parts and solder paste. The determination for automobile replacement parts and solder paste are supported by data that became available since publication of the Problem Formulation in 2018. In November 2018, an automotive industry association provided a list of 155 automobile replacement parts that contain HBCD and are actively produced. The processing of solder paste is based on newly available 2017 TRI data, which shows production-related waste management quantities of HBCD (i.e. from recyling, energy recovery, treatment, disposal, and releases) totaling less than 800 pounds from four reporting facilities. Two of the facilities are manufacturers that stopped producing HBCD by 2018. A third facility stopped using HBCD for manufacture of coatings in 2018, and one continued to process HBCD in 2018 for the manufacture of solder paste.

EPA included the recycling of HBCD-containing EPS and XPS insulation boards in this risk evaluation. HBCD was broadly used in EPS and XPS insulation boards, historically, and the recycling of EPS and XPS construction material was found to occur. While environmental exposures are expected to decline as importing and processing of the chemical are phased out, based on past production volumes (millions of pounds per year) and that cessation of domestic manufacturing is recent, reductions in environmental and biological concentrations will likely occur gradually over a period of time for this persistent and bioaccumulative compound. The time scales for this are dependent on the age of the products, their useful service lives and time lines for replacement.

In the problem formulation, EPA identified the conditions of use and presented conceptual models and an analysis plan for this draft risk evaluation. The conditions of use evaluated for HBCD, as further described in Section 1.4.1 of the draft risk evaluation for HBCD, include:

- Importation of HBCD
- Processing of flame retardants: use in custom compounding of resin and solder paste
- Processing of flame retardants: use in manufacture of XPS and EPS foam; use in manufacture of structural insulated panels; use in automobile replacement parts from XPS and EPS foam
- Processing: recycling of XPS and EPS foam, resin, panels containing HBCD; plastic articles
- Distribution: activities related to distribution
- Building and construction materials
- Automobile replacement parts
- Disposal

In this draft risk evaluation, EPA quantitatively evaluated the risk to the environment and health for the conditions of use described in Section 1.4.1 of this draft risk evaluation using both modeling and monitoring approaches. EPA evaluated risk to workers and occupational non-users (ONUs are workers who do not directly handle HBCD but perform work in an area where HBCD is present) from inhalation and dermal exposures by comparing the estimated occupational exposures to acute and chronic human health hazards. EPA also evaluated the risk to consumer, general and highly exposed populations from inhalation, dermal and oral exposures, including exposures to consumer articles and mouthing of recycled articles by children. Lifestages from infants to adults were included in the draft evaluation, by comparing the estimated exposures to acute and chronic human health hazards. In addition, EPA quantitatively evaluated risk to aquatic vertebrates, invertebrates, and aquatic plants from exposure to surface water and sediment; and risk to terrestrial species from exposure to soils.

HBCD is present and persistent in various environmental media such as surface water, sediment, soil and air. EPA quantitatively evaluated inhalation, ingestion and dermal exposures to the general population; potentially exposed or susceptible populations via exposure to indoor and ambient air; dermal contact with soil and dust and oral exposures via ingestion of food, breast milk, soil, dust and fish.

While environmental exposures are expected to decline as importing and processing of the chemical are being phased out, based on past production volumes (millions of pounds per year) and that cessation of domestic manufacturing is recent, reductions in environmental and biological concentrations will likely occur gradually over a period of time for this persistent and bioaccumulative compound. The time scales for this are dependent on the age of the products, their useful service lives and time lines for replacement.

Approach

EPA used reasonably available information, defined as information that EPA possesses, or can reasonably obtain and synthesize for use in risk evaluations, considering the deadlines for completing the evaluation, in a fit for purpose approach, to develop risk evaluations that rely on the best available science and are based on the weight of scientific evidence. EPA used previous analyses as a starting point for identifying key and supporting studies to inform the fate, exposure, and hazard assessments. EPA evaluated other studies that were published since these reviews. EPA reviewed the information and evaluated the quality of the methods and reporting of results of the individual studies using the evaluation strategies described in *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a).

EPA utilized environmental fate parameters, physical-chemical properties, monitoring data and modeling approaches to assess ambient water exposure to aquatic organisms, sediments and soil exposure to terrestrial species. The exposure and environmental hazard analyses for the environmental release pathways for ambient water exposure to aquatic organisms, sediments, and soils was conducted based on a quantitative assessment predicted environmental concentrations in the environment. A quantitative comparison of exposures (see Section 2.3.2 to 2.3.6) and hazards (see Section 3.1) for aquatic and terrestrial organisms.

In the human hazard section, EPA evaluated reasonably available information and identified hazard endpoints including acute/chronic toxicity, non-cancer effects, associated with inhalation, oral and dermal exposures. EPA used an approach based on the Framework for Human Health Risk Assessment to Inform Decision Making (U.S. EPA, 2014e) to evaluate, extract and integrate HBCD's human health

hazard and dose-response information. EPA reviewed key and supporting information from previous hazard assessments as well as the existing body of knowledge on HBCD's human health hazards. These data sources[1] included the TRI Technical Review of HBCD (U.S. EPA, 2016c), the *TSCA Work Plan Problem Formulation and Initial Assessment*, (U.S. EPA, 2015), *Preliminary Materials for the IRIS Toxicological Review of HBCD* (U.S. EPA, 2014f) as well as other publications (U.S. EPA, 2016c, 2014d; NICNAS, 2012a; EC/HC, 2011; EINECS, 2008; U.S. EPA, 2008a; OECD, 2007b). Additional scientific support from the EPA's Office of Research and Development subsequent to the listed publications also contributed to the human health hazard assessment.

The EPA considered adverse effects for HBCD across organ systems. EPA considered data on toxicity following acute and chronic exposures, for irritation, sensitization, genotoxicity, reproductive, developmental and other systemic toxicity and carcinogenicity. From these effects, the EPA selected endpoints supported by the evidence for non-cancer that were amenable to quantitative analysis for dose-response assessment as discussed in more detail in Section 3.2.5. Based on the weight of the evidence evaluation, four health effect domains were selected for non-cancer dose-response analysis: (1) thyroid; (2) liver; (3) female reproductive; and (4) developmental. These hazards were carried forward for dose-response analysis. Given the different HBCD exposure scenarios considered (both acute and chronic), different endpoints were used based on the expected exposure durations.

Potentially Exposed Susceptible Subpopulations

TSCA § 6(b)(4) requires that EPA conduct a risk evaluation to "*determine whether a chemical substance presents an unreasonable risk of injury to health or the environment, without consideration of cost or other non-risk factors, including an unreasonable risk to a potentially exposed or susceptible subpopulation identified as relevant to the risk evaluation by the Administrator, under the conditions of use*." TSCA § 3(12) states that "*the term 'potentially exposed or susceptible subpopulation' means a group of individuals within the general population identified by the Administrator who, due to either greater susceptibility or greater exposure, may be at greater risk than the general population of adverse health effects from exposure to a chemical substance or mixture, such as infants, children, pregnant women, workers, or the elderly*."

In developing the draft risk evaluation, the EPA analyzed the reasonably available information to ascertain whether some human receptor groups may have greater exposure than the general population to the hazard posed by a chemical. The results of the available human health data for all routes of exposure evaluated (i.e., oral, dermal and inhalation) indicate that there is no evidence of increased susceptibility for any single group relative to the general population. Exposures of HBCD would be expected to be higher amongst workers and occupational non-users (ONUs) using HBCD as compared to the general population. Exposures of HBCD would be expected to be higher amongst individuals exposed to scenario-specific exposures, from releases to water, air, and consumer articles as compared to the general population. In particular, exposures resulting from ingestion of fish consumption are expected to be the largest contributor to overall dose given the persistent and bioaccumulative properties of HBCD.

Risk Determination

In each risk evaluation under TSCA section 6(b), EPA determines whether a chemical substance presents an unreasonable risk of injury to health or the environment, under the conditions of use. In making this determination, EPA considered relevant risk-related factors, including, but not limited to: the effects of the chemical substance on health and human exposure to such substance under the

[1] HBCD does not have an existing EPA IRIS Assessment.

conditions of use (including cancer and non-cancer risks); the effects of the chemical substance on the environment and environmental exposure under the conditions of use; the population exposed (including any potentially exposed or susceptible subpopulations); the severity of hazard (including the nature of the hazard, the irreversibility of the hazard); and uncertainties. EPA considered the confidence in the data used in the risk estimates and whether estimates might be over estimates or underestimates of risk. The rationale for the risk determination is located in 5.2.

Environmental Risks:
There is no evidence that domestic manufacturing or import of HBCD is occurring. With this understanding in mind, EPA relied on available environmental monitoring data to estimate risk to aquatic and sediment-dwelling organisms. The modeling incorporated several assumptions that could overestimate exposures, such as the production volumes for certain conditions of use and the levels of removal assumed prior to release. A key uncertainty related to the use of the monitoring data is that the levels of HBCD found in the environment cannot be attributed to a particular condition of use. However, assuming that the monitored concentration values are attributed to each of the conditions of use individually in this evaluation, the Agency views this as a conservative approach that does not underestimate risk for any particular condition of use. Another uncertainty introduced by using the monitoring data is that the data was collected between 5-10 years ago at a time when the use of HBCD was significantly more widespread and at much higher volumes that is currently the case. For terrestrial mammals, EPA used a model to estimate potential exposure and subsequent risks to mammals via consumption of contaminated aquatic prey. Based on the model, some risk quotients exceeded the Agency's benchmark for a terrestrial mammal, however there are sources of uncertainty in the model that may lead to over estimation of exposure and calculated risk.

Overall while there are some risk estimates higher than Agency benchmarks, EPA determined that HBCD does not present unreasonable risk to the environment under the identified conditions of use.

Workers and Occupational Non-Users (ONUs):
For the conditions of use (Processing: Repacking of Import Containers, Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch, Processing: Manufacturing of XPS Foam using HBCD Powder and Processing: Formulation of Flux/Solder Paste), inhalation and dermal exposure scenarios for workers resulted in calculated MOEs below agency benchmarks. While risk estimates for pathways of occupational exposure for the conditions of use (chronic inhalation exposures and chronic dermal exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered. Quantitative dermal risk estimates that account for the use of gloves were not calculated for HBCD because the substance is in a solid form for this condition of use such that the use of impervious gloves is expected to prevent exposures. Dermal exposures are only expected for solder paste use for this condition of use. EPA expects exposures to ONUs are significantly less than those for workers. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposures to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical.

General Population and Highly Exposed Populations:
For human health, all risk estimates for the most highly exposed groups in the general population are above Agency benchmarks. Therefore, risk is not unreasonable.

EPA concludes that HBCD does not present an unreasonable risk of injury to the environment under all conditions of use within the scope of the risk evaluation. (See Section 1.4.1). EPA makes this determination without considering costs or other non-risk factors.

EPA concludes that HBCD does not present an unreasonable risk of injury to health for workers, occupational non-users, consumers, and the general population by inhalation, oral, or dermal exposure under all conditions of use within the scope of the risk evaluation. (See Section 1.4.1). EPA makes this determination considering risk to potentially exposed or susceptible subpopulations identified as relevant, and without considering costs or other non-risk factors.

1 INTRODUCTION

This document presents for comment the draft risk evaluation for HBCD under the Frank R. Lautenberg Chemical Safety for the 21st Century Act. The Frank R. Lautenberg Chemical Safety for the 21st Century Act amended the Toxic Substances Control Act, the Nation's primary chemicals management law, in June 2016.

The Agency published the *Scope of the Risk Evaluation for HBCD* (U.S. EPA, 2017d) in June 2017, and the *Problem Formulation for Cyclic Aliphatic Bromide Cluster (HBCD)* in June 2018 (U.S. EPA, 2018f), which represented the analytical phase of risk evaluation in which "the purpose for the assessment is articulated, the problem is defined, and a plan for analyzing and characterizing risk is determined" as described in Section 2.2 of the *Framework for Human Health Risk Assessment to Inform Decision Making*.

The problem formulation identified the conditions of use and presented a conceptual model and an analysis plan. Based on EPA's analysis of the conditions of use, physical-chemical and fate properties, environmental releases, and exposure pathways, the problem formulation preliminarily concluded that further analysis was necessary for exposure pathways to ecological receptors, workers, consumers and the general population. The mouthing of articles pathway was added to the conceptual model for the draft risk evaluation. Further analysis was not conducted for the drinking water pathway based on a qualitative assessment of the physical chemical properties and fate of HBCD in the environment.

In this draft risk evaluation, Section 1 presents the basic physical-chemical characteristics of HBCD, as well as a background on regulatory history, conditions of use, and conceptual models, with particular emphasis on any changes since the publication of the problem formulation. This section also includes a discussion of the systematic review process utilized in this draft risk evaluation. Section 2 provides a discussion and analysis of the exposures, both health and environmental, that can be expected based on the conditions of use for HBCD. Section 3 discusses environmental and health hazards of HBCD. Section 4 presents the risk characterization, where EPA integrates and assesses reasonably available information on health and environmental hazards and exposures, as required by TSCA (15 U.S.C 2605(b)(4)(F)). This section also includes a discussion of any uncertainties and how they impact the draft risk evaluation. Section 5 presents EPA's proposed determination of whether the chemical presents and unreasonable risk under the conditions of use, as required under TSCA 15 U.S.C. 2605(b)(4).

As per EPA's final rule, *Procedures for Chemical Risk Evaluation Under the Amended Toxic Substances Control Act* (82 Fed. Reg. 33726 (July 20, 2017)), this draft risk evaluation will be subject to both public comment and peer review, which are distinct but related processes. EPA is providing 60 days for public comment on any and all aspects of this draft risk evaluation, including the submission of any additional information that might be relevant to the science underlying the risk evaluation and the outcome of the systematic review associated with HBCD. This satisfies TSCA section 6(b)(4)(H) which requires the EPA to provide public notice and an opportunity for comment on a draft risk evaluation prior to publishing a final risk evaluation.

Peer review will be conducted in accordance with EPA's regulatory procedures for chemical risk evaluations, including using the *EPA Peer Review Handbook* and other methods consistent with section 26 of TSCA (*See* 40 CFR 702.45). As explained in the Risk Evaluation Rule, the purpose of peer review is for the independent review of the science underlying the risk assessment. Peer review will therefore

address aspects of the underlying science as outlined in the charge to the peer review panel such as hazard assessment, assessment of dose-response, exposure assessment, and risk characterization.

As the EPA explained in the Risk Evaluation Rule (82 Fed. Reg. 33726 (July 20, 2017)), it is important for peer reviewers to consider how the underlying risk evaluation analyses fit together to produce an integrated risk characterization, which forms the basis of an unreasonable risk determination. EPA believes peer reviewers will be most effective in this role if they receive the benefit of public comments on draft risk evaluations prior to peer review. For this reason, a portion of the public comment period will precede peer review on this draft risk evaluation. The final risk evaluation may change in response to public comments received on the draft risk evaluation and/or in response to peer review, which itself may be informed by public comments. EPA will respond to public and peer review comments received on the draft risk evaluation and will explain changes made to the draft risk evaluation for HBCD in response to those comments in the final risk evaluation.

EPA solicited input on the first 10 chemicals as it developed use documents, scope documents, and problem formulations. At each step, the EPA has received information and comments specific to individual chemicals and of a more general nature relating to various aspects of the risk evaluation process, technical issues, and the regulatory and statutory requirements. EPA has considered comments and information received at each step in the process and factored in the information and comments as the Agency deemed appropriate and relevant including comments on the published problem formulation of HBCD. Thus, in addition to any new comments on the draft risk evaluation, the public should re-submit or clearly identify at this point any previously filed comments, modified as appropriate, that are relevant to this risk evaluation and that the submitter feels have not been addressed (see specific instructions and comment on Docket ID Number: EPA-HQ-OPPT-2016-0735). EPA does not intend to further respond to comments submitted prior to the publication of this draft risk evaluation unless they are clearly identified in comments on this draft risk evaluation.

1.1 Physical and Chemical Properties

Physical-chemical properties influence the environmental behavior and the toxic properties of a chemical, thereby informing the potential conditions of use, exposure pathways and routes and hazards that EPA intends to consider. For development of the draft risk evaluation, EPA considered the measured or estimated physical-chemical properties set forth in Table 1-1. EPA found no additional information during the risk evaluation that would change these values.

HBCD is a white odorless non-volatile solid that is used as a flame retardant. Technical HBCD is often characterized as a mixture of mainly three diastereomers, which differ only in the spatial disposition of the atoms. Commercial-grade HBCD may contain some impurities, such as tetrabromocyclododecene or other isomeric HBCDs (UNEP, 2010), which are not included in this risk evaluation. The density of HBCD is greater than that of water (2.24 g/cm^3 at 20°C). It has low water solubility (66 µg/L at 20°C) and a log octanol:water partition coefficient (log K_{ow}) of 5.62.

Table 1-1. Physical and Chemical Properties of HBCD

Property	Value [a]	References
Molecular formula	$C_{12}H_{18}Br_6$	
Molecular weight	641.7 g/mole	
Physical form	White solid; odorless	EINECS (2008)
Melting point	Ranges from approximately: 172-184°C to 201-205°C	EINECS (2008)
Boiling point	>190°C (decomposes)	EINECS (2008)
Density	2.24 g/cm^3	EINECS (2008)
Vapor pressure	4.7E-07 mmHg at 21°C	EINECS (2008)
Vapor density	Not readily available	EINECS (2008)
Water solubility	66 µg/L at 20°C	EINECS (2008)
Octanol:water partition coefficient (log K_{ow})	5.625 at 25°C	EINECS (2008)
Henry's Law constant	7.4E-06 atm-m^3/mole (estimated)	U.S. EPA (2012b)
Flash point	Not readily available	EINECS (2008)
Autoflammability	Decomposes at >190°C	EINECS (2008)
Viscosity	Not readily available	EINECS (2008)
Refractive index	Not readily available	EINECS (2008)
Dielectric constant	Not readily available	EINECS (2008)

[a] Measured unless otherwise noted.

1.2 Uses and Production Volume

1.2.1 Data and Information Sources

The summary of use and production volume information for HBCD presented below is based on research conducted for the *Problem Formulation Document for Cyclic Aliphatic Bromide Cluster (HBCD)* and any additional information that was learned since the publication of that document. The previous research was based on reasonably available information, including the *Use and Market Profile for HBCD,* (EPA-HQ-OPPT-2016-0735-0049), public meetings, and meetings with companies, industry groups, chemical users and other stakeholders to aid in identifying and verifying the conditions of use included in this draft risk evaluation. The information and input received from the public, stakeholder meetings and the additional contacts was incorporated into this section, as applicable.

1.2.2 Domestic Manufacture of HBCD

Domestic manufacture of HBCD had ceased as of 2017 and is not intended, known to occur, or reasonably foreseen, and is therefore not considered a condition of use under which EPA will evaluate HBCD.

A shown in Table 1-2, data reported for the CDR period for 2016 for HBCD indicate that between 1 and 10 million pounds of each CASRN were manufactured in or imported into the United States in 2015; the national production volume is CBI (U.S. EPA, 2016b). These are the most recent CDR data available. The data provides an overview of the historic trends in production volume of HBCD. For both CASRNs, site-specific production volumes for the 2015 reporting year were withheld as TSCA CBI. Six firms comprising nine sites are identified by the 2016 CDR as manufacturers or importers of HBCD: Chemtura Corporation, Albemarle Corporation, Dow Chemical Company, Campine NV, BASF Corporation, and Styropek USA, Inc (U.S. EPA, 2016b). ICL-IP2 previously manufactured an HBCD-containing flame retardant marketed as FR-1206. This product has been discontinued, and ICL-IP has reportedly ceased production of products containing HBCD (Anon, 2015). The 2016 CDR reporting data for HBCD from EPA's CDR database (U.S. EPA, 2016b) are provided in Table 1-2. Because CDR data collection occurs every four years (next reporting period will be in 2020), this information has not changed from that provided in the 2018 HBCD Problem Formulation Document.

Table 1-2. Production Volume (Manufacture and Import) of HBCD in CDR Reporting Period (2012 to 2015)[a]

Reporting Year		2012	2013	2014	2015
Total Aggregate Production Volume (lb)	CASRN 25637-99-4	1-10 million	1-10 million	1-10 million	1-10 million
	CASRN 3194-55-6	10-50 million	10-50 million	1-10 million	1-10 million

[a] The CDR data for the 2016 reporting period is available via ChemView (https://java.epa.gov/chemview) (U.S. EPA, 2016b).

U.S. manufacturers have indicated complete replacement of HBCD in their product lines (U.S. EPA, 2017i) and that depletion of stockpiles and cessation of export was completed in 2017, based on communications with recent manufacturers. Communication with Chemtura (Lanxess Solutions, US) indicates that the company has not manufactured HBCD since 2015, and that there are currently no U.S. manufacturers of the chemical (LANXESS, 2017b). The company does not intend to manufacture, import, or export HBCD in the future and has no existing stockpiles (LANXESS, 2017a). Albemarle Corporation, another historic manufacturer of HBCD, indicated that they stopped manufacturing HBCD flame retardants in 2016 and do not intend to resume the manufacture of HBCD-based flame retardants. In 2017, Albemarle exported its entire inventory of approximately 57 metric tons (MT) of HBCD to Mexico and Turkey for use in construction (EPS/XPS) applications (Albemarle, 2017b). Albemarle does not intend to import HBCD in the future (Albemarle, 2017a).

Communications from industry indicate that domestic manufacture has ceased and the status of import is given in Section 1.2.3. Table 1-3 below presents the various conditions under which a company must report to CDR ("x" indicates reporting required). Typically, a manufacturer is required to report any volume above 25,000 pounds, while small manufacturers[2] are only required to report any volume above 100,000 pounds. Since HBCD is subject to a TSCA Section 5(a)(2) Significant New Use Rule (SNUR),

[2] The definition of a small manufacturer varies depending on the sector.

the threshold has been reduced to 2,500 pounds for large size firms. For small manufacturers, however, the threshold remains at 100,000 pounds. EPA has no indication that small manufacturers are manufacturing HBCD and the cost of manufacturing small quantities would be prohibitive. For these reasons, manufacturing of HBCD is not reasonably foreseen and therefore, not included in the draft risk evaluation.

Table 1-3. Conditions under Which a Company Must Report to CDR (shaded area applies to HBCD reporting specifically and "x" indicates broad conditions requiring reporting.)

	Obligation to Report to CDR Information When Subject to TSCA Action as Indicated in Left column			
TSCA Action	**Subject to 25,000 lb reporting threshold**	**Subject to 2,500 lb reporting threshold**	**Not eligible for certain full or partial exemptions from reporting**	**Not eligible for small manufacturer exemption**
Not subject to TSCA action	X			
TSCA section 4 rules (proposed or promulgated)	X		X	X
Enforceable Consent Agreements (ECAs)	X		X	
TSCA section 5(a)(2) SNURs (proposed or promulgated)		X	X	
TSCA section 5(b)(4) rules (proposed or promulgated)		X	X	X
TSCA section 5(e) orders		X	X	X
TSCA section 5(f) orders		X	X	
TSCA section 5 civil actions		X	X	X
TSCA section 6 rules (proposed or promulgated)		X	X	X
TSCA section 7 civil actions		X	X	X

1.2.3 Importation of HBCD

The companies that previously reported HBCD import volumes to CDR have stated to EPA that they permanently stopped the activity in 2016 or 2017. The Dow Chemical Company imported 19 metric tons (MT) of HBCD in 2016 and roughly 48 MT in 2017. Dow possessed roughly 41 MT of HBCD in stockpiles as of September 2017, which the company then used to produce XPS foam. By November 2017, Dow had stopped using HBCD at all of its plants and had no intention of importing HBCD in the future (Dow Chemical, 2017).

Similarly, Campine NV indicated in a correspondence with EPA that they had ceased importation of HBCD in 2016 (Campine, 2017). BASF has indicated in a correspondence with EPA (BASF, 2017) that the company ceased importing HBCD in 2016 and currently has no stockpiles. Styropek also indicated in its correspondences with EPA that the company phased out HBCD as a flame retardant in 2016.

Datamyne (http://www.datamyne.com) collects import data on shipments into the United States and provides information on each shipment. Datamyne is a commercial searchable trade database that covers the import and export data and global commerce of more than 50 countries across 5 continents (approximately 76% of the world's import trade by value) and includes the cross-border commerce of the United States with over 230 trading partners. EPA queried the database for bills of lading related to HBCD. Due to the nature of Datamyne data, some shipments containing the chemical of concern may be excluded due to being categorized under other names that were not included in the search terms. Datamyne does not include articles/products containing the chemical unless the chemical name is included in the description of the article/product. Datamyne indicates that there was import of HBCD in 2016 and 2017, however, shows no import in 2018 through the month of October when the last run was conducted for this assessment (Datamyne), as shown in Table 1-4.

Table 1-4. U.S. Volume of Imports of HBCD, 2016 through October 2018

Year	Total Import Volume (lb)	Number of Unique Consignees
2016	399,315	5[a]
2017	46,096	1
2018 (through Oct)	0	0

[a] One consignee did not declare their name.
Source(s): Descartes Datamyne (2018)

Although there are a number of possible source countries for importation of HBCD to the United States, under the Stockholm Convention on Persistent Organic Pollutants (POPs), 171 of the 188 Parties (countries) have agreed to ban the production, use, import, and export of HBCD, consistent with the obligations of that Convention (SCCH, 2018a, b). The Convention does include a process by which a party can apply for a time limited exemption to continue production and/or use of a listed chemical, however, that exemption is limited to the specific use(s) identified in the Convention. In accordance with Article 4, specific exemptions expire five years after the date of entry into force of the Convention with respect to that particular chemical, unless an additional five-year extension is granted by the Conference of the Parties (SCCH, 2018b). For HBCD, the specific uses for which a Party can register a production or use exemption is limited to use "in EPS and XPS in buildings." According to the *Register of Specific Exemptions* for the Convention, there are currently three Parties registered for production for those uses and six Parties registered for use. The United States is not a Party to the Convention (SCCH, 2018c).

Given the possibility that small firms could import quantities of up to 100,000 lb of HBCD per year without reporting in the CDR, EPA is including the importation of HBCD as a condition of use in this draft risk evaluation.

1.2.4 Toxics Release Inventory Data on HBCD

After the Problem Formulation was published in 2018, information became available for HBCD as reported by facilities to the Toxics Release Inventory (TRI) program. Under the Emergency Planning and Community Right-to-Know Act (EPCRA) Section 313, HBCD is a TRI-reportable category[3] effective January 1, 2017 and EPA has finalized the addition of the HBCD category to the list of

[3] The HBCD category covers HBCD as identified through two primary Chemical Abstracts Service Registry Numbers (CASRNs): 3194-55-6 (1,2,5,6,9,10-hexabromocyclododecane) and 25637-99-4 (hexabromocyclododecane).

chemicals with special concern (see 40 CFR 372.28(a)(2)) and established a 100-pound reporting threshold.

Four facilities reported HBCD use for the 2017 TRI reporting year; follow-up with the companies indicates that only one facility is involved in ongoing processing of HBCD. Two facilities belong to Dow Chemical, which said it stopped producing HBCD by 2018 (U.S. EPA, 2017c). A third facility, owned by Flame Control Coatings, said in 2018 that it had stopped using HBCD for manufacture of coatings. The fourth facility, Indium Corporation of America, continues to process HBCD for use in the manufacture of solder paste (see more at Section 1.2.4).

Table 1-5 provides production-related waste management data for HBCD reported by industrial facilities in covered sectors to the TRI program from reporting year 2017[4]. In reporting year 2017, four facilities reported a total of approximately 724 pounds of HBCD waste managed. Of this total, zero pounds were recycled, 51 pounds were recovered for energy, 82 pounds were treated, and 591 pounds were disposed of or otherwise released into the environment.

Table 1-5. Summary of HBCD TRI Production-Related Waste Managed in 2017 (lbs)

Number of Facilities	Recycling	Energy Recovery	Treatment	Releases [a,b,c]	Total Production Related Waste
4 [d]	0	51	82	591	724

Data source: 2017 TRI Data (Updated October 2018) U.S. EPA (2017g).
[a] Terminology used in these columns may not match the more detailed data element names used in the TRI public data and analysis access points.
[b] Does not include releases due to one-time events not associated with production such as remedial actions or earthquakes.
[c] Counts all releases including release quantities transferred and release quantities disposed of by a receiving facility reporting to TRI.
[d] Reporting facilities include: The Dow Chemical Company (2 locations), Flame Control Coatings LLC, Indium Corporation of America.

Table 1-6 provides a summary of HBCD TRI releases to the environment for the same reporting year as Table 1-5. There were zero pounds of HBCD reported as released to water via surface water discharges, and a total of 79 pounds of air releases from collective fugitive and stack air emissions reported in 2017. The majority of HBCD was disposed of to landfills other than Resource Conservation and Recovery Act (RCRA) Subtitle C (511 pounds), and there was one pound of HBCD transferred to a waste broker for disposal.

[4] Reporting year 2017 is the first year and most recent TRI data available for HBCD. Data presented in Table 1-5 and Table 1-6 were queried using TRI Explorer and uses the 2017 National Analysis data set (released to the public in October 2018).

Table 1-6. Summary of HBCD TRI Releases to the Environment in 2017 (lbs)

	Number of Facilities	Air Releases		Water Releases	Land Disposal			Other Releases [a]	Total On- and Off-Site Disposal or Other Releases [b, c]
		Stack Air Releases	Fugitive Air Releases		Class I Under-ground Injection	RCRA Subtitle C Landfills	All other Land Disposal [a]		
Subtotal		77	2		0	0	511		
Totals	4 [e]	79 [d]		0	511 [d]			1	591

Data source: 2017 TRI Data (Updated October 2018) U.S. EPA (2017g).
[a] Terminology used in these columns may not match the more detailed data element names used in the TRI public data and analysis access points.
[b] These release quantities do include releases due to one-time events not associated with production such as remedial actions or earthquakes.
[c] Counts release quantities once at final disposition, accounting for transfers to other TRI reporting facilities that ultimately dispose of the chemical waste.
[d] Value shown may be different than the summation of individual data elements due to decimal rounding.
[e] Reporting facilities include: The Dow Chemical Company (2 locations), Flame Control Coatings LLC, Indium Corporation of America.

While production-related waste managed shown in Table 1-5 excludes any quantities reported as catastrophic or one-time releases (TRI section 8 data), release quantities shown in Table 1-6 include both production-related and non-routine quantities (TRI section 5 and 6 data) for 2017. As a result, release quantities may differ slightly and may further reflect differences in TRI calculation methods for reported release range estimates (U.S. EPA, 2017g).

1.2.5 Ongoing Uses of HBCD

Descriptions of the industrial, commercial and consumer use categories identified from the 2016 CDR (U.S. EPA, 2016b) and included in the life cycle diagram are summarized in Section 1.4.1. The descriptions provide a brief overview of uses by life cycle stage in Table 1-8. The descriptions provided below are primarily based on the corresponding industrial function category and/or commercial and consumer product category descriptions from the 2016 CDR and can be found in EPA's Instructions for Reporting 2016 TSCA Chemical Data Reporting (U.S. EPA, 2016a).

1.2.5.1 Automotive Replacement Parts

EPA received a public comment from the Global Automakers Association stating that HBCD is no longer used in new automobile manufacturing and is only present in replacement parts manufactured prior to the date of the EPA HBCD Scoping Document (Public comment, EPA-HQ-OPPT-2016-0735-0027). Major automobile manufacturers have phased out use of HBCD in U.S. automobile and part production but continue to use it in 155 replacement parts, according to a list provided to EPA by the Alliance of Automotive Manufacturers in November 2018 after publication of the Problem Formulation (Alliance of Automobile Manufacturers, 2018b). For approximately 80% of the automobile replacement parts, the HBCD is in polystyrene headliners; most of the remaining 20% are other parts made with HBCD-containing polystyrene or other plastics. A total of five parts have HBCD in solder (Alliance of Automobile Manufacturers, 2018a). The Association was unable to confirm whether the 155 parts are domestically manufactured or imported. EPA is including the use of HBCD in automotive replacement parts in the draft risk evaluation.

1.2.5.2 Expanded Polystyrene (EPS) and Extruded Polystyrene (XPS) Foam

"Building/Construction Materials" include products containing HBCD as a flame retardant primarily in XPS and EPS foam insulation products that are used for the construction of residential, public, commercial or other structures (UNEP, 2010; Weil and Levchik, 2009).

Use in EPS and XPS foam had accounted for 95% of all HBCD applications in the past decade (U.S. EPA, 2014d; UNEP, 2010). Based on information from market reports (U.S. EPA, 2017i), HBCD is used primarily in construction materials, which may include structural insulated panels (SIPS). The building and construction industry uses EPS and XPS foam thermal insulation boards and laminates for sheathing products. EPS foam prevents freezing, provides a stable fill material and creates high-strength composites in construction applications. XPS foam board is used mainly for roofing applications and architectural molding. HBCD is used in both types of foams because it is highly effective at levels less than 1% and, therefore, maintains the insulation properties of EPS and XPS foam (Morose, 2006b). EPS foam boards contain approximately 0.5% HBCD by weight in the final product and XPS foam boards contain 0.5-1% HBCD by weight (Public comment, EPA-HQ-OPPT-2016-0735-0017) (XPSA, 2017b; U.S. EPA, 2014d; Morose, 2006a).

According to the EPS Industry Alliance (EPS-IA), an estimated 80-85% of EPS rigid foam insulation manufactured in the United States is molded from EPS resins supplied by EPS-IA member companies, none of whom use HBCD. EPS-IA believes the remaining 15-20% of EPS manufacturers that are not part of the EPS-IA are not located in the U.S., but have also phased out use of HBCD (EPS Industry Alliance, 2017).

The XPS Association (XPSA) stated that its members, who are the major producers of XPS resin, supply the resin for more than 95% of the XPS foam insulation products manufactured for the North American market and that the remaining small percentage is probably made using imported resin (XPSA, 2017a). This imported resin may contain HBCD, however, the extent to which EPA does not know.

EPA is including the use of HBCD in XPS and EPS insulation using imported HBCD in the draft risk evaluation. There is a potential for import of HBCD for use in the manufacture of EPS and XPS foam insulation. Taking into account the high percentage of HBCD production volume dedicated to these two uses in previous years, and the fact that small HBCD companies could import low volumes of the chemical that would not be reported to CDR leaves open the possibility that EPS and XPS manufacturers that are not members of the EPS-IA and XPSA may currently be using imported HBCD resins in their processes. EPA is including the processing and use of HBCD in XPS and EPS insulation and import of HBCD resin in the draft risk evaluation.

1.2.5.3 Solder Paste

Following the publication of the HBCD Problem Formulation document (U.S. EPA, 2018f), EPA learned of an ongoing use of HBCD from newly available TRI data reported by the Indium Corporation. As indicated in Table 1-5. and Table 1-6., the company reported the processing of HBCD for the manufacture of formulated products to TRI in 2017. In follow-on communications with EPA, Indium said it processes and uses HBCD as a fluxing aid in solder paste, which it supplies to electronics manufacturers for use on circuit boards (Indium, 2018b). While the quantity of HBCD is not known, EPA assumes it is greater than the TRI reporting threshold of 100 lbs. per year for HBCD. According to the company, the amount of HBCD used varies depending on demand from customers (Indium, 2018a). The company purchases HBCD in a formulated mixture from a single supplier to manufacture flux and solder paste the Indium facility in Utica, NY. Indium ships the products to their overseas facilities for the final mixing step and for sales to electronics manufacturers in China and the United States. Indium

produces four products containing HBCD: Tacflux 023, Tacflux 101, Tacflux 483, and Tacflux NC 422, and does not sell directly to consumers, although the final consumer electronics products might be imported into the US. The company no longer ships the HBCD-containing products to the EU (Indium, 2018a, b). Another solder manufacturer called Kester reported HBCD use to TRI in 2017, but in a phone conversation with EPA indicated that they have discontinued use (Kester, 2018).

Based on the information above, EPA is including the processing of HBCD in the manufacture of solder paste in the draft risk evaluation.

1.2.6 Recycling of EPS and XPS Foam

There is limited information about the recycling of EPS and XPS products containing HBCD. Schlummer et al. (Schlummer et al., 2017) notes that EPS and XPS foam in construction insulation materials may not be frequently recycled for numerous reasons, including that insulation waste is typically not separated from mixed waste stream and most insulation containing HBCD is still in place. Schlummer et al. (Schlummer et al., 2017) describe technologies available only on a small scale to separate HBCD from insulation panels and recycled polystyrene.

Reuse and recycling of EPS and XPS foam insulation board, siding, roof membrane and roofing ballast material are available in the United States for consumers. Two companies were identified that directly reuse (e.g., reuse without reforming) and recycle (e.g., melting and inserting into the manufacturing process) XPS and EPS foam insulation.
• Green Insulation Group: http://www.greeninsulationgroup.com/products/
• Nationwide Foam Recycling: http://nationwidefoam.com/what-you-can-recycle.cfm

Nationwide Foam Recycling, which is owned by Conigliaro Industries, Inc., indicate that their plant recycles all EPS insulation and reuses all XPS insulation (U.S. EPA, 2017i). Once processed, their recycled EPS roofing insulation is taken to polystyrene product manufacturers, notably picture frame manufacturers, mostly in China but also in domestic markets. The company also delivers recycled roofing material to other local EPS recycling plants that may use different processes. Nationwide Foam Recycling processes 90,000 pounds/year of EPS standard packaging and 10,000 pounds/year of EPS roofing material and estimated only about 10-20% of EPS roofing material is recycled nationally (U.S. EPA, 2017i). It is not clear what happens to the remaining volume of waste. The company also reuses XPS roofing material due the special equipment needed to recycle XPS and indicated that XPS is rarely recycled in the United States. It was estimated that the majority (>50%) of XPS roofing material is sent to landfills or waste energy plants. Processing estimates for XPS material were not provided by the company.

The recycling of HBCD-containing EPS and XPS insulations boards for use in construction materials is included as a condition of use in this draft risk evaluation. The problem formulation stated that recycled materials that contain HBCD and are used for articles other than insulation boards for construction are not considered a condition of use in this evaluation. However, public commenters on the problem formulation stated that EPA should assess the risk from all recycled materials that could contain HBCD because of the potential for exposure, regardless of intent to use the flame retardant properties in the recycled product and because recycling is a condition of use. EPA agrees with the commenters. Recycling of a product containing a chemical constitutes processing of the chemical, which is a condition of use. HBCD was broadly used in EPS and XPS insulation boards historically, and recycled construction material would typically be required to meet fire resistant construction codes. EPA believes

that this recycling of insulation materials occurs such that the flame-retardant attributes of the insulation boards is maintained, and EPA is including this recycling and the use of HBCD in the recycled boards in the scope of this draft risk evaluation. EPA is also including consumer articles made from recycled HBCD-containing insulation boards based on experimental product-testing information on HBCD content in consumer articles, and recognition this as an important pathway for young children who may exhibit mouthing behaviors. Reuse, disposal, and recycling of HBCD-containing products from legacy uses are not within the conditions of use of the draft risk evaluation.

1.2.7 Discontinued Uses

Historically, HBCD was used in a number of functional uses that have been phased out. As noted in the Problem Formulation Document for Cyclic Aliphatic Bromide Cluster (HBCD), these uses have included use as a flame retardant in: high impact polystyrene (HIPS) for electrical and electronic appliances, consumer and commercial textiles, adhesives, coatings, children's products including toys and car seats; furniture (such as bean bag chairs). Based on the information provided in the Problem Formulation, EPA has determined that these discontinued uses are not included as a condition of use.

The first reports to TRI for HBCD became available after publication of the 2018 HBCD Problem Formulation. Releases of HBCD to the environment were reported by four facilities in the 2017 TRI, as described in Section 1.2.4. All companies reported processing HBCD as a formulation component. Two of the facilities belong to Dow Chemical Company, which had reportedly stopped using HBCD at all of its plants by November 2017 with no intent to resume using HBCD in the future (Dow Chemical, 2017). A different company, Indium Corporation of America, told EPA in a personal communication that it uses HBCD as a fluxing aid for solder as described in Section 1.2.5.3. The fourth facility, Flame Control Coatings, used HBCD for at least 15 years for one coating product, described as a "military specs marine coating". Follow up communications with the company revealed that they switched to another product that does not use HBCD and that their supplier no longer sells HBCD (FCC, 2018). Based on the foregoing information, EPA has determined that coatings are not a condition of use.

1.3 Regulatory and Assessment History

EPA conducted a search of existing domestic and international laws, regulations and assessments pertaining to HBCD. EPA compiled this summary from data available from federal, state, international and other government sources, as cited in Table 1-7. EPA evaluated and considered the impact of these existing laws and regulations (e.g. regulations on landfill disposal, design and operations) in the problem formulation step to determine what, if any further analysis might be necessary as part of the draft risk evaluation.

Federal Laws and Regulations

HBCD is subject to federal statutes or regulations, other than TSCA, that are implemented by other offices within EPA and/or other federal agencies/departments. A summary of federal laws, regulations and implementing authorities is provided in Appendix A.1.

State Laws and Regulations

HBCD is subject to state statutes or regulations implemented by state agencies or departments. A summary of state laws, regulations and implementing authorities is provided in Appendix A.2

Laws and Regulations in Other Countries and International Treaties or Agreements

HBCD is subject to statutes or regulations in countries other than the United States and/or international treaties and/or agreements. A summary of these laws, regulations, treaties and/or agreements is provided in Appendix A.3.

EPA has identified assessments conducted by other EPA Programs and other organizations. Depending on the source, these assessments may include information on conditions of use, hazards, exposures and potentially exposed or susceptible subpopulations. Table 1-7. shows the assessments that have been conducted.

Table 1-7. Assessment History of HBCD

Authoring Organization	Assessment
EPA assessments	
EPA, Office of Chemical Safety and Pollution Prevention (OCSPP), Office of Pollution Prevention and Toxics (OPPT)	Initial Risk Based Prioritization of High Production Volume Chemicals. Chemical/Category: Hexabromocyclododecane (HBCD) (U.S. EPA, 2008b)
EPA, OCSPP, OPPT	Hexabromocyclododecane (HBCD) Action Plan (U.S. EPA, 2010)
EPA, OCSPP, OPPT	Flame Retardant Alternatives for Hexabromocyclododecane (HBCD) (U.S. EPA, 2014d)
EPA, OCSPP, OPPT	Toxic Chemical Work Plan Problem Formulation and Initial Assessment for HBCD, Cyclic Aliphatic Bromide Cluster (U.S. EPA, 2015)
EPA, OCSPP, OPPT	Scope of the Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD) (U.S. EPA, 2017
EPA, OCSPP, OPPT	Problem Formulation for Cyclic Aliphatic Bromide Cluster (HBCD) (U.S. EPA, 2018)
Other U.S.-based organizations	
Consumer Product Safety Commission (CPSC)	CPSC Staff Exposure and Risk Assessment of Flame Retardant Chemicals in Residential Upholstered Furniture (CPSC, 2001)
National Research Council	National Academy of Sciences Report: Toxicological Risks of Selected Flame Retardant Chemicals (NRC, 2000a)
International	
Organisation for Economic Co-operation and Development (OECD), Screening Information Data Set (SIDS)	OECD SIDS Initial Assessment Profile (SIAP) (OECD, 2007b)

Authoring Organization	Assessment
European Commission (EC), European Chemicals Bureau	European Union Risk Assessment Report, Hexabromocyclododecane CASRN 25637-99-4. EINECS No: 247-148-4 (EINECS, 2008)
United Nations Environment Programme (UNEP); Stockholm Convention on Persistent Organic Pollutants (POPs)	Hexabromocyclododecane Draft Risk Profile (UNEP, 2010) Hexabromocyclododecane Risk Management Evaluation (2011) (UNEP, 2011)
Environment Canada and Health Canada	Draft Screening Assessment of Hexabromocyclododecane (Environment Canada, 2011)
Australian Government Department of Health, National Industrial Chemicals Notification and Assessment Scheme (NICNAS)	Priority Existing Chemical Assessment Report, Hexabromocyclododecane (NICNAS, 2012a)

1.4 Scope of the Evaluation

1.4.1 Conditions of Use Included in the Risk Evaluation

TSCA § 3(4) defines the conditions of use as ‘‘the circumstances, as determined by the Administrator, under which a chemical substance is intended, known, or reasonably foreseen to be manufactured, processed, distributed in commerce, used, or disposed of.” The conditions of use are described below in Table 1-8.

Based on the information described in Section 1.2, EPA is evaluating the importation of HBCD; processing of HBCD for use in the manufacturing of automotive replacement parts; solder paste; and incorporation into formulation, mixture or reaction product (e.g. compounding of masterbatch XPS); the processing of HBCD for incorporation into articles (e.g. manufacture of EPS and XPS and the manufacture of structural insulated panels from EPS and XPS); the industrial, commercial and consumer use of EPS and XPS in construction materials (e.g. insulation boards); distribution; disposal; and recycling of XPS and EPS foam, resin, and panels containing HBCD.

Table 1-8. presents the conditions of use that are considered within the scope of the draft risk evaluation during various life cycle stages including manufacturing, processing, use (industrial, commercial, and consumer), distribution and disposal. The activities that EPA has determined are out of scope are not included in the life cycle diagram. The information is grouped according to Chemical Data Reporting (CDR) processing codes and use categories (including functional use codes for industrial uses and product categories for industrial, commercial and consumer uses), in combination with other data sources (e.g., published literature and consultation with stakeholders) to provide an overview of conditions of use. EPA notes that some subcategories of use may be grouped under multiple CDR categories.

Use categories include the following: “industrial use” means use at a site at which one or more chemicals or mixtures are manufactured (including imported) or processed. “Commercial use” means the use of a chemical or a mixture containing a chemical (including as part of an article) in a commercial enterprise providing saleable goods or services. “Consumer use” means the use of a chemical or a mixture containing a chemical (including as part of an article, such as furniture or clothing) when sold to or made available to consumers for their use (U.S. EPA, 2016b).

To understand conditions of use relative to one another and associated potential exposures under those conditions of use, Figure 1-1 depicts the life cycle diagram and includes the production volume associated with each stage of the life cycle. The life cycle diagram for HBCD does not include specific production volumes because the information was claimed as confidential business information (CBI) in the 2016 CDR reporting (U.S. EPA, 2016b).

Table 1-8. Categories and Subcategories of Conditions of Use Included in the Scope of the Risk Evaluation for HBCD [a]

Life Cycle Stage	Category [b]	Subcategory [c]	References
Manufacture	Import	Import	U.S. EPA (2016b)
Processing	Processing – incorporated into formulation, mixture or reaction product	Flame retardants used in custom compounding of resin (e.g., compounding in XPS masterbatch) and in solder paste	EINECS (2008); (U.S. EPA, 2017h)
	Incorporated into article	Flame retardants used in plastics product manufacturing (manufacture of XPS and EPS foam; manufacture of structural insulated panels (SIPS) and automobile replacement parts from XPS and EPS foam)	Use Document, EPA-HQ-OPPT-2016-0735-0003; Market Profile, EPA-HQ-OPPT-2016-0735- 0049; (Alliance of Automobile Manufacturers, 2018a).
	Recycling	Recycling of XPS and EPS foam, resin, panels containing HBCD	Use Document, EPA-HQ-OPPT-2016-0735-0003
Distribution	Distribution	Activities related to distribution (e.g., loading, unloading) are considered throughout the life cycle, rather than using a single distribution scenario.	
Commercial/consumer Use	Building/construction materials	Plastic articles (hard): construction and building materials covering large surface areas (e.g., EPS/XPS foam insulation in residential, public and commercial buildings, and other structures)	Use Document, EPA-HQ-OPPT-2016-0735-0003; U.S. EPA (2016b); U.S. EPA (2014d)
	Other	Automobile replacement parts	(Alliance of Automobile Manufacturers, 2018a)
Disposal	Disposal	Other land disposal (e.g. Construction and Demolition Waste)	EINECS (2008)

[a] This table presents categories and subcategories of conditions of use that are based on the 2016 CDR industrial function category and industrial sector descriptions and the OECD product and article category descriptions for the HBCD uses identified. Clarification on the subcategories of use from the listed data sources are provided in parentheses.
[b] These categories of conditions of use appear in the Life Cycle Diagram, reflect CDR codes and broadly represent conditions of use of HBCD in industrial and/or consumer settings.
[c] These subcategories reflect more specific uses of HBCD.

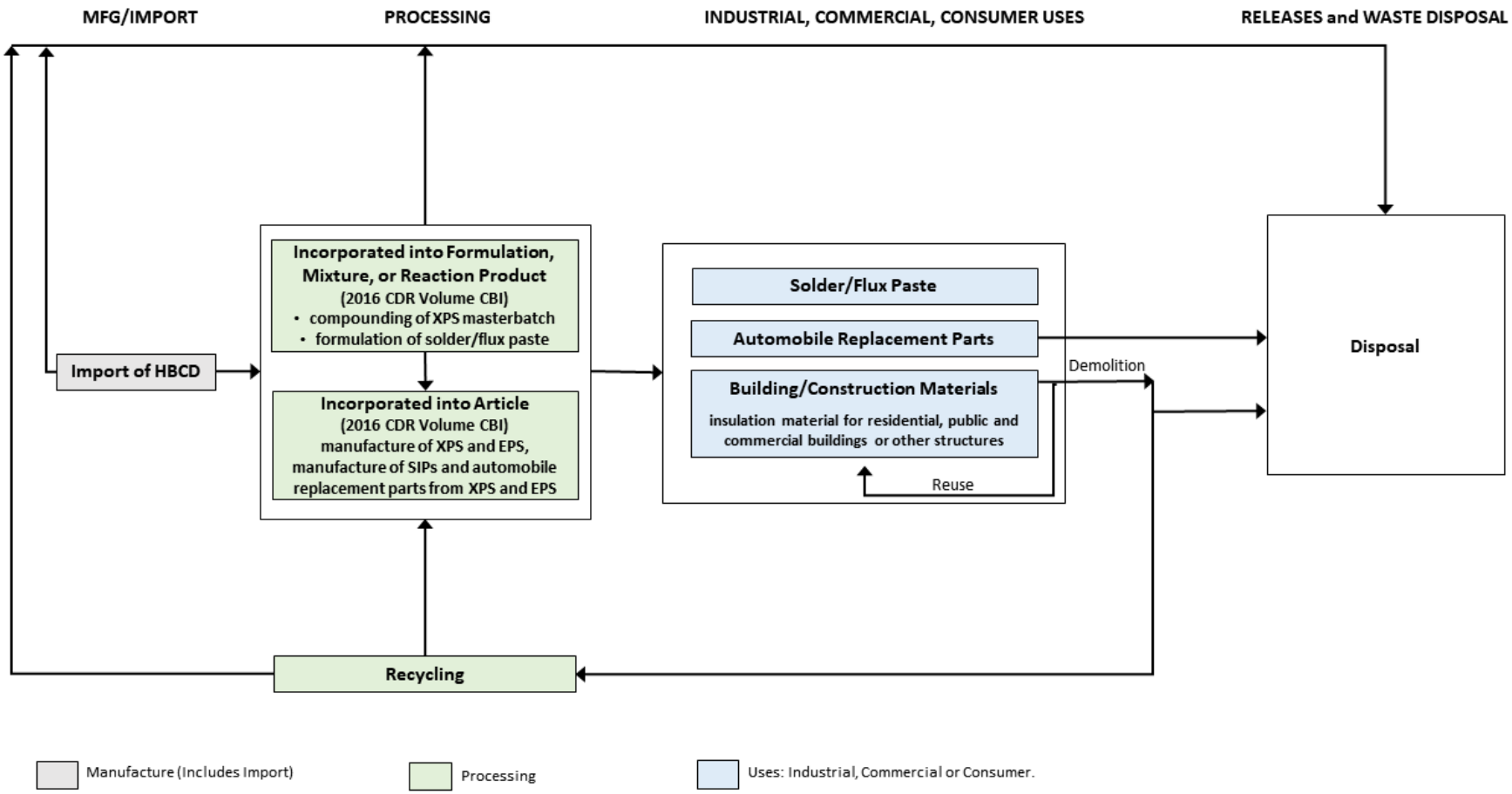

Figure 1-1. HBCD Life Cycle Diagram

The life cycle diagram depicts the conditions of use that are within the scope of the risk evaluation during various life cycle stages including manufacturing, processing, use (industrial, commercial, consumer), distribution and disposal. Activities related to distribution (e.g., loading, unloading) will be considered throughout the HBCD life cycle, rather than using a single distribution scenario.

1.4.2 Conceptual Models

The conceptual models for this risk evaluation are shown below in Figure 1-2., Figure 1-3, Figure 1-4. and Figure 1-5. EPA considered the potential for hazards to human health and the environment resulting from exposure pathways outlined in the preliminary conceptual models of the HBCD scope document (U.S. EPA, 2017e). The conceptual models indicate potential exposures resulting from consumer activities and uses, industrial and commercial activities, and environmental releases and wastes. The problem formulation documents refined the initial conceptual models and analysis plans that were provided in the scope documents (U.S. EPA, 2018b).

For the purpose of this assessment, EPA considered workers and occupational non-users, which includes men and women of reproductive age (Figure 1-2). Consumer exposure was assessed for various pathways for all age-groups, including adults and children (Figure 1-3). Non-users could be any age group ranging from infants to adults. Also, EPA considered exposures to the general population for all age-groups, as well as additional considerations for other exposed groups (Figure 1-3 and 1-4).

EPA has made three modifications to the conceptual model since the publication of the problem formulation document. The first was the addition of the solder/flux paste as a condition of use based on information reported to the TRI, as discussed in Section 1.2.5.3.

The second change was made to include exposure to liquids for workers associated with solder/flux paste as this use is expected to be in liquid formulations.

The third change was to more fully describe the use of HBCD in recycled products via the mouthing pathway. EPA identified information in the open literature that describes articles which contain HBCD, and recognizes this as an important pathway for young children who may mouth articles. EPA considered mouthing of recycled plastic products using experimental product-testing information on HBCD content in consumer articles. See Section 2.4.2.6. and in Appendix G for a more detailed discussion of this exposure scenario.

These changes are reflected in the life cycle diagram and conceptual models.

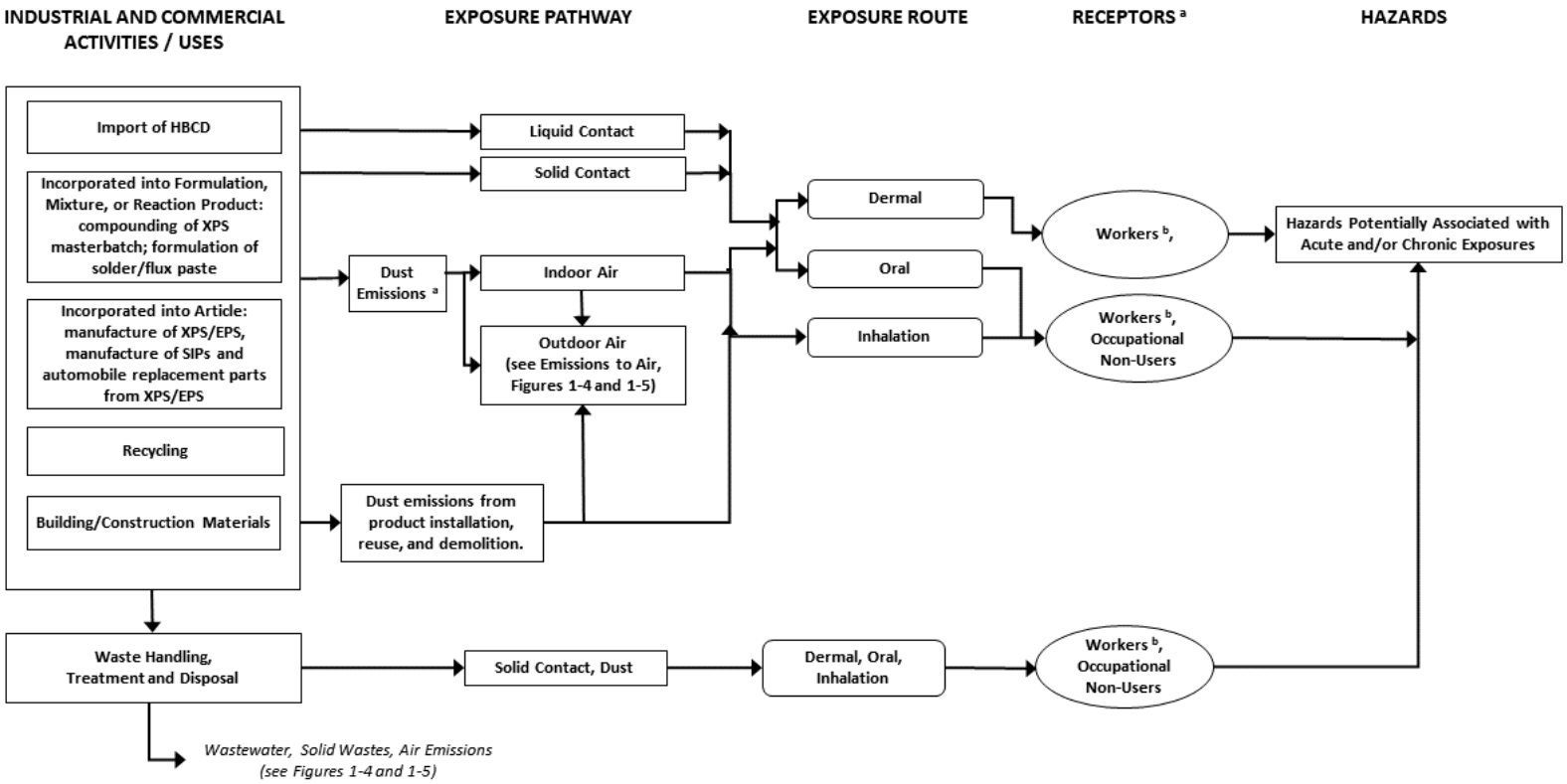

Figure 1-2. HBCD Conceptual Model for Industrial and Commercial Activities and Uses: Worker and Occupational Non-User Exposures and Hazards

The conceptual model presents the exposure pathways, exposure routes and hazards to human receptors from industrial and commercial activities and uses of HBCD.

[a] Receptors include potentially exposed or susceptible subpopulations.

[b] When data and information are available to support the analysis, EPA also considers the effect that engineering controls and/or personal protective equipment have on occupational exposure levels.

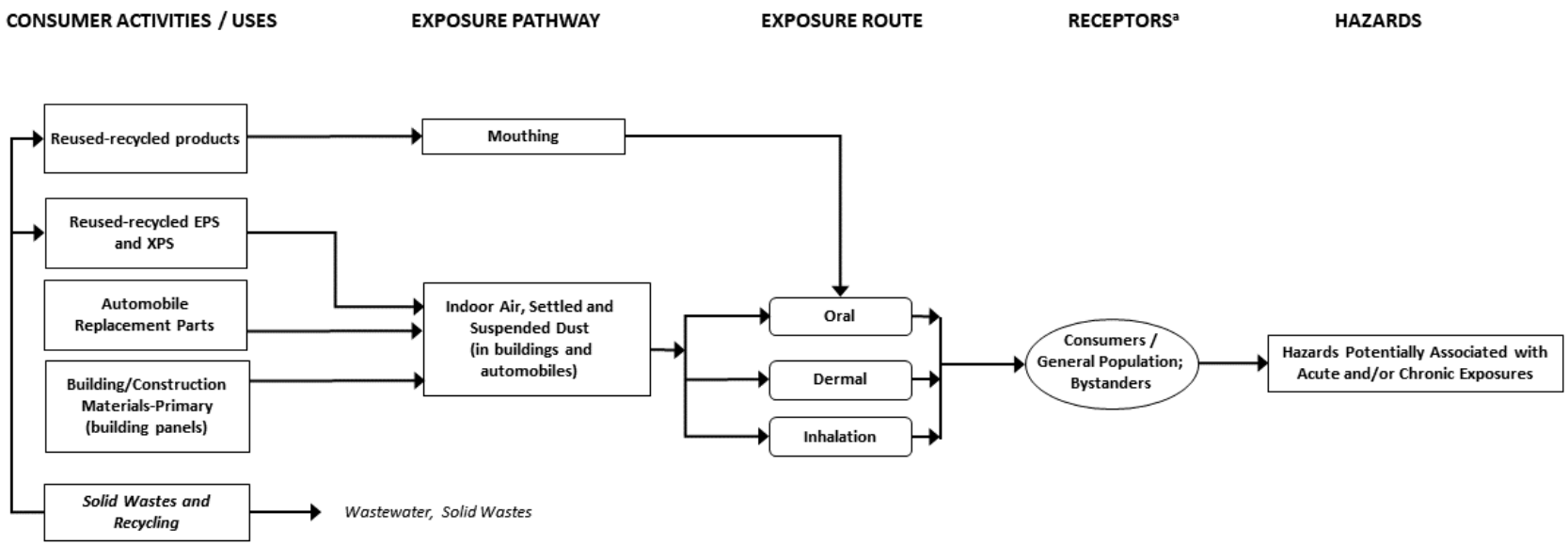

Figure 1-3. HBCD Conceptual Model for Consumer Activities and Uses: Consumer Exposures and Hazards
The conceptual model presents the exposure pathways, exposure routes and hazards to human receptors from consumer activities and uses of HBCD.
[a] Receptors include potentially exposed or susceptible subpopulations.

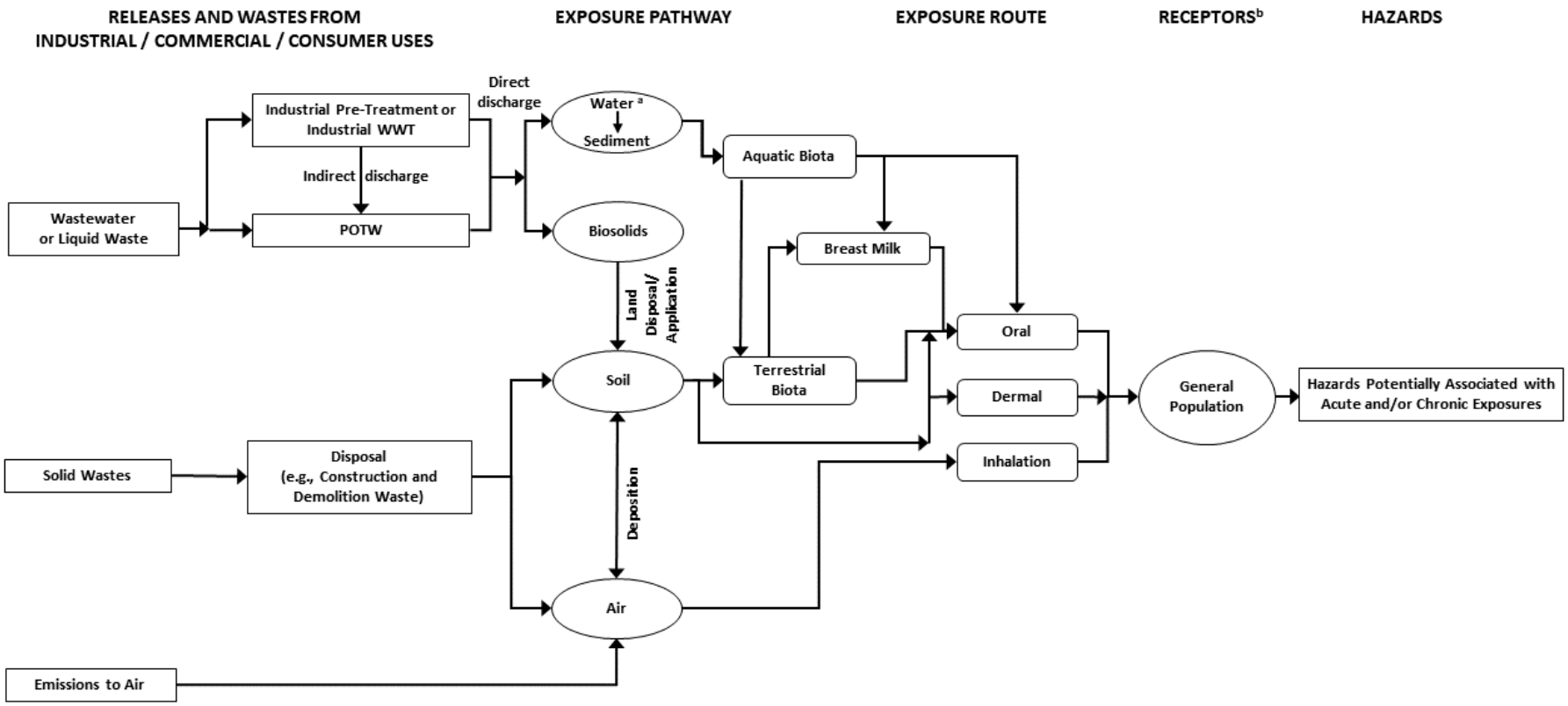

Figure 1-4. HBCD Conceptual Model for Environmental Releases and Wastes: General Population Exposures and Hazards
The conceptual model presents the exposure pathways, exposure routes and hazards to human receptors from releases and wastes from industrial and commercial uses of HBCD.
[a] Industrial wastewater or liquid wastes may be treated on-site and then released to surface water (direct discharge), or pre-treated and released to POTW (indirect discharge). For consumer uses, such wastes may be released directly to POTW (i.e., down the drain).
[b] Receptors include potentially exposed or susceptible subpopulations.

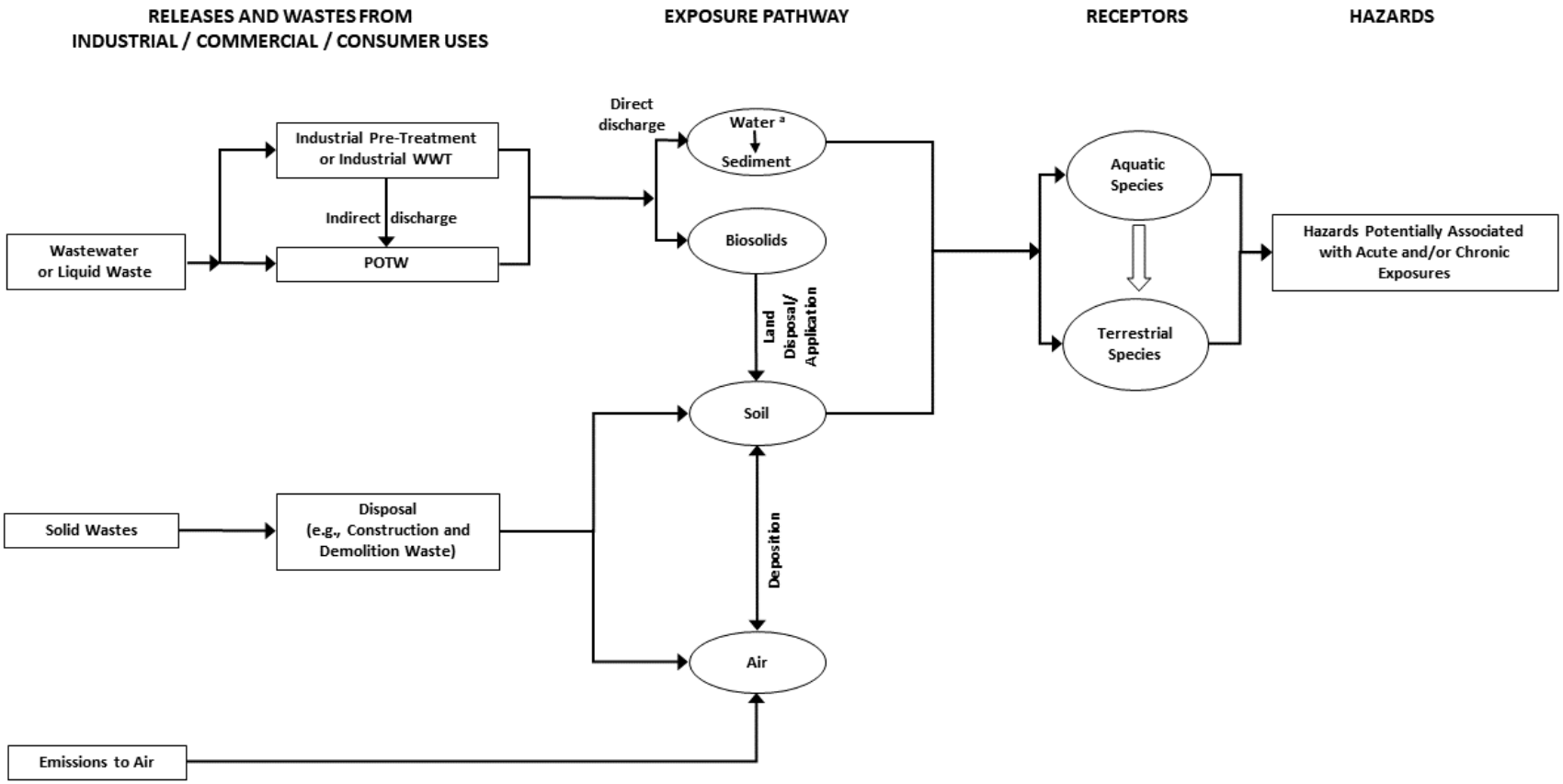

Figure 1-5. HBCD Conceptual Model for Environmental Releases and Wastes: Ecological Exposures and Hazards
The conceptual model presents the exposure pathways and hazards for environmental receptors from industrial and commercial uses of HBCD.
[a] Industrial wastewater or liquid wastes may be treated on-site and then released to surface water (direct discharge), or pre-treated and released to POTW (indirect discharge). For consumer uses, such wastes may be released directly to POTW (i.e., down the drain).

1.5 Systematic Review

TSCA requires EPA to use scientific information, technical procedures, measures, methods, protocols, methodologies and models consistent with the best available science and base decisions under section 6 on the weight of scientific evidence. Within the TSCA risk evaluation context, the weight of the scientific evidence is defined as "a systematic review method, applied in a manner suited to the nature of the evidence or decision, that uses a pre-established protocol to comprehensively, objectively, transparently, and consistently identify and evaluate each stream of evidence, including strengths, limitations, and relevance of each study and to integrate evidence as necessary and appropriate based upon strengths, limitations, and relevance". (40 C.F.R. 702.33).

To meet the TSCA § 26(h) science standards, EPA used the TSCA systematic review process described in the *Application of Systematic Review in TSCA Risk Evaluations* document (U.S. EPA, 2018a, b). The process complements the risk evaluation process in that the data collection, data evaluation and data integration stages of the systematic review process are used to develop the exposure and hazard assessments based on reasonably available information. EPA defines "reasonably available information" to mean information that EPA possesses, or can reasonably obtain and synthesize for use in risk evaluations, considering the deadlines for completing the evaluation (Citation to Final Rule).

EPA is implementing systematic review methods and approaches within the regulatory context of the amended TSCA. Although EPA will make an effort to adopt as many best practices as practicable from the systematic review community, EPA expects modifications to the process to ensure that the identification, screening, evaluation and integration of data and information can support timely regulatory decision making under the aggressive timelines of the statute.

1.5.1 Data and Information Collection

EPA planned and conducted a comprehensive literature search based on key words related to the different discipline-specific evidence supporting the risk evaluation (e.g., environmental fate and transport; environmental releases and occupational exposure; exposure to general population, consumers and environmental exposure; and environmental and human health hazards). EPA then developed and applied inclusion and exclusion criteria during the title/abstract screening to identify information potentially relevant for the risk evaluation process. The literature and screening strategy as specifically applied to HBCD is described in the *Strategy for Conducting Literature Searches for Cyclic Aliphatic Bromine Cluster (HBCD): Supplemental Document to the TSCA Scope Document* (U.S. EPA, 2017f) and the results of the title and abstract screening process were published in the *Cyclic Aliphatic Bromide Cluster (HBCD) (CASRN: 25637-99-4; 3194-55-6; 3194-57-8) Bibliography: Supplemental File for the TSCA Scope Document* (U.S. EPA, 2017a, b).

For studies determined to be on-topic (or relevant) after title and abstract screening, EPA conducted a full text screening to further exclude references that were not relevant to the risk evaluation. Screening decisions were made based on eligibility criteria documented in the form of the populations, exposures, comparators, and outcomes (PECO) framework or a modified framework[5]. Data sources that met the criteria were carried forward to the data evaluation stage. The inclusion and exclusion criteria for full

[5] A PESO statement was used during the full text screening of environmental fate and transport data sources. PESO stands for Pathways and Processes, Exposure, Setting or Scenario, and Outcomes. A RESO statement was used during the full text screening of the engineering and occupational exposure literature. RESO stands for Receptors, Exposure, Setting or Scenario, and Outcomes.

text screening for HBCD are available in Appendix E of the Problem Formulation Document (U.S. EPA, 2018f).

Although EPA conducted a comprehensive search and screening process as described above, EPA generally used previous chemical assessments[6] to identify key and supporting information that would be influential in the risk evaluation, in other words, information supporting key analyses, arguments, and/or conclusions in the risk evaluation. When applicable, EPA also considered newer information not considered in the previous chemical assessments and identified during the comprehensive search. Using this pragmatic approach, EPA evaluated the confidence of the key and supporting data sources as well as newer information instead of evaluating the confidence of all the underlying evidence ever published on HBCD's fate and transport, environmental releases, and environmental and human exposure and hazards. This allowed EPA to maximize the scientific and analytical efforts of other regulatory and non-regulatory agencies by accepting for the most part the scientific knowledge gathered and analyzed by others except for influential information sources that may have an impact on the weight of the scientific evidence and ultimately the risk findings. The influential information (i.e., key/supporting) came from a smaller pool of sources subject to the rigor of the TSCA systematic review process to ensure that the risk evaluation uses the best available science and the weight of the scientific evidence.

Although EPA conducted a comprehensive search and screening process as described above, EPA made the decision to leverage the literature published in previous assessments[7] when identifying relevant key and supporting data[8] and information for developing the HBCD risk evaluation. This is discussed in the *Strategy for Conducting Literature Searches for Cyclic Aliphatic Bromine Cluster (HBCD): Supplemental Document to the TSCA Scope Document* (U.S. EPA, 2017f). In general , many of the key and supporting data sources were identified in the comprehensive *Cyclic Aliphatic Bromide Cluster (HBCD) (CASRN: 25637-99-4; 3194-55-6; 3194-57-8) Bibliography: Supplemental File for the TSCA Scope Document* (U.S. EPA, 2017a, b). However, there were instances that EPA missed relevant references that were not captured in the initial categorization of the on-topic references. EPA found additional relevant data and information using backward reference searching, which was a technique that will be included in future search strategies. This issue was discussed in Section 4 of the *Application of Systematic Review for TSCA Risk Evaluations*. Other relevant key and supporting references were identified through targeted supplemental searches to support the analytical approaches and methods in the HBCD risk evaluation (e.g., to locate specific information for exposure modeling) or to identify new data and information published after the date limits of the initial search.

EPA used previous chemical assessments to quickly identify relevant key and supporting information as a pragmatic approach to expedite the quality evaluation of the data sources, but many of those data sources were already captured in the comprehensive literature as explained above. EPA also considered newer information not taken into account by previous chemical assessments as described in the S*trategy for Conducting Literature Searches for Cyclic Aliphatic Bromine Cluster (HBCD): Supplemental*

[6] Examples of existing assessments are EPA's chemical assessments (e.g. previous work plan risk assessments, problem formulation documents), ATSDR's Toxicological Profiles, EPA's IRIS assessments and ECHA's dossiers. This is described in more detail in the *Strategy for Conducting Literature Searches for Cyclic Aliphatic Bromine Cluster (HBCD): Supplemental Document to the TSCA Scope Document* (U.S. EPA, 2017f).

[7] Examples of existing assessments are EPA's chemical assessments (e.g. previous work plan risk assessments, problem formulation documents), ATSDR's Toxicological Profiles, EPA's IRIS assessments and ECHA's dossiers. This is described in more detail in the *Strategy for Conducting Literature Searches for Cyclic Aliphatic Bromine Cluster (HBCD): Supplemental Document to the TSCA Scope Document* (U.S. EPA, 2017f).

[8] Key and supporting data and information are those that support key analyses, arguments, and/or conclusions in the risk evaluation.

Document to the TSCA Scope Document (U.S. EPA, 2017f). EPA then evaluated the confidence of the key and supporting data sources as well as newer information instead of evaluating the confidence of all the underlying evidence ever published on a chemical substance's fate and transport, environmental releases, environmental and human exposure and hazards. Such comprehensive evaluation of all of the data and information ever published for a chemical substance would be extremely labor intensive and could not be achieved under the TSCA statutory deadlines for most chemical substances especially those that have a data rich database. Furthermore, EPA evaluated how EPA's evaluation of the key and supporting data and information and newer information would change the previous conclusions presented in the previous assessments.

EPA generally used previous chemical assessments[9] to identify key and supporting information that would be influential in the risk evaluation, in other words, information supporting key analyses, arguments, and/or conclusions in the risk evaluation. When applicable, EPA also considered newer information not considered in the previous chemical assessments and identified during the comprehensive search. Using this pragmatic approach, EPA evaluated the confidence of the key and supporting data sources as well as newer information instead of evaluating the confidence of all the underlying evidence ever published on HBCD's fate and transport, environmental releases, and environmental and human exposure and hazards. This would allow EPA to maximize the scientific and analytical efforts of other regulatory and non-regulatory agencies by accepting for the most part the relevant scientific knowledge gathered and analyzed by others except for influential information sources that may have an impact on the weight of the scientific evidence and ultimately the risk findings. The influential information (i.e., key/supporting) would come from a smaller pool of sources subject to the rigor of the TSCA systematic review process to ensure that the risk evaluation uses the best available science and the weight of the scientific evidence.

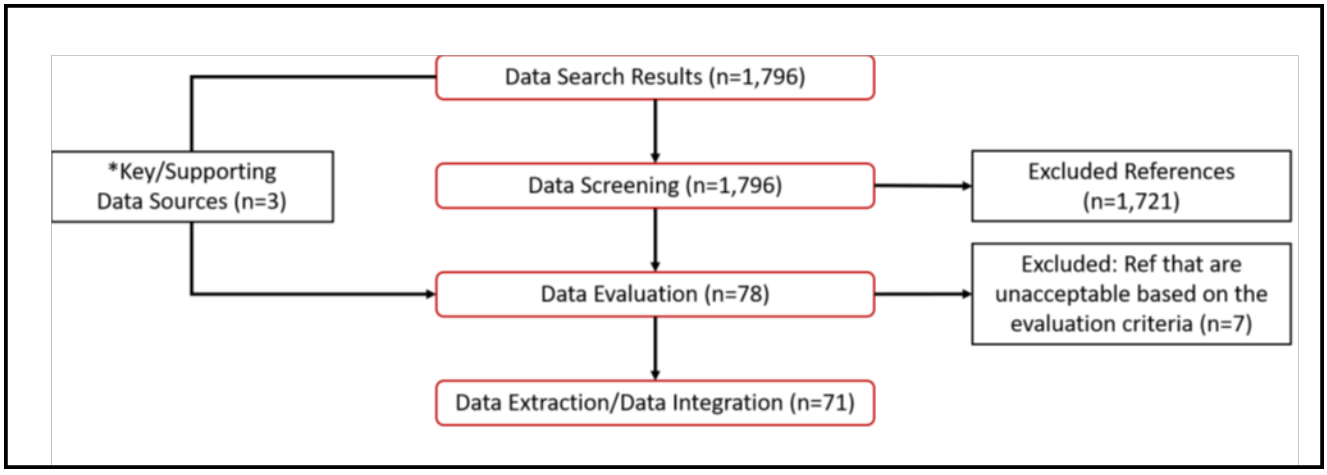

Figure 1-6 to Figure 1-10 depict literature flow diagrams illustrating the results of this process for each scientific discipline–specific evidence supporting the draft risk evaluation. Each diagram provides the total number of references at the start of each systematic review stage (i.e., data search, data screening, data evaluation, data extraction/data integration) and those excluded based on criteria guiding the screening and data quality evaluation decisions.

EPA made the decision to bypass the data screening step for data sources that were highly relevant to the draft risk evaluation as described above. These data sources are depicted as "key/supporting data

[10] There are various supplemental files accompanying the risk evaluation:

sources" in the literature flow diagrams. Note that the number of "key/supporting data sources" were excluded from the total count during the data screening stage and added, for the most part, to the data evaluation stage depending on the discipline-specific evidence. The exception was the environmental releases and occupational exposure data sources that were subject to a combined data extraction and evaluation step (Figure 1-7).

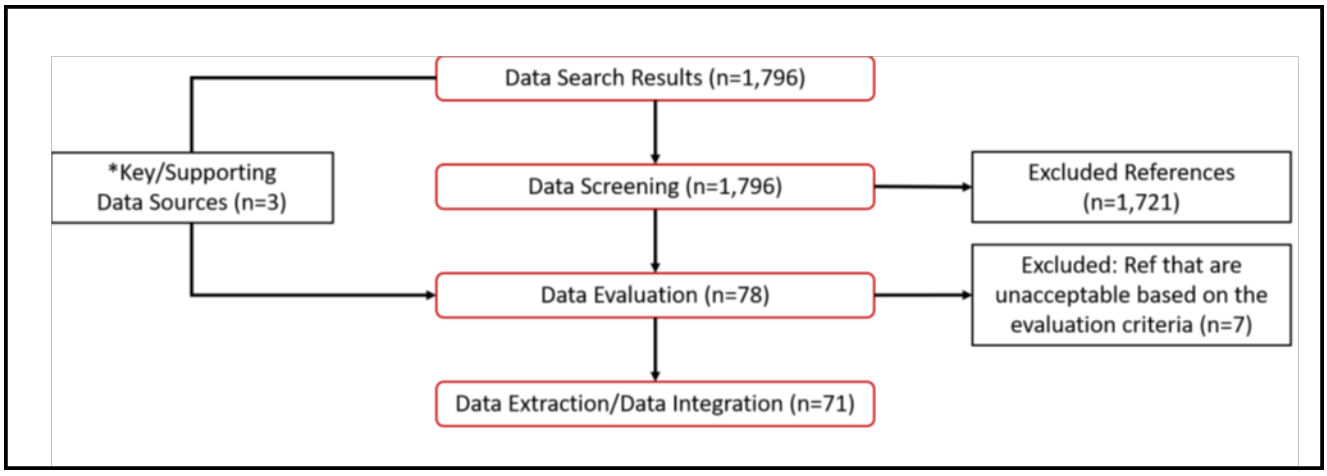

Figure 1-6. HBCD Literature Flow Diagram for Environmental Fate and Transport Data Sources

Note: Literature search results for the environmental fate and transport of HBCD yielded 1,796 studies. Of these studies, 1,721 were determined to be off topic. The remaining 75 studies entered full text screening for the determination of relevance to the risk evaluation. Seven studies were deemed unacceptable based on the evaluation criteria for fate and transport studies and the remaining 68 studies were carried forward to data extraction/data integration.

* These are key and supporting studies from existing assessments (e.g., EPA IRIS assessments, ATSDR assessments, ECHA dossiers) that were considered highly relevant for the TSCA risk evaluation. These studies bypassed the data screening step and moved directly to the data evaluation step.

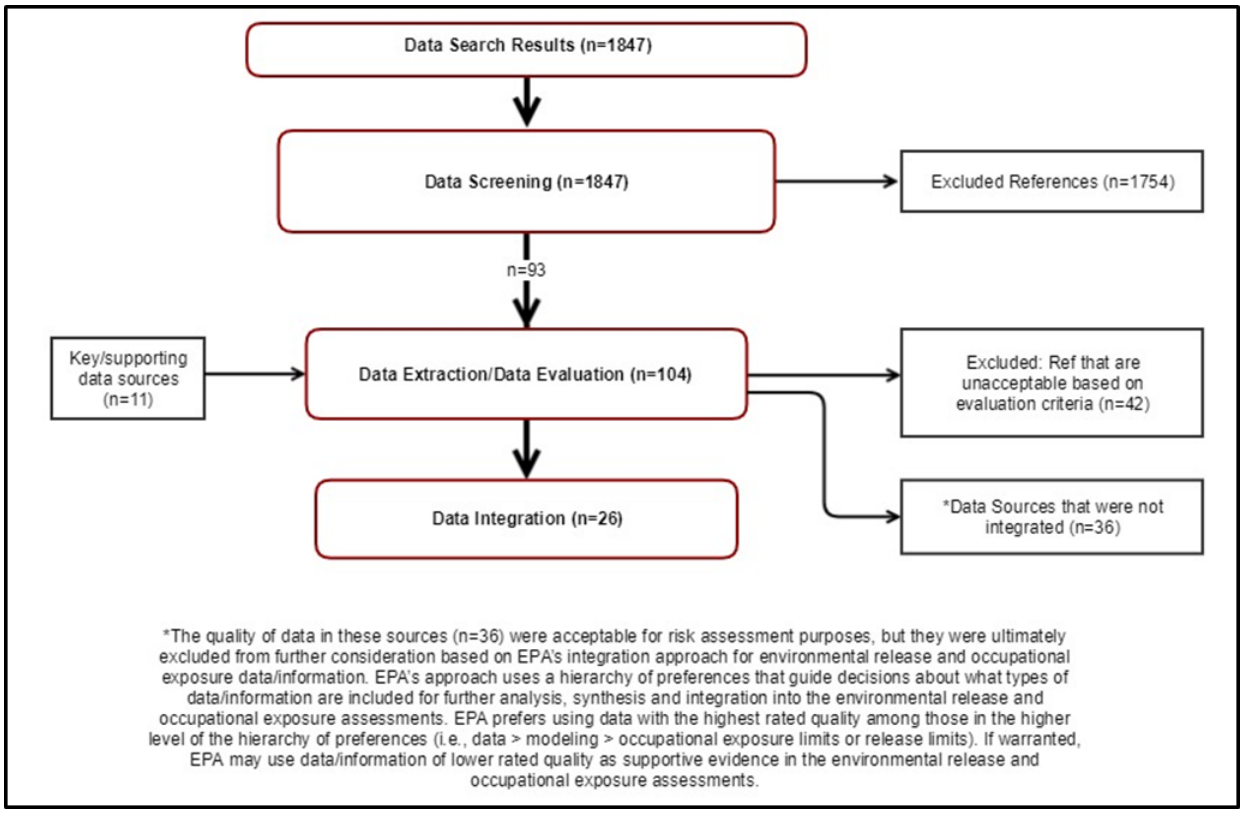

Figure 1-7. HBCD Literature Flow Diagram for Environmental Releases and Occupational Exposure Data Sources

Note: Literature search results for environmental release and occupational exposure yielded 1,847 data sources. Of these data sources, 93 were determined to be relevant for the risk evaluation through the data screening process. These relevant data sources were entered into the data extraction/evaluation phase. After data extraction/evaluation, EPA identified several data gaps and performed a supplemental, targeted search to fill these gaps (e.g. to locate information needed for exposure modeling). The supplemental search yielded 11 relevant data sources that bypassed the data screening step and were evaluated and extracted in accordance with *Appendix D: Data Quality Criteria for Occupational Exposure and Release Data of the Application of Systematic Review for TSCA Risk Evaluations* document. Twenty-six (26) of these were forwarded for data integration, while 42 of these data sources were rated as unacceptable based on serious flaws detected during the evaluation and 36 data sources that were not integrated.

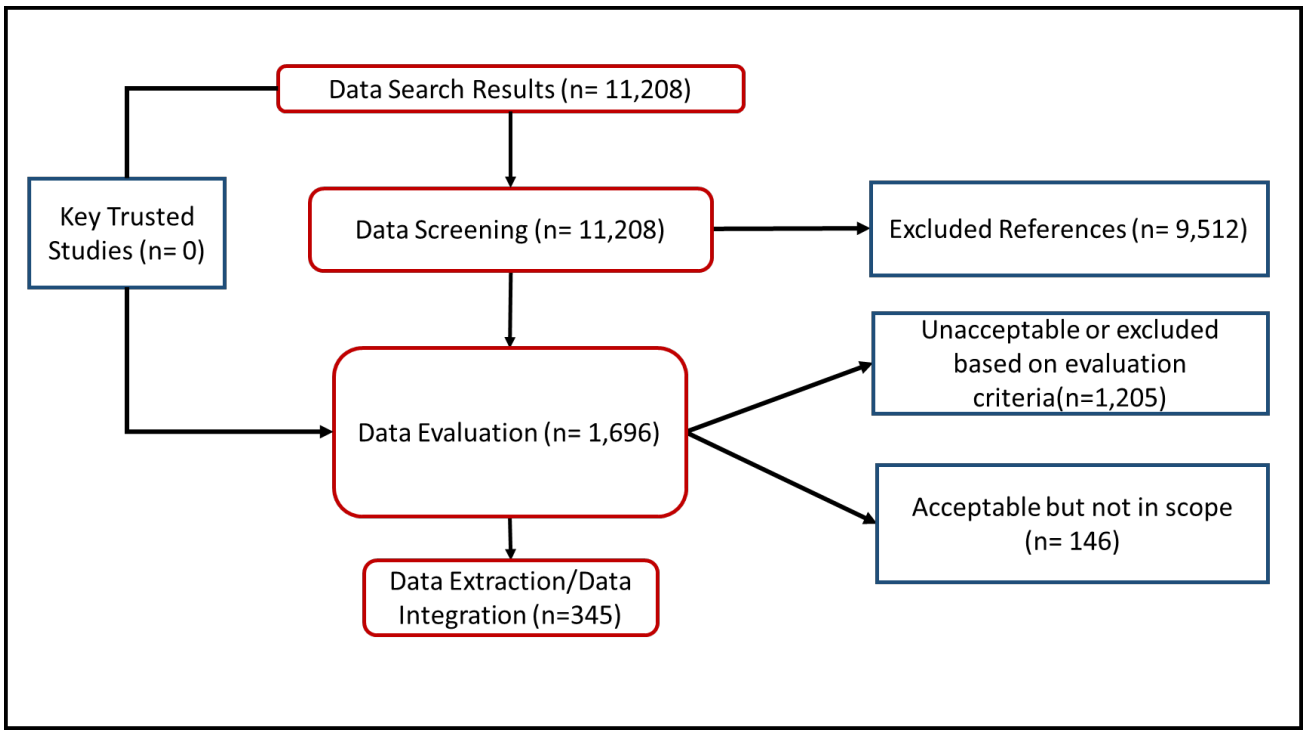

Figure 1-8. Literature Flow Diagram for General Population, Consumer and Environmental Exposure Data Sources for HBCD

Note: EPA conducted a literature search to determine relevant data sources for assessing exposures for HBCD within the scope of the risk evaluation. This search identified 11,208 data sources including relevant supplemental documents. Of these, 9,512 were excluded during the screening of the title, abstract, and/or full text and 1,696 data sources were recommended for data evaluation across up to five major study types in accordance with *Appendix E: Data Quality Criteria for Studies on Consumer, General Population and Environmental Exposure of the Application of Systematic Review for TSCA Risk Evaluations* document. (U.S. EPA, 2018b). Following the evaluation process, 345 references were forwarded for further extraction and data integration.

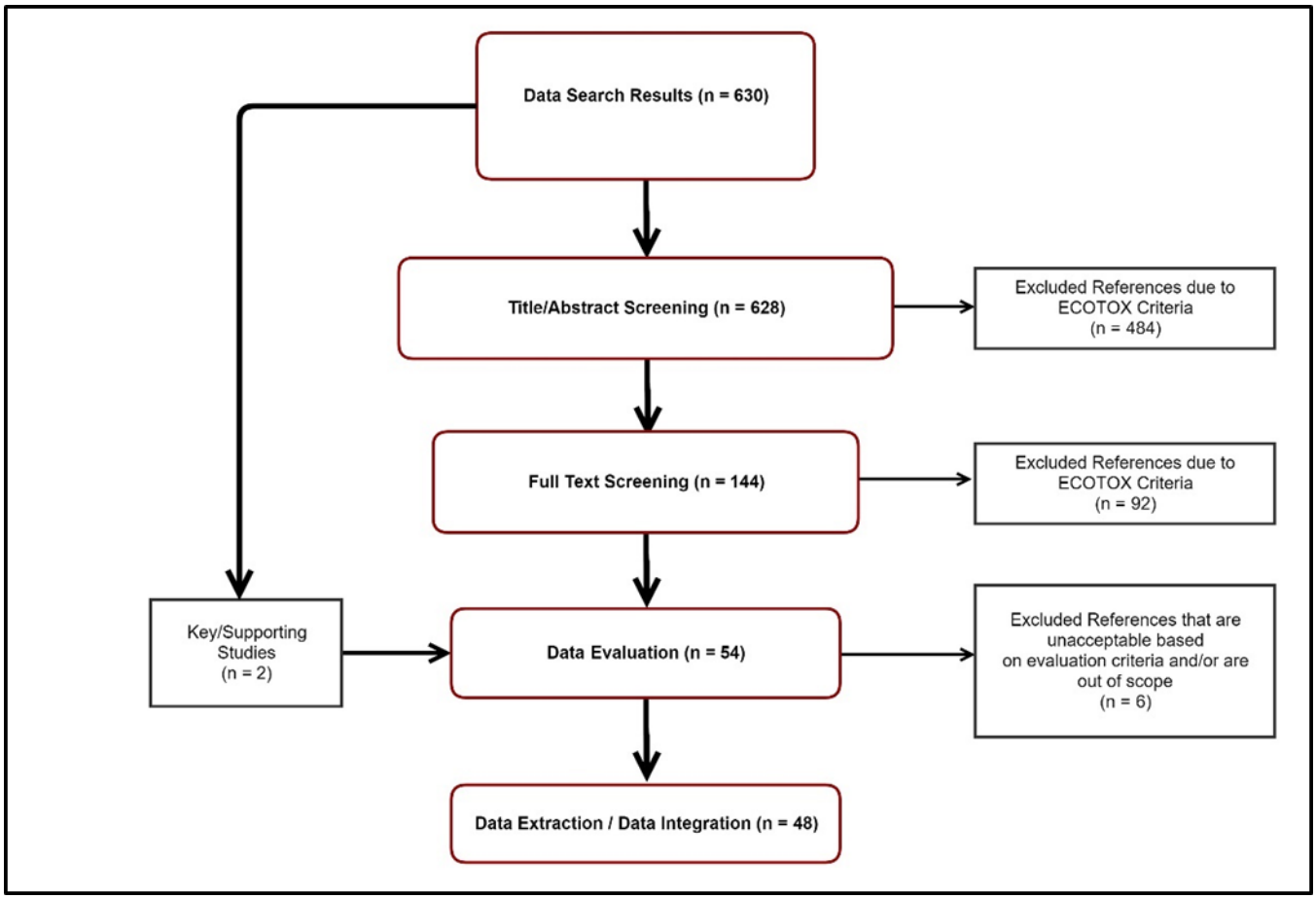

Figure 1-9. Literature Flow Diagram for Environmental Hazard Data Sources for HBCD

Note: The environmental hazard data sources were identified through literature searches and screening strategies using the ECOTOXicology Knowledgebase System (ECOTOX) Standing Operating Procedures. For studies determined to be on-topic after title and abstract screening, EPA conducted a full text screening to further exclude references that were not relevant to the risk evaluation. Screening decisions were made based on eligibility criteria as documented in the ECOTOX User Guide (U.S. EPA, 2018d)). Additional details can be found in the *Strategy for Conducting Literature Searches for Hexabromocyclododecane Supplemental Document to the TSCA Scope Document* (U.S. EPA, 2018g).

The "Key/Supporting Studies" box represents data sources typically cited in existing assessments and considered highly relevant for the TSCA risk evaluation because they were used as key and supporting information by regulatory and non-regulatory organizations to support their chemical hazard and risk assessments. These citations were found independently from the ECOTOX process. These studies bypassed the data screening step and moved directly to the data evaluation step.

Studies could be considered "out of scope" after the screening steps, and therefore excluded from data evaluation, due to the elimination of pathways during scoping/problem formulation.

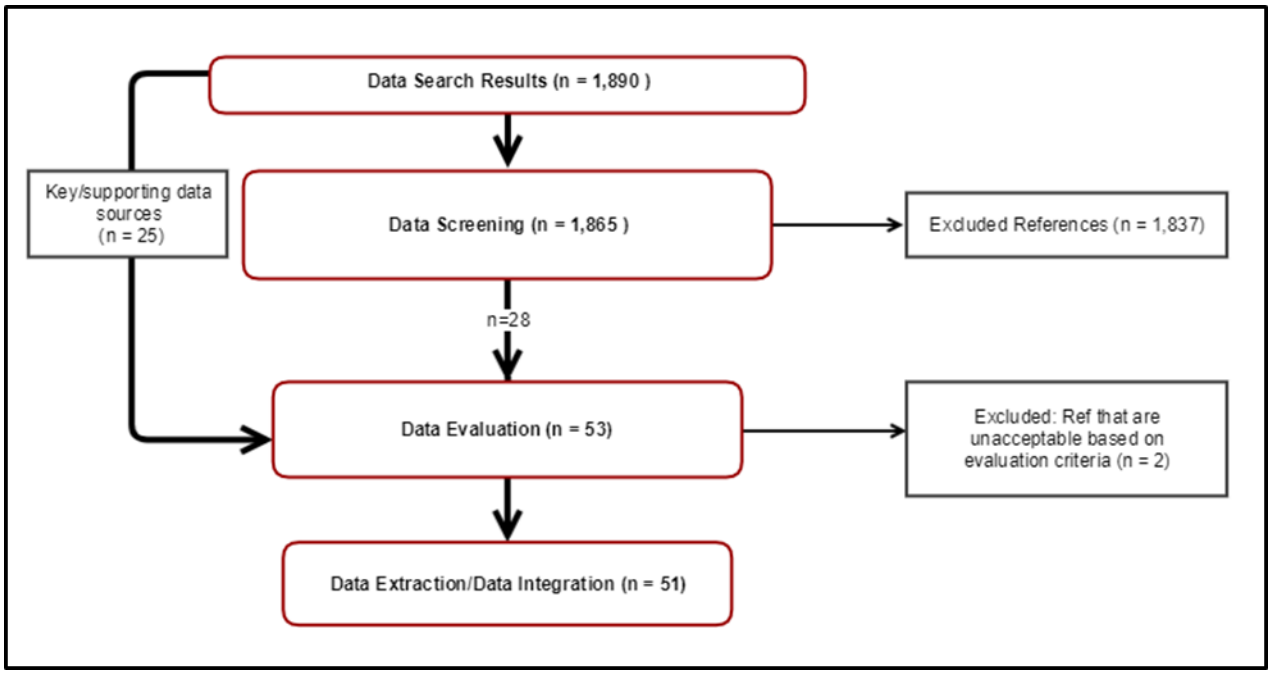

Figure 1-10. Literature Flow Diagram for Human Health Hazard Key/Supporting Data Sources for HBCD

Note: Literature search results for human health hazard of HBCD yielded 1,890 studies. This included 25 key and supporting studies identified from previous EPA assessments (see Section 3.2.1). Of the 1,865 new studies screened for relevance, 1,837 were excluded as off topic. The remaining 28 new studies together with the 25 key and supporting studies entered full text screening for the determination of relevance to the risk evaluation. Two studies were deemed unacceptable based on the evaluation criteria human health hazard and the remaining 51 studies were carried forward to data extraction/data integration.

1.5.2 Data Evaluation

During the data evaluation stage, EPA assesses the quality of the data sources using the evaluation strategies described in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a). For the data sources that passed full-text screening and the key and supporting data sources, EPA evaluated their quality and each data source received an overall confidence of high, medium, low or unacceptable.

The results of the data quality evaluations are summarized in Sections 2.1 (Fate and Transport), 2.2 (Releases to the Environment), 2.3 (Environmental Exposures), 2.4 (Human Exposures), 3.1 (Environmental Hazards) and 3.2 (Human Health Hazards). Additional information is provided in the appendices of the main document. Supplemental files[10] also provide details of the data evaluations including individual metric scores and the overall study score for each data source.

[10] There are various supplemental files accompanying the risk evaluation:
- Systematic Review Supplemental File: Data Quality Evaluation of Environmental Fate and Transport Studies
- Systematic Review Supplemental File: Data Quality Evaluation for Engineering Releases and Occupational Exposure Data Sources
- Systematic Review Supplemental File: Data Quality Evaluation of Consumer, General Population and Environmental Exposure Data Sources
- Systematic Review Supplemental File: Data Quality Evaluation of Environmental Hazard Studies
- Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies, Animal and *In Vitro* Studies
- Systematic Review Supplemental File: Data Quality Evaluation of Epidemiological Studies
- Systematic Review Supplemental File: Updates to the Data Quality Criteria for Epidemiological Studies

1.5.3 Data Integration

Data integration includes analysis, synthesis and integration of information for the risk evaluation. During data integration and analysis, EPA considers quality, consistency, relevancy, coherence and biological plausibility to make final conclusions regarding the weight of the scientific evidence. As stated in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a), data integration involves transparently discussing the significant issues, strengths, and limitations as well as the uncertainties of the reasonably available information and the major points of interpretation (U.S. EPA, 2018g).

The EPA used previous assessments to identify key and supporting information and then analyzed and synthesized available evidence regarding HBCD's chemical properties, environmental fate and transport properties, potential for exposure and hazard. EPA's analysis also considered recent data sources that were not considered in the previous assessments (Section 1.5.1) as well as reasonably available information on potentially exposed or susceptible subpopulations.

The exposures and hazards sections describe EPA's analysis of the influential information (i.e., key and supporting data) that were found acceptable based on the data quality reviews as well as discussion of other scientific knowledge using the approach described in Section 1.5.1. The exposure section also describes whether aggregate or sentinel exposures to a chemical substance were considered under the conditions of use within the scope of the risk evaluation, and the basis for that consideration.

2 EXPOSURES

This section describes EPA's approach to assessing environmental and human exposures. First, the fate and transport of HBCD in the environment is characterized. Then, releases of HBCD into the environment are assessed. Last, this information is integrated into an assessment of occupational, general population (including highly exposed subpopulations), and environmental exposures for HBCD. For all exposure-related disciplines, EPA screened, evaluated, extracted, and integrated available empirical data. In addition, EPA used models to estimate exposures. Both empirical data and modeled estimates were considered when selecting values for use in the exposure assessment.

Exposure equations and selected values used in the exposure assessment are presented in the following sections. More specific information is provided in *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment. (U.S. EPA, 2019d).*

Following the inclusion of HBCD on EPA's workplan list in 2012, EPA published a 2015 problem formulation prior to passage of the Lautenberg amendments, and published an updated scope in 2017 and problem formulation document in 2018. EPA has incorporated the following refinements based on public comments and review of data since initial work began on HBCD.

- More complete assessment of human dietary exposure from multiple sources (estimates for all food groups and more specific estimates for breast milk ingestion and fish ingestion) for the general population,
- Inclusion of dermal pathway,
- Inclusion of refined models used to estimate surface water and ambient air as well as sediment and indoor dust,
- Inclusion of additional contextual information from monitoring data to determine which data is likely more applicable to exposure scenarios of interest, and
- Assessment of bioaccumulation and wildlife as part of environmental exposure assessment.

2.1 Fate and Transport

The environmental fate studies considered for this risk evaluation are summarized in Appendix C. This information is based on studies published in (U.S. EPA, 2015, 2014d; NICNAS, 2012a; EC/HC, 2011; EINECS, 2008; U.S. EPA, 2008b; OECD, 2007a) and was supplemented by an updated literature search following problem formulation.

2.1.1 Fate and Transport Approach and Methodology

EPA gathered and evaluated environmental fate information according to the process described in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a). Reasonably available environmental fate information was used in the current evaluation. Furthermore, EPA used previous regulatory and non-regulatory chemical assessments of HBCD to inform the environmental fate and transport information discussed in this section and Appendix C. EPA had confidence in the information used in the previous assessments to describe the environmental fate and transport of HBCD based on scientific review of the methodologies and quality of the data presented and thus used it to make scoping decisions.

EPA also used the previous assessment to identify key and supporting fate information that would be influential in the risk evaluation, as described in Section 1.5.1. For instance, EPA assessed the quality of an HBCD aerobic freshwater sediment biodegradation study (Davis et al., 2006) based on the data

quality criteria described in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a) and the study was rated 'high' confidence. The atmospheric oxidation half-life fate estimate was based on modeling results from EPI Suite™ (U.S. EPA, 2012c), a predictive tool for physical/chemical and environmental fate properties. The data evaluation table describing their review as well as other studies included in Table 2-1 can be found in the supplemental document, *Data Quality Evaluation of Environmental Fate and Transport Studies* (U.S. EPA, 2019, HERO ID).

The HBCD environmental fate characteristics and physical-chemical properties used in fate assessment are presented in Table 2-1. EPA used EPI Suite™ estimations and reasonably available fate information to characterize the environmental fate and transport of HBCD. As part of problem formulation, EPA also analyzed the fate of HBCD in air, water, soil, sediment, and bioaccumulation. The results of the analyses are described in the 2018 problem formulation for HBCD (U.S. EPA, 2018f) and presented again in Appendix C. Note that this section and Appendix C may also cite other data sources as part of the reasonably available information on the fate and transport properties of HBCD. EPA did not subject these other data sources to the later phases of the systematic review process (i.e., data evaluation and integration) as explained in Section 1.5.1.

2.1.2 Summary of Fate and Transport

Environmental fate includes both transport and transformation processes. Environmental transport is the movement of the chemical within and between environmental media. Transformation generally occurs through the degradation or reaction of the chemical with other species in the environment. Hence, knowledge of the environmental fate of the chemical informs the determination of the specific exposure pathways and potential human and environmental receptors EPA analyzed in the risk evaluation.

Table 2-1 provides a summary of a subset of the environmental fate data that EPA identified, evaluated and considered in the risk evaluation for HBCD. A full list of data considered, identified and evaluated is provided in Appendix C.

Table 2-1. Summary of Environmental Fate and Transport Properties for HBCD

Property	Value	Reference	Study Quality
Indirect Photolysis	Half-life 2.1 days in air (estimated)	(U.S. EPA, 2015)	NA
Hydrolysis	Not expected due to lack of functional groups that hydrolyze under environmental conditions and low water solubility (estimated)	(ECHA, 2008b)	NA
Aerobic Biodegradation in Water	No biodegradation observed in 28-day closed-bottle test Organisation for Economic Co-operation and Development (OECD) Guideline 301D, EPA OTS 796.3200	(Wildlife Intl, 1996)	Medium
Aerobic Biodegradation in Sediment	Half-life: 128, 92, and 72 days for α-, γ-, and β-HBCD, respectively (estimated), based on a 44% decrease in total initial radioactivity in viable freshwater sediment of 14C-labeled HBCD (4.67 mg/kg dry weight) after 112 days; method based on OECD 308	(Davis et al., 2006)	High
	Half-life: >120 days (estimated), based on a 15% decrease in total initial radioactivity in abiotic freshwater sediment of 14C-labeled		High

Property	Value	Reference	Study Quality
	HBCD (4.67 mg/kg dry weight) after 112 days; method based on OECD 308		
	Half-life: 11 and 32 days (estimated) in viable sediment collected from Schuylkill River and Neshaminy creek, respectively, using nominal HBCD concentrations of 0.034–0.089 mg/kg; method based on OECD 308	(Davis et al., 2005)	High
	Half-life: 190 and 30 days (estimated) in abiotic sediment collected from Schuylkill River and Neshaminy creek, respectively, using nominal HBCD concentrations of 0.034–0.089 mg/kg; method based on OECD 308		High
	Half-life: 92 days (estimated), based on a 61% decrease in total initial radioactivity in viable freshwater sediment of 14C-labeled HBCD (4.31 mg/kg dry weight) after 113 days; method based on OECD 308	(Davis et al., 2006)	High
	Half-life: >120 days (estimated), based on a 33% decrease in total initial radioactivity in abiotic freshwater sediment of 14C-labeled HBCD (4.31 mg/kg dry weight) after 113 days; method based on OECD 308		High
	Half-life: 1.5 and 1.1 days (estimated) in viable sediment collected from Schuylkill River and Neshaminy creek, respectively, using nominal HBCD concentrations of 0.063–0.089 mg/kg; method based on OECD 308	(Davis et al., 2005)	High
	Half-life: 10 and 9.9 days (estimated) in abiotic sediment collected from Schuylkill River and Neshaminy creek, respectively, using nominal HBCD concentrations of 0.063–0.089 mg/kg; method based on OECD 308		High
Aerobic Biodegradation in Soil	Half-life: >120 days (estimated), based on a 10% decrease in total initial radioactivity in viable soil of 14C-labeled HBCD after 113 days; method based on OECD 307 using HBCD at 3.04 mg/kg dry weight	(Davis et al., 2006)	High
	Half-life: >120 days (estimated), based on a 6% decrease in total initial radioactivity in abiotic soil of 14C-labeled HBCD after 113 days; method based on OECD 307 using HBCD at 3.04 mg/kg dry weight		High
	Half-life: 63 days (estimated) in viable soil amended with activated sludge using a nominal HBCD concentration of 0.025 mg/kg dry weight; method based on OECD 307	(Davis et al., 2005)	High
	Half-life: >120 days (estimated) in		High

Property	Value	Reference	Study Quality
	abiotic soil using a nominal HBCD concentration of 0.025 mg/kg dry weight; method based on OECD 307		
	Half-life: 6.9 days (estimated) in viable soil amended with activated sludge using a nominal HBCD concentration of 0.025 mg/kg dry weight; method based on OECD 307		High
	Half-life: 82 days (estimated) in abiotic soil using a nominal HBCD concentration of 0.025 mg/kg dry weight; method based on OECD 307		High
Soil organic carbon:water partition coefficient (log Koc)	Log Koc = 4.9 (79,433) estimated	(U.S. EPA, 2015)	NA
	Log Koc > 5 (> 100,000) OECD Guideline 121 Estimation of the Adsorption Coefficient (Koc) on Soil and on Sewage Sludge using High Performance Liquid Chromatography (HPLC)	(ECHA, 2017a)	High
Field Measured Bioaccumulation Factor (BAF)	Upper trophic level lipid normalized BAF for total HBCDs of approximately 90,090,000 calculated from the mean HBCD lipid normalized fish tissue concentration and the HBCD dissolved water concentration. Wet weight BAF 290,880	(He et al., 2013)	High
	Upper trophic level lipid normalized BAF for total HBCDs of approximately 3,120,000 calculated from the mean HBCD lipid normalized fish tissue concentration and the HBCD dissolved water concentration. Wet weight BAF 46,488	(Wu et al., 2011)	High
Bioconcentration Factor (BCF)	fathead minnow 18,100 (whole body)	(Veith et al., 1979)	High
	[a]BCF (steady state, edible portion) rainbow trout 4650 at 1.8 µg/L exposure concentration) BCF rainbow trout (kinetic, edible portion) 14,039 calculated at 0.18 µg/L exposure concentration)	Drottar (Wildlife Intl, 2000) as cited in (ECHA, 2008b)	High

[a] HBCD exposure concentrations 1.8 and 0.18 µg/L. Steady state achieved at 1.8 ug/L but not at 0.18 ug/L

2.1.2.1 Air

HBCD is not expected to undergo significant direct photolysis since it does not absorb radiation in the environmentally available region of the electromagnetic spectrum that has the potential to cause molecular degradation (HSDB, 2008). HBCD in the vapor phase will be degraded by reaction with photochemically produced hydroxyl radicals in the atmosphere. A half-life of 2.1 days was calculated from an estimated rate constant of 5.01×10^{-12} cm^3/molecules-second at 25 °C, assuming an atmospheric hydroxyl radical concentration of 1.5×10^6 molecules/cm^3 and a 12-hour day (U.S. EPA, 2011a, 1993a). Based on an estimated octanol air partition coefficient (Koa) of 1.6 x 10^9, HBCD is expected to associate strongly with airborne particulates. HBCD associated with particulates is expected to be less

subject to hydroxy radical oxidation in the atmosphere and primarily removed from the atmosphere through wet or dry deposition.

2.1.2.2 Water

HBCD is not expected to undergo hydrolysis in environmental waters because of its lack of hydrolyzable functional groups. Based on a measured soil organic carbon:water partition coefficient (Koc) of >100,000, HBCD is expected to partition from the water column, bind strongly to and be transported with suspended and benthic sediments. A Henry's Law constant of 6×10^{-6} atm-m^3/mol at 25 °C, calculated based on a vapor pressure of 4.70×10^{-7} mm Hg at 21 °C and a water solubility of 66 µg/L at 25 °C, indicates that HBCD may volatilize slowly from moist soil and water surfaces. However, adsorption to suspended solids and sediment will reduce the rate of volatilization from water. An OECD 301D ready biodegradability study (aerobic aqueous medium) on HBCD resulted in no observed biodegradation in 28 days, suggesting that aerobic biodegradation in the water column may not be rapid (Wildlife Intl, 1996).

2.1.2.3 Soil and Sediment

Based on a measured Koc value of >100,000 HBCD is expected to bind strongly to soil, sediment, and suspended organic matter. It may undergo abiotic and microbial degradation while associated with solids. Tests with viable microbes demonstrated increased HBCD degradation compared to the biologically inhibited control studies. In combination, these studies suggest that HBCD will degrade slowly in the environment, although faster in sediment than in soil, faster under anaerobic conditions than aerobic conditions, faster with microbial action than without microbial action, and at different rates for individual HBCD diastereomers (slower for α-HBCD than for the γ- and β- stereoisomers). The biodegradation half-lives for aerobic sediment and aerobic soil calculated from Davis (2006) (Davis et al., 2006) and Davis (2005) (Davis et al., 2005) were used for the assessment. HBCD has been reported to undergo abiotic degradation in aerobic and anaerobic sediment and aerobic soil (ECHA, 2008b; Davis et al., 2006). The degradation was attributed to abiotic reductive dehalogenation which can form tetrabromo and dibromocyclododecane and 1,5,9-cyclododecatriene. Further degradation of 1,5,9-cyclododecatriene was not observed.

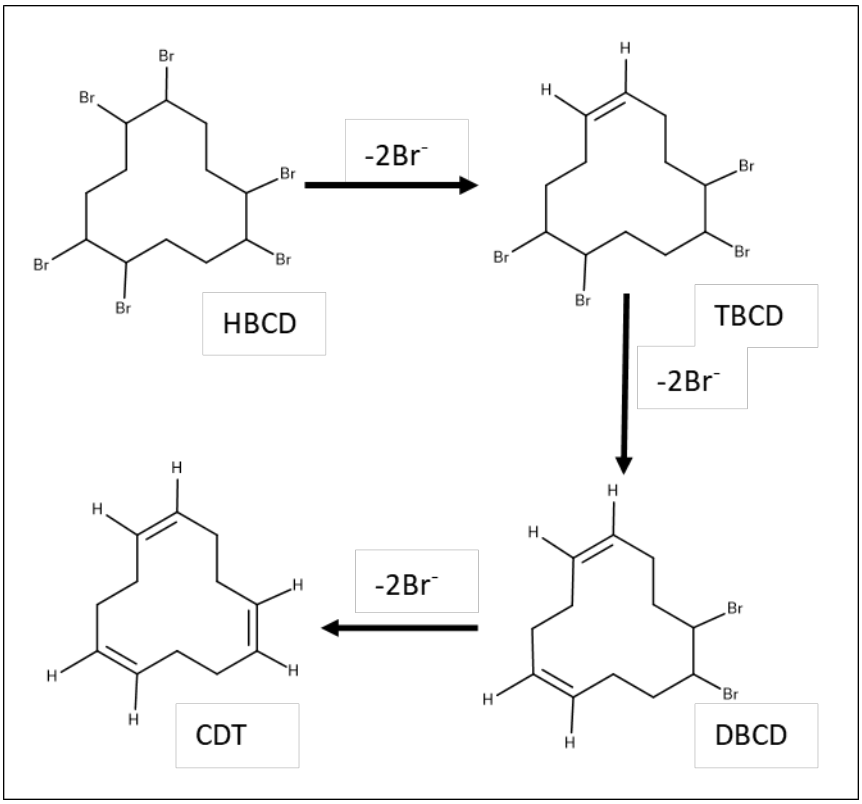

Figure 2-1. Abiotic reduction of HBCD to 5,6,9,10-tetrabromocyclododec-1-ene (TBCD), 9,10-dibromocyclododeca-1,5-diene (DBCD), and 1,5,9-cyclodecatriene (CDT) in aerobic and anaerobic sediments (Davis et al., 2006).

2.1.2.4 Wastewater Treatment Plants

No information was found on the removal of HBCD in Publicly Owned Treatment Works (POTWs) in the United States. However, a study on the removal of HBCD in sewage treatment systems in the Yodo river basin in Japan was identified and reviewed. Ichihara et al. 2014 (Ichihara et al., 2014) measured influent and effluent concentrations of HBCD diastereoisomers in 12 sewage treatment plants in the river basin. The range of removal rates was 80 – 99% with an average of 93% removal. Considering the low volatility and biodegradability of HBCD, the removal was most likely due to sorption to activated sludge solids. The EPA EPISuite STP (Sewage Treatment Plant) model was run for HBCD to provide additional information on HBCD removal. The model simulates an activated sludge wastewater treatment system and includes the processes of volatilization, adsorption to sludge and biodegradation. The model was run using the physical-chemical properties reported in Section 1.1, Table 1-1.The biodegradation half-life was set at 10,000 hours, a default for a non-biodegradable substance. The model calculated approximately 90% removal of HBCD by adsorption to sludge with less than 1% removed by biodegradation and volatilization. No information on the treatability of HBCD bound to plastic particles was found. However, based on the density of these particles a qualitative assessment of their fate in activated sludge systems can be made. Considering the low volatility and biodegradability of HBCD these process are not likely important. Dense particulate HBCD and HBCD associated with polystyrene beads are expected to be removed with sludge during the sludge settling process. Less dense HBCD associated with polystyrene foam may be removed in clarification by skimmers designed to remove floating matter. Based on these findings, HBCD entering activated sludge wastewater treatment systems is expected to be removed with a treatment efficiency in the range of 90% primarily by adsorption to sludge. Volatilization and biodegradation of HBCD are not expected to be important removal processes.

Sludge bound HBCD may be further processed or disposed of by several methods including land application.

2.1.2.5 Persistence

Based on the studies described later in this section HBCD is expected to be persistent in soil, surface water and groundwater. It may be biodegraded slowly under aerobic and anaerobic conditions with half-lives on the order of months.

2.1.2.6 Bioaccumulation/Bioconcentration

Bioaccumulation and bioconcentration in aquatic and terrestrial organisms, including humans, are important environmental processes for HBCD. Bioconcentration is the net accumulation of a chemical by an aquatic organism as a result of uptake directly from the ambient water, through gill membranes or other external body surfaces. Bioaccumulation is the net accumulation of a chemical by an aquatic organism as a result of uptake from all environmental sources. For hydrophobic chemicals such as HBCD, aquatic organisms are exposed via both the diet and ambient water. Thus, bioaccumulation measurements for HBCD more accurately reflect the contribution of all the routes by which aquatic organisms are exposed.

Bioaccumulation factors were calculated for freshwater food webs in industrialized areas of Southern China in two separate field studies. He et al. (He et al., 2013) calculated lipid normalized log BAFs of 4.8 – 7.7 (corresponding to BAFs of 63,000 – 50,000,000) for HBCD diastereomer in carp, tilapia, and catfish, and found higher BAFs for α-HBCD than β- and γ-HBCD. Wu et al. (Wu et al., 2011) calculated log BAFs of 2.85 – 5.98 for the total of all HBCD diastereomers (corresponding to BAFs of 700 – 950,000) in a freshwater food web. Log BAFs for each diastereomer in this study were comparable to one another (see Appendix C.2). La Guardia et al. (La Guardia et al., 2012) calculated log BAFs in bivalves and gastropods collected downstream of a textile manufacturing outfall; these ranged from 4.2 to 5.3 for α- and β-HBCD (BAFs of 16,000 – 200,000), and from 3.2 to 4.8 for γ-HBCD (BAFs of 1,600 – 63,000).

Drottar and Kruger, 2000 (Wildlife Intl LTD, 2000) as cited in (ECHA, 2008b) measured BCF values ranging from 8,974 to 13,085 for HBCD in rainbow trout. Veith et al. (Veith et al., 1979) measured a BCF of 18,100 for HBCD in fathead minnows. These BCF values indicate that HBCD exhibits very high bioconcentration in fish. Widespread detection of this substance in aquatic organisms is further evidence that HBCD bioconcentrates (Marvin et al., 2011; ECHA, 2008b; Covaci et al., 2006). HBCD has also been shown to biomagnify. Based on measurements of HBCD in invertebrates, fish, birds, and marine mammals, biomagnification of HBCD in the aquatic food web is evident, with the highest levels of HBCD measured in seals and porpoises (Shaw et al., 2012; Letcher et al., 2009; ECHA, 2008b; Covaci et al., 2006; De Boer et al., 2002). Terrestrial food chain bioaccumulation has also been demonstrated. In a study using breeding peregrine falcon populations in northern and southwestern Sweden, HBCD concentrations were measured in the eggs of two groups of wild falcons and one group of captive falcons fed only domestic chickens not exposed to HBCD. HBCD was not detected in the eggs of the captive falcons but 150 and 250 ng/g lipid was measured in the eggs of the northern and southwestern populations, respectively, indicating that HBCD bioaccumulation in terrestrial food chains may also be important (Lindberg et al., 2004).

2.1.2.7 PBT Characterization

HBCD has been found to meet the criteria for Persistent, Bioaccumulative and Toxic (PBT) chemicals in assessments conducted by EPA's TRI Program (U.S. EPA, 2016c), ECB (European Chemicals Bureau)

(ECHA, 2008b), Environment Canada/Health Canada (Environment Canada, 2011) and NICNAS (NICNAS, 2012a).

In 2016, EPA finalized a rule adding a hexabromocyclododecane (HBCD) category to the Toxics Release Inventory (TRI) list of reportable chemicals with a 100-pound reporting threshold. EPA set reporting threshold for the Toxics Release Inventory (TRI) HBCD category after determining that it meets the criteria for a PBT chemical. For purposes of EPCRA section 313 reporting, EPA established persistence half-life criteria for PBT chemicals of 2 months in water/sediment and soil and 2 days in air, and established bioaccumulation criteria for PBT chemicals as a bioconcentration factor (BCF) or bioaccumulation factor (BAF) of 1,000 or higher.

In its HBCD risk assessment the European Chemicals Bureau determined that while HBCD does not unequivocally fulfil the specific P (persistence) criterion, with some reliable studies indicating that biodegradation can occur, it does not degrade rapidly, and monitoring data indicate a significant degree of environmental transport and overall stability. The HBCD BCF of 18,100 selected for use in the risk assessment met the vB (very bioaccumulative) criterion. T (toxicity) criterion was found to be fulfilled according to available data. The risk assessment further noted that HBCD is ubiquitous in the environment, being also found in remote areas far away from point sources. The presence of the highest concentrations of HBCD in marine top-predators such as porpoise and seals provided evidence that HBCD bioaccumulates up the food chain. Based on an overall assessment it was concluded that HBCD has PBT properties according to the PBT criteria of the TGD (Technical Guidance Document).

Environment Canada/Health Canada in its Screening Assessment Report on Hexabromocyclododecane determined HBCD meets the criteria for persistence in water, soil, and sediment as outlined in the *Persistence and Bioaccumulation Regulations* under CEPA 1999 (i.e., half-life in water and soil of 182 days or more, and half-life in sediment of 365 days or more). Additionally, HBCD meets the criteria for persistence in air set out in the same regulations (i.e., half-life of two days or more, or being subject to atmospheric transport from the source to a remote area), and the criteria for bioaccumulation as specified in the *Persistence and Bioaccumulation Regulations* under CEPA 1999 (i.e., bioaccumulation factors [BAFs] or bioconcentration factors [BCFs] of 5000 or more).

The Australian Government Department of Health, National Industrial Chemicals Notice and Assessment Scheme (NICNAS) compared the PBT characteristics of HBCD to Australian PBT criteria and POPs criteria described in the Stockholm Convention. Based on laboratory data and international environmental monitoring data, sufficient evidence was found to conclude that HBCD will persist in the environment and meets both Australian and POPs criteria for persistence. Data provided through both laboratory testing and environmental sampling of biota show the chemical (particularly the α isomer) is highly bioaccumulative and can be biomagnified through the food chain. HBCD meets both Australian and POPs criteria for bioaccumulation.

2.1.3 Assumptions and Key Sources of Uncertainty for Fate and Transport

A range of aerobic and anaerobic biodegradation half-lives and bioaccumulation and bioconcentration values have been reported for HBCD. The range of biodegradation half-lives reported were measured in laboratory studies based on OECD methods for biodegradation in water, soil and sediment. These studies are subject to several sources of variability including the specific microbial populations used, water, soil and sediment chemistry, oxygen concentration/redox potential of the collected samples used in the study, temperature and test substance concentration as well as variability inherent in the methodology and interlaboratory variability. No single value of bioconcentration or bioaccumulation is

universally applicable as it is influenced by these variables and possibly others. However, the results of these studies do inform the range of environmental half-lives HBCD might exhibit.

Media specific biodegradation half-lives selected for use in the risk evaluation are used as input to the VVWM-PSC environmental exposure model discussed further in Section 2.3.2. Due to the partitioning properties of HBCD its major pathway is expected to be partitioning to sediments where it is subject to biodegradation. The use of a range of half-lives for aerobic sediment are recommended below. The selection of shorter half-lives in the range as input to the model will result in lower concentrations of HBCD in sediments and lower exposures to sediment dwelling organisms, possibly reducing risk estimates for benthic organisms compared to using half-lives at the longer end of the range.

Half-lives estimated from studies ranged from days to greater than 6 months. Taken as a whole, the studies demonstrate that under some conditions HBCD may undergo some degree of biodegradation (complete biodegradation has not been reported) while under other conditions it does not appreciably biodegrade. When this information is combined with environmental monitoring showing the presence of HBCD in dated sediment cores it can be concluded that HBCD is persistent in the environment. Furthermore, multiple jurisdictions have agreed, based on the available scientific evidence, that HBCD meets criteria for persistence under their regulatory schemes (see Section 2.1.2.7 PBT Characterization)

Although a broad range of biodegradation half-lives for HBCD have been reported in laboratory studies using aerobic and anaerobic soils and sediments and a single study of the biodegradation of HBCD in water has been reviewed, a limited number of quantitative half-life ranges were selected for use in the environmental and general population exposure assessments. Three studies (Davis et al., 2006; Davis et al., 2005; Wildlife Intl, 1996) were used to assess the biodegradation half-lives of HBCD. The results form a dataset that is too small for rigorous analysis. In lieu of such analysis, studies were selected for use in the risk evaluation based of their relevance to the routes of entry of HBCD into the environment. Releases of HBCD in particulate form to air and water are expected from many industrial activities. Based on the environmental transport properties of HBCD, releases to air are expected to be subject to wet and dry deposition to water bodies and soil. HBCD entering water bodies is not expected be to present at high levels in solution, but to sorb to suspended solids and ultimately deposit to sediments. HBCD deposited to soil is expected to sorb strongly with little movement through the soil column. Soil bound HBCD can enter water through run-off. Thus, half-lives for water, soil and sediment were determined to be most relevant for the risk evaluation. The assumption that HBCD enters aerobic sediments leads to the use of aerobic sediment biodegradation half-lives for this medium. As discussed further below, HBCD aerobic biodegradation half-lives are longer than anaerobic half- lives for soil (63 to greater than 120 days aerobic vs 6.9 days anaerobic) and sediment (11 to 128 days aerobic vs 1.1 to 92 days anaerobic). The use of the longer aerobic sediment biodegradation half-lives as input to the environmental exposure model used in the risk evaluation will result in higher concentrations of HBCD in sediments, possibly increasing risk estimates for benthic organisms compared to using anaerobic sediment biodegradation half-lives at the shorter end of the range. Soil biodegradation half-lives were not used as input to exposure models because monitored soil concentrations were available and were used to assess soil related exposure. Thus, the selection of a particular soil biodegradation half-life did not impact the exposure or risk evaluation.

An OECD ready biodegradability study (aerobic aqueous medium) on HBCD resulted in no observed biodegradation in days. This result suggests that aerobic biodegradation in the water column will not be rapid. Adsorption to suspended solids with subsequent deposition to the upper layer of sediment is likely a more rapid process than biodegradation in the water column. Thus, sediment half-life in the upper

sediment layer is more relevant than the water column half-life. It is assumed that the upper layer of sediments is aerobic. HBCD released to air and deposited on soil surfaces is assumed to sorb strongly and remain in the surface layer where aerobic conditions prevail. Thus, aerobic soil biodegradation half-lives are considered most relevant for the soil compartment.

Two studies (Davis et al., 2006; Davis et al., 2005) were selected to assess the biodegradation half-life of HBCD in aerobic soils and aerobic sediments. Davis et al. 2005 and Davis et al. 2006, reported aerobic soil biodegradation half-lives ranging from 63 days to greater than 120 days in viable test systems. Aerobic sediment biodegradation half-lives ranging from 11 days for an HBCD mixture to 128, 92 and 72 days for α-, γ-, and β – HBCD, respectively, were reported. From these studies, half-life values of 2 to 6 months for aerobic soils and 11 days to 4 months for aerobic sediments were chosen. For aerobic soils these values represent the range reported for biodegradation half-lives of HBCD mixtures. For aerobic sediments these values represent the shortest half-life reported for an HBCD mixture and the longest half-life reported for a diastereomer (α- HBCD).

Table 2-2. HBCD Biodegradation Half-Lives Selected for Use in Risk Evaluation

Property	Value	Reference	Study Quality
Aerobic Biodegradation in Water	No biodegradation observed in 28-day closed-bottle test Organisation for Economic Co-operation and Development (OECD) Guideline 301D, EPA OTS 796.3200	(Wildlife Intl, 1996) as cited in (EC, 2008)	Medium
Aerobic Biodegradation in Sediment	Half-life: 128, 92, and 72 days for α-, γ-, and β - HBCD, respectively (estimated), based on a 44% decrease in total initial radioactivity in viable freshwater sediment of 14C-labeled HBCD (4.67 mg/kg dry weight) after 112 days; method based on OECD 308	(Davis et al., 2006)	High
	Half-life: 11 and 32 days (estimated) in viable sediment collected from Schuylkill River and Neshaminy creek, respectively, using nominal HBCD concentrations of 0.034–0.089 mg/kg; method based on OECD 308	(Davis et al., 2005)	High
Aerobic Biodegradation in Soil	Half-life: >120 days (estimated), based on a 10% decrease in total initial radioactivity in viable soil of 14C-labeled HBCD after 113 days; method based on OECD 307 using HBCD at 3.04 mg/kg dry weight	(Davis et al., 2006)	High
	Half-life: 63 days (estimated) in viable soil amended with activated sludge using a nominal HBCD concentration of 0.025 mg/kg dry weight; method based on OECD 307	(Davis et al., 2005)	High

A range of bioconcentration/bioaccumulation values have been reported for HBCD and separately for the three stereoisomers. The range of reported values were measured in laboratory studies or estimated from field collected data. These studies are subject to several sources of variability including variability inherent in the methodology, interlaboratory variability and variability due to factors such as the test species used, test substance concentration, as well as temporal and spatial factors in collection of field samples. No single value is universally applicable as it is influenced by these variables and possibly others. However, taken as a whole, studies indicate HBCD is subject to bioconcentration, bioaccumulation and trophic magnification.

Field measured bioaccumulation factors (BAFs) selected for use in the risk evaluation are used as input to the estimation of general population fish ingestion exposure discussed further in Section 2.4.2.3. The consideration of two BAF values, one higher and one lower, is recommended below. Both studies were rated high for data quality. The differences in reported BAFs could be due to a number of factors including the metabolic differences in the test species selected. The selection of the higher BAF as input to the estimation of general population fish ingestion exposure will result in higher fish tissue concentrations of HBCD and higher exposures to general population via fish ingestion. This will lead to estimates of higher risk for this population compared to using the lower BAF value. Due to the small number of field derived fish BAF studies found (2) it was not possible to assess the variability in field derived BAFs across field conditions, dissolved HBCD concentrations, species and trophic levels. In the studies EPA identified, the reported dissolved HBCD concentrations in Chinese water bodies were in the range of 0.04 to 0.06 ng/L. These are about an order of magnitude lower than the range of dissolved HBCD surface water concentrations reported in surface water monitoring studies. The range of HBCD surface water concentrations biota are assumed to be exposed to for the risk evaluation was determined using monitoring data and model estimates. Using available data, an upper trophic level lipid normalized field measured BAF (northern snakehead) was selected for use as a surrogate species for the fish ingestion exposure assessment. The use of lipid normalized field measured BAF data for an upper trophic level species incorporates results of dietary exposure and biomagnification in the food web. However, the small number of BAF values, the limited number of species and field conditions add to uncertainty associated with the use of these BAFs in estimating human exposure to HBCD via fish ingestion.

For the purposes of the risk evaluation, lipid normalized bioaccumulation factors in whole fish consumed by humans, and bioconcentration factors in species in aquatic and terrestrial food webs were used. These values are converted to wet weight BAF values (BAF_{WW}) for use in dietary exposure calculations using the following formula:

$$BAF_{WW} = BAF_{LW} * \text{lipid fraction}$$

See Appendix C.3 for underlying data and calculations of BAFs for HBCD.

Field-measured bioaccumulation factors for HBCD were preferentially used over bioconcentration factors for the risk evaluation. A BAF derived from data obtained from field-collected samples of tissue and water is the most direct measure of bioaccumulation. A field-measured BAF is determined from measured chemical concentrations in an aquatic organism and the ambient water collected from the same field location. Because the data are collected from a natural aquatic ecosystem, a field-measured BAF reflects an organism's exposure to a chemical through all relevant exposure routes (e.g., water, sediment, diet). A field-measured BAF also reflects factors that influence the bioavailability and metabolism of a chemical that might occur in the aquatic organism or its food web. Therefore, field-measured BAFs are appropriate for all chemicals, regardless of the extent of chemical metabolism in biota (U.S. EPA, 2003). Specifically, the field measured BAFs reported by (He et al., 2013) and (Wu et al., 2010) were selected. These studies scored high using data quality metrics for environmental fate studies. In addition, the studies reported BAF values in upper trophic level (i.e., piscivorous fish). BAFs in organisms occupying higher trophic levels in food webs may better reflect exposure due to dietary uptake than organisms in lower trophic levels. Using data from He, et al, 2013, an upper trophic level lipid normalized BAF for total HBCDs of approximately 9,090,000 was calculated from the mean HBCD lipid normalized fish tissue concentration and the HBCD dissolved water concentration. Using data from Wu, et al, 2010, an upper trophic level lipid normalized BAF for total HBCDs of approximately 3,120,000 was calculated

from the mean HBCD lipid normalized fish tissue concentration and the HBCD dissolved water concentration. It should be noted that in both the studies, sample sizes for fish were small (n= 6 – 15) and variability in tissue concentrations for a single species of fish was as high as 3 times the mean value. While this variability leads to uncertainty in the use of the data, the preference for the use of upper trophic level field measured BAFs and lack of other similar studies was considered in the decision to use the study. The steady-state BCF values in rainbow trout edible portions. (Wildlife Intl LTD, 2000) as cited in (ECHA, 2008b) were used to supplement the risk evaluation. A kinetic BCF value of 14,039 for the 0.18 µg/L exposure concentration was calculated to address the possibility that steady state was not reached (ECHA, 2008b). The study received a high confidence score based on evaluation metrics for fate studies.

Due to the small number of field derived fish BAF studies found (2) it was not possible to assess the variability in field derived BAFs. EPA did not have a sufficient number of bioaccumulation studies to follow the Office of Water methodology for deriving bioaccumulation factors intended to develop BAFs for setting national water quality criteria (U.S. EPA 2000)(U.S. EPA) The methodology is generally used with large sets of BAF data for multiple trophic levels and species from studies reflecting a range of geochemical and biological conditions. EPA identified two BCF studies and two BAF studies on HBCD. BAF studies are preferred over BCF studies because they represent exposure of the organism to HBCD via all routes, including diet which is important for a hydrophobic chemical such as HBCD. The BAF studies (Wu et al. 2010; He et al. 2013) reported data EPA used to calculate upper trophic level lipid normalized BAFs for several trophic levels, however, the species reported were native to China. With limited available data EPA chose to use the upper trophic level species (northern snakehead) as a surrogate for an upper trophic level species native fish and assume its lipid normalized BAF as equivalent to that of an upper trophic level native fish. Because a single BAF from a single species is used, impacts of factors including lipid content, organism size, spatial and temporal variability in exposure concentrations, sample size, trophic position and differences in food webs and ecosystems cannot be considered. The absence of this information creates uncertainty in how representative the BAF may be and if its use will under or overpredict fish tissue concentrations and human exposure via fish ingestion.

Table 2-3. HBCD Bioaccumulation and Bioconcentration Factors Selected for Consideration in Risk Evaluation

Property	Value	Reference	Study Quality
Field Measured Bioaccumulation Factor (BAF)	Upper trophic level lipid normalized BAF for total HBCDs of approximately 9,090,000 calculated from the mean HBCD lipid normalized fish tissue concentration and the HBCD dissolved water concentration. Wet weight BAF 290,880	(He et al., 2013)	High
	Upper trophic level lipid normalized BAF for total HBCDs of approximately 3,120,000 calculated from the mean HBCD lipid normalized fish tissue concentration and the HBCD dissolved water concentration. Wet weight BAF 46,488	(Wu et al., 2010)	High
Bioconcentration Factor (BCF)	fathead minnow 18,100 (whole body)	(Veith et al., 1979)	High
	rainbow trout 4650 – 6531 (edible portion) 14039 (kinetic BCF 0.18 µg/L exposure concentration)	(Wildlife Intl LTD, 2000) as cited in (ECHA, 2008b)	High

2.2 Releases to the Environment

EPA assessed environmental releases of HBCD for the following HBCD conditions of use:

1. Processing: Repackaging of Import Containers
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch
4. Processing: Manufacturing of XPS Foam using HBCD Powder
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam
7. Use: Installation of Automobile Replacement Parts
8. Use: Installation of XPS/EPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures
9. Demolition and Disposal of XPS/EPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures
10. Processing: Recycling of EPS Foam
11. Processing: Formulation of Flux/Solder Pastes
12. Use of Flux/Solder Pastes

Appendix E includes a crosswalk between the subcategories of use listed in the *Problem Formulation Document for Cyclic Aliphatic Bromide Cluster (HBCD)* and the conditions of use assessed in this risk evaluation.

Components of the Environmental Release Assessment

The environmental release assessment of each condition of use comprises the following components:

- **Process Description:** A description of the condition of use, including the role of the chemical in the use; process vessels, equipment, and tools used during the condition of use; and descriptions of the worker activities, including an assessment for potential points of worker exposure and environmental releases.
- **Facility Estimates / Processing or Use Volume and Number of Sites:** An estimate of the quantity of HBCD imported, processed, or otherwise used for each condition of use. An estimate of the number of sites that use the chemical for the given condition of use.
- **Environmental Releases:** Estimates of chemical released into the environment (air, surface water, land) and wastes disposed to treatment methods (incinerators, wastewater treatment plants).

2.2.1 Release Assessment Approach and Methodology

Process Description

EPA performed a literature search to find descriptions of processes involved in each condition of use to identify worker activities that could potentially result in releases to the environment. Where process descriptions were unclear or not available, EPA referenced relevant emission scenario documents (ESD's) and generic scenarios (GS's), specifically the 2009 OECD ESD on Plastic Additives, the 2014 Draft OECD ESD on Use of Additives in Plastics Compounding, and the 2010 OECD ESD on Chemicals Used in the Electronics Industry. The process description for each condition of use will be discussed in this section.

Processing or Use Volume and Number of Sites

As indicated in Section 1.2.2 and 1.2.3, EPA has determined that the import of HBCD constitutes an intended, known and reasonably foreseen activity. The companies identified by the 2016 CDR as importers of HBCD have ceased importing, processing and using HBCD. The possibility exists that small firms could import quantities of up to 100,000 lbs/year per site without reporting to CDR. For the purpose of this risk evaluation, EPA used the CDR reporting threshold for small manufacturers (importers) of 100,000 pounds per year as the volume of HBCD imported by a possible unidentified site. EPA believes this volume is not unreasonable considering the recent relatively high volumes of HBCD manufactured / imported, processed and used through 2017 for XPS/EPS foam as shown in Table 1-2. and Table 1-4. EPA does note, however, that 100,000 pounds per year is an upper bound for the import volume for the unknown site, otherwise, the site would be out of compliance with CDR reporting requirements. The lifecycle of the imported HBCD and more specifically the percentage of the volume used for each of the COUs is uncertain, and therefore, EPA uses the volume basis of 100,000 pounds per site per year to estimate environmental releases and exposures of each of the following COUs that entail the processing of HBCD for products and formulations containing HBCD:

1. Processing: Repackaging of Import Containers
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch
4. Processing: Manufacturing of XPS Foam using HBCD Powder
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam (the processing volume for each condition of use is 100,000 pounds/year)

The import volume of 100,000 pounds per year is also used for assessing releases, number of sites, and exposures for the following conditions of use and will be further described in Sections 2.2.8 and 2.2.9, respectively:

a) Use: Installation of Automobile Replacement Parts
b) Use: Installation of XPS/EPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

EPA performed the sensitivity analysis for selected conditions of use using import volumes of 50,000 lbs/yr and 25,000 lbs/yr to examine the effect of process volume on environmental releases and resulting general population exposures and the environment. This is discussed in Section 2.2.14.

Environmental Release Assessment

EPA assessed, where applicable, releases to fugitive or stack air, discharges to on-site wastewater treatment (WWT), Publicly Owned Treatment Works (POTWs), or surface water, disposal to landfill, and treatment via incineration. EPA refers to these as methods of release, disposal, treatment, or disposal in the remainder of this section. All releases assessed are of solid HBCD or solid mixtures containing HBCD.

EPA assessed releases to landfill for Processing: Repackaging of Import Containers, Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads, Processing: Recycling of EPS Foam and Reuse of XPS Foam, Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam, and Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures in accordance with the 2009 OECD ESD on Plastic Additives. EPA assessed releases to landfill for Demolition and Disposal in accordance with data from

(Managaki et al., 2009) and for Use of Flux/Solder Pastes in accordance with the 2010 OECD ESD on Chemicals Used in the Electronics Industry. The landfill types is not specified in these sources. Releases to RCRA Subtitle C hazardous waste landfills and RCRA Subtitle D municipal solid waste landfills (MWSLFs) are not included in the risk evaluation, as discussed in the PF document (U.S. EPA, 2018f). However, because HBCD is not designated as hazardous waste, EPA believes that HBCD waste may be sent to industrial non-hazardous landfills, which are described here: https://www.epa.gov/landfills/industrial-and-construction-and-demolition-cd-landfills. Therefore, EPA assessed releases to these types of landfills.

EPA gathered and evaluated environmental release information according to the process described in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a). The key data sources resulting from this process that were used to assess releases include 2017 TRI data, the European Union Risk Assessment Report (EURAR), and Managaki et al (Managaki et al., 2009). The 2017 TRI data has an overall confidence rating of medium. The EURAR and Managaki et al (2009) have overall confidence ratings of high. EPA prefers directly applicable release data; however, where these data were not available, EPA used emission factors from the 2009 OECD ESD on Plastic Additives, the 2018 Draft GS on the Application of Spray Polyurethane Foam, and the 2010 OECD ESD on Chemicals Used in the Electronics Industry.

Where available, EPA used 2017 TRI data to provide a basis for estimating releases. Facilities are only required to report to TRI if the facility has 10 or more full-time employee equivalents, is included in an applicable NAICS code, and manufactures, processes, or otherwise uses the chemical in quantities greater than a certain threshold in a given year (100-pound threshold for HBCD). Due to these limitations, some sites that use HBCD may not report to TRI and are not included in these datasets. EPA did not use some of the TRI data based on additional information gathered about current uses and reported releases. Specifically, EPA did not use the 2017 releases reported by Flame Control Coatings, LLC. The company indicated that they have ceased the use of HBCD in coatings. As indicated in Section 1.2.7, EPA determined this is a discontinued use of HBCD.

Where releases are possible, but TRI data were not available, releases were estimated using release data from the European Union Risk Assessment Report (EURAR) or relevant OECD Emission Scenario Documents (ESDs) or EPA Generic Scenarios (GSs). EPA rated the release data from the EURAR an overall confidence rating of High during the systematic review process. This rating takes into account the reliability of the data (EPA considers the European Chemicals Agency [ECHA] to be a reliable source), the representativeness of the data, the accessibility / clarity of the data, and the variability and uncertainty of the data. ESDs and GSs are standard sources used by RAD for engineering assessments. These documents provide information on particular processes, including release sources, emission factors, and method of release, disposal, treatment, or discharge.[11] EPA attempts to address variability in releases estimated with EURAR or OECD ESD and EPA GS data by estimating ranges of emission factors and release days, as further described below.

Specifically, for each condition of use, EPA estimated daily and annual quantities of HBCD released, where applicable using the following parameters:

- The annual importation, processing, or use volume per site.
- The number of importation, processing, or use sites.

[11] Additional information on OECD ESDs can be found at: http://www.oecd.org/chemicalsafety/risk-assessment/introductiontoemissionscenariodocuments.htm. Additional information on EPA GSs can be found at: https://www.epa.gov/tsca-screening-tools/chemsteer-chemical-screening-tool-exposures-and-environmental-releases.

- The emission factors for releases of HBCD.
- The number of days of HBCD releases.

The general approach for determining annual importation, processing, or use volume and the associated number of sites for each condition of use is discussed above.

An emission factor is the fraction of material emitted or released per unit volume (i.e., kg released/kg throughput) during a specific activity or condition of use (e.g., import, processing, or use). EPA determined emission factors either from EURAR data or from ESDs or GSs. Where available, EPA used EURAR release data, which is available as annual site-specific HBCD release quantities. The associated HBCD processing volumes at these sites were not provided in the EURAR. The EURAR only provided the combined HBCD processing volume for all the sites for which release data was provided. EPA could not calculate site-specific emission factors due to the lack of site-specific HBCD processing volumes. Using EURAR data, EPA calculated overall emission factors for a condition of use by dividing the total amount of HBCD released for all sites by the total HBCD processing volume for all the sites. For the purpose of this risk evaluation, EPA refers to these emission factors as average emission factors. In some cases, the EURAR provided what they call "worst-case" emission factors, described as being derived from the site with the highest release estimates. In these cases, EPA used these "worst-case" emission factors as they were reported by the EURAR because EPA could not calculate them without the site-specific HBCD processing volumes. EPA used both the average and "worst-case" emission factors from the EURAR to provide a range of emission factors and release quantities.

Where EURAR data were not available, EPA used emission factors that were reported in OECD ESDs or EPA GSs. Where there were multiple approaches for estimating emission factors in the ESDs or GSs, such as from assuming different types of containers or vessels are being cleaned, EPA assessed a range of emission factors. The information provided in ESDs and GSs generally do not have statistical characterization of the emission factors.

EPA calculated a range of annual release quantities for each condition of use by multiplying the range of emission factors and the annual throughput of HBCD at a site that was assumed by EPA for this risk evaluation. EPA calculated daily release quantities by dividing the range of annual release quantities by the estimated number of release days. For all conditions of use, EPA estimated a range of release days to generate a range of daily release estimates. In general, EPA used the lowest estimated value and the highest estimated value of number of release days to develop a range. EPA does not know the statistical characterization (e.g., mean, maximum, 95th percentile) of these ranges because EPA did not find a comprehensive dataset of release days from which these statistics could be calculated. In order to develop estimates of release days in support of determining these ranges, EPA used one or a combination of the following approaches, in order of priority:

- Where available, EPA used the number of release days reported in the EURAR for the sites with HBCD release days. The number of release days is based on industry data for sites that perform the same operations as those being assessed.
- Where data on release days reported by industry was not available, EPA estimated the number of release days using ESDs or GSs.
- Where data were limited using the above two approaches, EPA estimated the number of release days using the European Communities Technical Guidance Document (ECB, 2003). This technical guidance document contains methodology for estimating the number of release days using the industry category (i.e., chemical manufacturing, polymer processing, electronics), function within the industry (i.e., manufacturing, formulation, or use), and the throughput of the

chemical of interest (i.e., HBCD importation, processing, or use volume). EPA estimated the number of release days using the most applicable industry category, which was the polymer processing industry in most, but not all, conditions of use. EPA then selected the most applicable function within the industry for the condition of use and used the assessed site-specific HBCD throughput to determine the number of release days. In some cases, where the above two approaches could not be used, EPA developed ranges of release days using this method by determining the lowest and highest number of potential release days by varying the function and HBCD throughput within an industry category.

Using the HBCD throughput, number of sites, a range of emission factors, and a range or release days, EPA calculated a range of daily releases per site for each condition of use using Equation 2-1:

Equation 2-1 $$\boldsymbol{R = [(V \div N_s) \times f] \div N_d}$$

Where:

R = the amount of HBCD released per day to water, air, or landfill from a site (kg per day per site)
V = annual U.S. HBCD importation, processing, or use volume (kg per yr)
N_s = the number of U.S. importation, processing, or use sites (sites)
f = emission factor for release of HBCD to water, air, or landfill from a process (kg of HBCD released to water or air or landfill per kg of HBCD imported, processed or used)
N_d = the number of release days per year from a site (days)

Specific details related to the use of release data or models and the calculation of ranges of emission factors and release days for each condition of use are further described below.

Releases to air were assessed as hourly rates to enable the modeling of these releases for the assessment of general population exposure. EPA assumes the industrial processes that are associated with the condition of use are operated at least 8 hours per day . Furthermore, air release sources such as unloading and addition into processing equipment may occur throughout a day, so EPA assumes air releases may occur over the entire operation time of 8 hours/day. This may result in underestimation or overestimation of the hourly rate of releases to air.

2.2.2 Processing: Repackaging of Import Containers

In the United States, HBCD was manufactured in three grades: fine powder, standard grade powder, and granules (ECHA, 2008b). HBCD particle size distribution in HBCD products varied depending on the producer and is summarized as follows (NICNAS, 2012b; ECHA, 2008b):

- For fine grade powder, the mean particle size was 2 to 19 µm.
- For standard grade powder, the mean particle size was 20 to 150 µm.
- For granules, the mean particle size was 560 to 2,400 µm.

HBCD was manufactured at a purity of 90% to 100% HBCD (NICNAS, 2012b; KemI, 2009). EPA expects that HBCD would also be imported into the United States at this purity in standard grade powder or granular form as specified above. HBCD may also be imported in EPS resin beads at a concentration of 0.7% or in XPS masterbatch at a concentration of 40-70% (NICNAS, 2012b; ECHA, 2008b). Micronized (fine grade) powder is typically used in textile and adhesive formulations

(NICNAS, 2012b; ECHA, 2008b), which EPA has determined are no longer conditions of use in the United States and are not assessed in this risk evaluation.

EPA has not identified information on the importation and repackaging of HBCD within the United States. However, EPA expects that importation activities described in risk assessments performed by other countries are similar to those performed in the United States.

The Australian Priority Existing Chemical Assessment Report on HBCD indicates that powder or granular HBCD was imported into Australia in 25-kg polylined paper bags and states that this took place prior to 2010. The report also indicates that EPS resin beads containing HBCD were imported in 25-kg polylined paper bags and 700-kg lined meshed plastic bags (NICNAS, 2012b). The European Union Risk Assessment Report (EURAR) on HBCD indicates that HBCD powder was packaged in 850-kg boxes (ECHA, 2008b). Based on information from the Australian Report and the EURAR, EPA evaluated releases from repackaging assuming HBCD may be imported in 700-kg bags or 850-kg boxes, which may be repackaged into differently sized containers, depending on customer demand, and quality control (QC) samples may be taken for analyses.

Once imported into the United States, HBCD powder is used to produce XPS masterbatch or to directly produce XPS foam.[12] Imported EPS resin beads are used to produce EPS foam. Repackaging of import containers occurs on an as-needed basis, driven by customer demand. Exposures and releases are not expected if repackaging of HBCD into smaller containers does not occur.

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.1, EPA estimates environmental releases based on a processing volume of 100,000 pounds per site per year and estimates a single unidentified site for this condition of use.

Release Sources

Based on the process description, EPA infers that releases may occur from dust generation during the transfer of HBCD powder, granules, or masterbatch from import containers into new containers and from residual HBCD in the emptied import containers that are disposed. NICNAS (2012b) includes information from one company that repackaged HBCD in an open or semi-closed process. EPA does not know the prevalence of closed repackaging systems in the United States and estimates dust releases as described below. Repackaging of HBCD into smaller containers may involve the use of equipment, such as hoppers. However, EPA believes that the cleaning of such equipment would be infrequent (e.g., done for maintenance purposes only) and there would be minimal residual material in the equipment prior to cleaning because such equipment would be designed for gravity flow of solid particulates. Therefore, EPA did not assess releases from equipment cleaning in this condition of use. NICNAS (2012b) and Environment Canada (EC/HC, 2011) did not assess release from equipment cleaning. The EURAR (ECHA, 2008b) did not assess repackaging as a condition of use.

Emission Factors

EPA used the emission factors given in the 2009 OECD ESD on Plastic Additives (OECD, 2009), specifically for flame retardants used in activities expected to occur during this condition of use, as

[12] In this Risk Evaluation, EPA refers to EPS and XPS foam articles, including insulation, as EPS and XPS foam. Note that the Problem Formulation for Cyclic Aliphatic Bromides Cluster (HBCD) prepared prior to this Risk Evaluation often referred to these foam articles simply as EPS and XPS.

described below. The 2009 OECD ESD on Plastics Additives estimates releases by applying emission factors to the throughput of the chemical of interest, in this case HBCD (OECD, 2009). For dust releases, the OECD ESD estimates an emission factor of up to 0.5% for fine particles (<40 µm) and 0.1% for coarse particles (>40 µm). EPA uses this range of emission factors to estimate dust releases. Per the OECD ESD, the initial release is to air, with particles eventually settling and being disposed of as solid waste or discharged in wastewater from cleaning of surfaces onto which the particles have settled (OECD, 2009). The specific method of release, disposal, treatment, or discharge is dependent on site-specific factors, such as any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the importation site. EPA does not know the prevalence of dust capture and control technologies at importation sites in the United States. Depending on site-specific conditions, HBCD may be released to stack air or fugitive air, discharged to POTW or onsite WWT, disposed of to landfill, or treated via incineration (OECD, 2009).

For container residue, the OECD ESD on Plastics Additives uses an emission factor of 1%. The OECD ESD indicates that containers are likely to be disposed of to landfill. EPA uses this emission factor to estimate release of solid HBCD from container disposal to landfill. Although there is no statistical characterization of this emission factor, EPA believes the 1% emission factor is in the upper end of the distribution based on EPA's experience. No other release sources are identified in the OECD ESD or expected by EPA, based on the process description, for this condition of use.

A summary of the release sources assessed by EPA is presented in Table 2-4.

Table 2-4. Summary of HBCD Release Sources During Repackaging of Import Containers

Release Source	Emission Factor used in this Risk Evaluation	Method of Release, Disposal, Treatment, or Discharge Assessed in this Risk Evaluation	Basis or Source
Dust generation from unloading solid standard grade powder from import containers into new containers	0.001-0.005 kg HBCD released/kg HBCD handled	Uncertain: Stack air, or Fugitive Air, POTW, Onsite WWT, Landfill, or Incineration	(OECD, 2009)
Disposal of import containers (bags) containing solid HBCD	0.01 kg HBCD released/kg HBCD in containers	100% Landfill	(OECD, 2009)

Number of Release Days

EPA estimated the number of release days based on information in the European Communities Technical Guidance Document (ECB, 2003). EPA estimated the lowest and highest possible number of release days per year using data from the basic chemicals industry category in the European Communities Technical Guidance Document. EPA calculates a lower value of 29 days/year and an upper value of 300 days/year. This range of number of release days per year seems reasonable in comparison to information from the Australian risk assessment (NICNAS, 2012b) which indicates that one company in Australia infrequently repackaged HBCD imported in 25-kg bags into 15-kg bags at a rate of one metric ton of HBCD repackaged every three months over a period of five days per repackaging campaign. Using this repackaging rate of one metric ton (2,205 pounds) over five days and EPA's production volume of 100,000 pounds HBCD/year, EPA calculates a United States repackaging frequency of approximately 227 days/year. The estimate of 227 day/year falls within the range of 29 to

300 days/year. Based on these data, EPA estimated a range of release days for this condition of use of 29 to 300 days/year.

The data sources used to estimate releases in this section are listed in Table 2-5 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-5. Repackaging of Import Containers - HBCD Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECB, 2003)	Days of Release	29 to 300 days/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-6.

Table 2-6. Input Variables to Equation 2-1 for Repackaging of HBCD Import Containers

Input Variable				
V (of HBCD)	N_S (sites)	f (kg HBCD released/kg HBCD imported)		N_d (days/yr)
		Lower value of emission factors	Upper value of emission factors	
100,000 pounds/year = 45,359 kg/year[a]	1	0.001 to Stack air, Fugitive Air, POTW, Onsite WWT, Landfill, and/or Incineration 0.01 to Landfill	0.005 to Stack air, Fugitive Air, POTW, Onsite WWT, Landfill, and/or Incineration 0.01 to Landfill	29-300

[a] CDR reporting threshold for small manufacturers (U.S. EPA, 2016a)

The results of these calculations for all methods of release, disposal, treatment, or discharge are summarized in Table 2-7. EPA presents a range of release estimates from the 2009 OECD ESD on Plastic Additives (OECD, 2009), varied over a range of release days, as previously discussed. The repackaging of import containers may result in releases to air, discharge to POTW, and/or disposal to landfill. Overall, disposal to landfill exceeds air releases and wastewater discharges, largely due to the disposal of the bags in which HBCD is imported.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates and medium confidence in the assessed range of number of release days per year that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA is highly confident in this assessment approach, which is a strength of the assessment. EPA implemented this approach using emission factor data and data on number of release days and assigned an overall confidence rating of medium to the data on number of release days using systematic review as discussed above; the quality of the emission factor data was not evaluated because this data was obtained from an OECD ESD. The limitations of the assessment are uncertainties about the extents to which the emission factor data and

the data on number of days of release per year are applicable to the HBCD processing that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-7. Summary of HBCD Releases from Repackaging of Import Containers

Release Source	Method of Release, Disposal, Treatment, or Discharge (a)	Releases calculated from lower value of range of emission factors [b]				Releases calculated from upper value of range of emission factors [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 29 days/year	Number of release days: 300 days/year			Number of release days: 29 days/year	Number of release days: 300 days/year		
Dust release during unloading of HBCD	May go to one or more: Stack air, Fugitive Air, on-site WWT, POTW, landfill, or incineration	45.4	45.4	1.56	0.15	227	227	7.82	0.756	1	8 hours/day
Disposal of transport bags containing solid HBCD residual	Landfill	454	454	15.64	1.51	454	454	15.64	1.51	1	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid HBCD.

2.2.3 Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch

Imported HBCD powder or granules may be compounded into an XPS masterbatch prior to being sold to XPS foam manufacturers, who then convert the XPS masterbatch into XPS foam. Imported HBCD powder may be sent to XPS masterbatch compounding sites in 25-kg bags or supersacks (ECHA, 2008b). HBCD is unloaded into a hopper and pre-blended with polystyrene in the hopper or else transferred directly to mixing equipment. From the mixer, the mixture is then fed into an extruder where it is extruded through a die to produce pellets or granules (NICNAS, 2012b). The pellets or granules are air-cooled or cooled in a water bath, dried, and then packaged (ECHA, 2008b). The HBCD content in the XPS masterbatch is up to 40-70% of the pellets (NICNAS, 2012b; ECHA, 2008b). The packaged XPS masterbatch is then sent to converting sites, where it is turned into XPS foam.

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.1, EPA estimates environmental releases based on a processing volume of 100,000 pounds per site per year and estimates a single unidentified site for this condition of use.

Release Sources

Based on the process description, EPA infers that releases may occur from: dust generation during unloading of the HBCD powder or granules from the bags in which they were received and during the compounding process; disposal of the bags in which the HBCD powder is received; and cleaning of process equipment.

Emission Factors

EPA estimated emission factors based on site-specific release data reported in the EURAR (ECHA, 2008b). The EURAR identified 14 sites in the EU that compound polystyrene to produce XPS masterbatch that is flame retarded with HBCD (ECHA, 2008b). Site-specific annual release rates of solid HBCD were reported for three of the sites, indicating releases to wastewater and air, which are summarized in Table 2-8. To maintain confidentiality, the EURAR did not provide site-specific HBCD processing volumes with which site-specific emission factors could be calculated. However, the EURAR provided the total HBCD processing volume for the three sites for which release data is available. EPA calculated overall average emission factors to air and water by dividing the total HBCD release to air or water from all three sites by the total HBCD processing volume for the three sites. EPA calculated overall average emission factors of 3.22×10^{-5} kg HBCD discharged/kg HBCD processed to water and 6.12×10^{-6} kg HBCD released/kg HBCD processed to air.

The EURAR also provided emission factors of 7.42×10^{-5} kg HBCD discharged/kg HBCD processed to water and 7.31×10^{-6} kg HBCD released/kg HBCD processed to air, indicating that these are the "worst-case" factors that the EURAR calculated using the site-specific release and HBCD processing volume data from the three sites. Because site-specific HBCD processing volume data were not provided, EPA could not calculate these "worst-case" emission factors. EPA used both the "worst-case" emission factors as they were reported in the EURAR and the average emission factors calculated by EPA to provide a range of release estimates during this condition of use.

The EURAR indicates that wastewater discharges are to wastewater treatment. EPA did not identify information about the prevalence of wastewater treatment at these types of processing sites in the United States and hence assumed that water discharges from this condition of use can be to surface water, POTW, and/or onsite wastewater treatment. The EURAR does not specify if the reported air releases for

these three sites are to stack or fugitive air. Sites may implement dust capture technologies that may determine whether this release is to stack or fugitive air. EPA did not identify information on the prevalence of dust capture technologies at processing sites in the United States and assesses this release may include stack air and/or fugitive air.

Table 2-8. HBCD Release Data Reported in the EURAR for XPS Masterbatch Production

Site-Specific Release Data			Process Volume
Site Identity	Release to Water	Release to Air	
	kg/yr	kg/yr	
Site 1	0.12	2.6	The EURAR identifies a total of 1,160 metric tons of HBCD is processed at the 3 sites with site-specific release data.
Site 2	0.27	1.2	
Site 3	37	3.3	

Number of Release Days

EPA estimated the number of release days based on information reported in the European Communities Technical Guidance Document (ECB, 2003) because the actual number of release days associated with the site-specific annual release rates discussed above is not reported in the EURAR. Instead, the number of release days reported in the EURAR are defaults recommended in the European Communities Technical Guidance Document (ECB, 2003). The Environment Canada assessment also estimated emission days for compounding with the same methodology (EC/HC, 2011). HBCD compounding occurs once per day at a site for the production polystyrene masterbatch according to the Australian risk assessment. EPA did not use this information because the HBCD processing volume is not reported. Using the European Communities Technical Guidance Document (ECB, 2003) and the defaults for formulation within the polymer industry, EPA estimated 60 emission days/year for an HBCD processing volume of 100,000 pounds (45.3 metric tons). EPA used the 2014 Draft OECD ESD on Use of Additives in the Plastics Compounding to estimate the number of release days during this condition of use. The OECD ESD indicates that, based on EPA new chemical submissions from industry, that the lowest number of operating days reported was 10 days/year (U.S. EPA, 2014a). Based on these data, EPA estimated a range of release days of 10 to 60 days/year.

The data sources used to estimate releases in this section are listed in Table 2-9 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-9. Compounding of Polystyrene to Produce XPS Masterbatch Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECHA, 2008b)	Site-Specific Release Data	See Table 2-8	High
(ECHA, 2008b)	"Worst-Case" Emission Factors	7.42×10^{-5} to water and 7.31×10^{-6} to air	High
(ECB, 2003)	Release Days	10 to 60 days/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-10.

Table 2-10. Input Variables to Equation 2-1 for XPS Masterbatch Production

Input Variable				
V (of HBCD)	N_S (sites)	f (kg HBCD released/kg HBCD processed)		N_d (days/yr)
		Average calculated from EURAR data	"Worst-case" given in EURAR	
100,000 pounds/year = 45,359 kg/year	1	6.12E-06 to stack air and/or fugitive air 3.22E-05 to surface water, onsite WWT, and/or POTW	7.31E-06 to stack air and/or fugitive air 7.42E-05 to surface water, onsite WWT, and/or POTW	10-60
Note: [a]CDR reporting threshold for small manufacturers (U.S. EPA, 2016a)				

The daily amount of solid HBCD released per site from compounding of polystyrene to produce XPS masterbatch was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-11.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates and medium confidence in the assessed range of number of release days per year that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA is highly confident in this assessment approach, which is a strength of the assessment. EPA implemented this approach using the following two groups of data: (a) release, processing volume and emission factor data and (b) data on number of release days and assigned an overall confidence rating of high and medium, respectively, to these two groups using systematic review as indicated above. The limitations of the assessment are uncertainties about the extents to which the emission factor data, including the emission factors

calculated from release and processing volume data, and the data on number of days of release per year are applicable to the HBCD processing that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-11. Summary of HBCD Releases from XPS Masterbatch Production

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from average emission factor based on EURAR release data [b]				Releases calculated from worst case emission factor as it was reported in the EURAR [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 10 days/year	Number of release days: 60 days/year			Number of release days: 10 days/year	Number of release days: 60 days/year		
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Stack air or fugitive air	0.278	0.278	0.028	4.63E-03	0.332	0.332	0.033	5.53E-03	1	8 hours/day
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Surface Water, Onsite WWT, or POTW	1.46	1.46	0.15	2.44E-02	3.37	3.37	0.337	5.61E-02	1	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid HBCD or solid mixtures containing polystyrene and HBCD.

2.2.4 Processing: Manufacturing of XPS Foam using XPS Masterbatch

XPS masterbatch is used to make XPS foam. The HBCD content in the XPS masterbatch ranges from 40 to 70 weight percent within the XPS masterbatch pellets or granules (NICNAS, 2012b; ECHA, 2008b).

Once received at XPS foam production sites, the XPS masterbatch, along with additional polystyrene and other additives such as dyes, are charged to an extruder (ECHA, 2008b). In the extruder, the polystyrene is melted, allowing the HBCD and other additives to become suspended in a polymer gel. Blowing agent is added to the gel, the gel is cooled, and it is then extruded through a die where the blowing agent volatilizes. This volatilization within the plastic gel causes the plastic to become a foam as it is extruded (ECHA, 2008b). HBCD content in XPS foam ranges from 0.5 to 3 wt% (U.S. EPA, 2015; Takigami et al., 2014; EC/HC, 2011; ECHA, 2008b).

Once the XPS foam is made, it may be cut, sawed, or machined into various shapes (often referred to as secondary processing), shrink-wrapped, palleted, and shipped to structural insulated panels (SIPs) and

automotive replacement part production sites or directly to end users for installation into structures such as buildings (ECHA, 2008b). Additionally, XPS foam scraps from secondary processing or off-specification products may be ground and recycled back into the XPS foam production process (often referred to as reclamation) (ECHA, 2008b).

Environmental Release Assessment Methodology

Facility Estimates
As discussed in Section 2.2.1, EPA estimates environmental releases based on a processing volume of 100,000 pounds per site per year and estimates a single unidentified site for this condition of use.

Release Sources
Based on the process description, EPA infers that HBCD releases may occur from: dust generation during unloading the XPS masterbatch from the bags in which they were received; disposal of the bags in which the XPS masterbatch is received; and periodic cleaning of process equipment.

Foam manufacturing sites may also generate dust and scraps from cutting or trimming of XPS foam into panels or other shapes for shipment to end users. However, both the EU and Australian risk assessments specify that industry provided information indicated that generated dust and trimmings may be recycled back into the foam molding process, thereby reducing or eliminating waste from the cutting and trimming process (NICNAS, 2012b; ECHA, 2008b). EPA does not know the extent that these practices are used in the United States and the assessed EURAR data is expected to account for any releases from this source (ECHA, 2008b).

Emission Factors
EPA estimated emission factors based on site-specific solid HBCD release data reported in the EURAR (ECHA, 2008b). The EURAR identified 17 sites in the EU that produce XPS foam using XPS masterbatch that is flame retarded with HBCD (ECHA, 2008b). Site-specific release quantities are provided for four of these sites, which are summarized in Table 2-12. The EURAR indicates that these sites did not provide air releases and that these air emissions were calculated using emission factors from a study on emissions at three European XPS foam manufacturing plants (ECHA, 2008b). To maintain confidentiality, the EURAR did not provide site-specific HBCD process volumes with which site-specific emission factors could be calculated. However, the EURAR provided the total production volume for the four sites for which release data are available. EPA calculated overall average emission factors to air and water by dividing the total HBCD releases to air or water from all four sites by the total HBCD processing volume for the four sites. From these calculations, EPA estimated average emission factors of 1.07×10^{-5} kg HBCD discharged/kg HBCD processed to water and 5.79×10^{-5} kg HBCD released/kg HBCD processed to air.

The EURAR also calculated estimates of releases to wastewater and air from 13 sites that did not provide release data using the "worst-case" emission factors that the EURAR calculated from the available site-specific HBCD release and processing volume data. However, the EURAR did not provide the "worst-case" emission factors used to determine these estimates. EPA calculated "worst-case" emission factors by using the total "worst-case" release estimates calculated by the EURAR for the 13 sites and the HBCD processing volume identified in the EURAR for these 13 sites, as presented in Table 2-12. EPA calculated "worst-case" emission factors to be 2.63×10^{-5} kg HBCD discharged/kg HBCD processed to water and 5.80×10^{-5} kg HBCD released/kg HBCD processed to air. Note that the "worst-case" air emission factor and average air emission factor are the same because the EURAR used

the same emission factor from a study of three European XPS foam manufacturing plants, as described above (ECHA, 2008b).

The EURAR indicates that wastewater discharges are to wastewater treatment. EPA did not find information about the prevalence of wastewater treatment at processing sites in the United States and hence assumed that wastewater discharges from this condition of use can be to surface water, POTW, and/or onsite wastewater treatment. The EURAR does not specify if the reported air releases for these three sites are to stack or fugitive air. Sites may implement dust capture technologies that affect if this release is to stack or fugitive air. EPA did not find information about the prevalence of dust capture technologies at processing sites in the United States and hence assumed this release may include stack air and/or fugitive air.

Table 2-12. HBCD Release Data Reported in the EURAR for Manufacturing of XPS Foam from XPS Masterbatch

Site	Release to Water	Release to Air [a]	Process Volume
	kg/yr	kg/yr	
Site 1	2.2	0.31	The EURAR identifies a total of 719 metric tons of HBCD is processed at the 4 sites with site-specific release data.
Site 2	0	18	
Site 3	1.3	14	
Site 4	4.2	9.3	
Total "worst-case" emissions calculated in the EURAR for 13 sites without release data	26.67	58.617	The EURAR identifies a total of 1,011 metric tons of HBCD is processed at the 13 sites without release data.

[a] These air releases were not reported by the sites by were estimated in the EURAR using emission factors from a study on emissions from three European XPS foam manufacturing sites (ECHA, 2008b).

Number of Release Days

The site-specific data in the EURAR indicates wastewater discharges occur over 1 to 15 days/year, which are values reported by the sites. Only one site reported emission days for air releases, reporting 15 days/year. Based on these data, EPA estimated wastewater discharges over a range of 1 to 15 days/year. The remaining three sites did not report emission days for air releases and the EURAR estimated 300 air emission days for all the sites using defaults in the European Communities Technical Guidance Document for industrial use in the polymers industry and processing volume at the individual sites (ECB, 2003). Using this same European guidance and EPA's HBCD processing volume of 100,000 pounds HBCD/year (45.4 metric tons), EPA estimated 16 days of emission per year. In lieu of using a range of 15 to 16 days of air emission per year, EPA used 1 day/year as the lower bounding estimate, using the same low-end of emission days as that reported by the EU sites for wastewater discharges, and 16 days/year based on the European Communities Technical Guidance Document.

The data sources used to estimate releases in this section are listed in Table 2-13 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-13. XPS Foam Manufacturing Using XPS Masterbatch Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECHA, 2008b)	Site-Specific Release Data	See Table 2-12	High
(ECHA, 2008b)	"Worst-Case" Emissions for Sites without Release Data	2.63×10^{-5} to water and 5.80×10^{-5} to air	High
(ECHA, 2008b)	Release Days	1 to 15 days/year for water releases; 15 days/year for air releases	High
(ECB, 2003)	Release Days	16 days/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-14.

Table 2-14. Input Variables to Equation 2-1 for XPS Foam Manufacturing Using XPS Masterbatch

Input Variable				
V (of HBCD)	N_S (sites)	f (kg HBCD released/kg HBCD processed)		N_d (days/yr)
		Average calculated from EURAR data	"Worst-Case" calculated from EURAR data	
100,000 pounds/year = 45,359 kg/year[a]	1	5.79E-05 to stack air and/or fugitive air 1.08E-05 to surface water, onsite WWT, and/or POTW	5.80E-05 to stack air and/or fugitive air 2.63E-05 to surface water, onsite WWT, and/or POTW	1-15 (wastewater discharge), 1-16 (air release)

[a] CDR reporting threshold for small manufacturers (U.S. EPA, 2016a)

The daily amount of solid HBCD released per site from XPS foam manufacturing from XPS masterbatch was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-15.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates and high confidence in the assessed range of number of release days per year that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA is highly confident in this assessment approach, which is a strength of the assessment. EPA implemented this approach using release, processing volume and emission factor data and data on number of release days and assigned an overall confidence rating of high to these data using systematic review as indicated above. The limitations of the assessment are uncertainties about the extents to which the emission factor data, including the emission factors calculated from release and processing volume data, and the data on

number of days of release per year are applicable to the HBCD processing that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-15. Summary of HBCD Releases from XPS Foam Manufacturing Using XPS Masterbatch

Release Source	Method of Release, Discharge, Treatment, or Disposal [a]	Releases calculated from average emission factor based on EURAR release data [b]				Releases calculated from "worst case" emission factor based on EURAR release data [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 1 day/year (water and air)	Number of release days: 15 day/year (water) and 16 day/year (air)			Number of release days: 1 day/year (water and air)	Number of release days: 15 day/year (water) and 16 day/year (air)		
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Stack air or fugitive air	2.63	2.63	2.63	0.164	2.63	2.63	2.63	0.164	1	8 hours/day
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Surface Water, Onsite WWT, or POTW	0.486	0.486	0.486	3.24E-02	1.19	1.19	1.19	0.080	1	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid HBCD or solid mixtures containing polystyrene and HBCD.

2.2.5 Processing: Manufacturing of XPS Foam using HBCD Powder

XPS foam can be produced from either XPS masterbatch, as described in Section 2.2.4, or from HBCD powder or granules. The process for producing XPS foam from HBCD powder is similar to that for production of HBCD foam from XPS masterbatch. Polystyrene, HBCD powder, and other additives are fed into an extruder, where the contents are melted to produce a plastic gel. Blowing agent is added to the gel, which is then sent through a die where the blowing agent volatilizes, producing the extruded plastic foam. The foam may be cut into shapes, packaged, and shipped to customers. HBCD content in XPS foam ranges from 0.5 to 3 weight percent (U.S. EPA, 2015; Takigami et al., 2014; EC/HC, 2011; ECHA, 2008b).

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.1, EPA estimates environmental releases based on a processing volume of 100,000 pounds per site per year and estimates a single unidentified site for this condition of use.

Release Sources

Based on the process description, EPA infers that releases may occur from: dust generation during unloading the HBCD powder from the bags in which they were received; disposal of the bags in which the HBCD powder is received; and periodic cleaning of process equipment.

Foam manufacturing sites may also generate dust and scraps from cutting or trimming of XPS foam into panels or other shapes for shipment to end users. However, both the EU and Australian risk assessments specify that industry provided information indicating that generated dust and trimmings may be captured and recycled back into the foam molding process, thereby reducing or eliminating waste from the cutting and trimming process (NICNAS, 2012b; ECHA, 2008b). EPA does not know the extent that these practices are used in the United States and the assessed TRI and EURAR data is expected to account for any releases from this source (ECHA, 2008b).

EPA estimated releases from this condition of use using 2017 TRI data and emission factors calculated from release data from the EURAR. EPA assessed both approaches because the company that reported to 2017 TRI indicated that they no longer conduct operations with HBCD, as discussed below.

TRI Data

The Dow Chemical Company reported releases for two sites that manufacture XPS foam with HBCD. The company has since indicated that operations with HBCD have ceased. The Dow Chemical Company communicated with EPA that they imported roughly 48 metric tons in 2017 as discussed earlier in Section 1.2, which is similar to the importation and processing volume of HBCD that EPA uses to estimate releases for this condition of use (approximately 45.4 metric tons) with the EURAR data. EPA assessed the 2017 TRI releases as they were reported by Dow. These releases are deemed to be representative of the potential releases that may occur from sites in the United States that would manufacture XPS foam with HBCD and have a similar processing volume of HBCD as Dow (approximately 48 metric tons), should additional sites commence such operations. The reported releases are summarized in the next section with the releases EPA calculated from the EURAR data. As discussed, the HBCD processing volume associated with the releases reported in the 2017 TRI (48 metric tons HBCD, provided through communication with Dow and discussed in Section 1.2) is slightly different than that EPA used to estimate releases from the EURAR data (45.4 metric tons).

Emission Factors

Although TRI data are available for this condition of use, EPA also estimated emission factors based on site-specific release data reported in the EURAR (ECHA, 2008b). The EURAR identified 18 sites in the EU that produce XPS foam using HBCD powder (ECHA, 2008b). Site-specific solid HBCD release quantities are provided for 17 of these sites and a calculated release estimate was provided for the remaining site. To maintain confidentiality, the EURAR did not provide site-specific HBCD processing volumes with which site-specific emission factors could be calculated. The EURAR only provided the total HBCD processing volume for all 18 sites (ECHA, 2008b).

EPA calculated overall average emission factors to water and air with this data by dividing the total HBCD releases for water or air for all sites by the total HBCD processing volume for all sites. The average emission factors are presented in Table 2-16.

The EURAR indicates that the HBCD release estimates to water presented in Table 2-16 may be estimated quantities either directly from process operations or from onsite wastewater treatment at these sites. The EURAR does not specify this detail for the individual sites, thus EPA is uncertain of the prevalence of onsite wastewater treatment at these European sites. For this risk evaluation, EPA assessed that wastewater discharges estimated using the emission factor determined from the EURAR data may be entirely to on or offsite wastewater treatment or to surface water. Depending on site-specific pollution controls, wastewater discharges from this condition of use can be to surface water, POTW, and/or onsite wastewater treatment and air releases may include stack air and/or fugitive air.

Table 2-16. HBCD Release Data Reported in the EURAR for Manufacturing of XPS Foam using HBCD Powder

Site-Specific Release Data	Release to Water	Release to Air	Process Volume
	kg/yr	kg/yr	
Site 1	4.4	1.5	The EURAR identifies a total of 3,232 metric tons of HBCD are processed into XPS masterbatch by 18 sites.
Site 2	1.2	1.4	
Site 3	0.055	3.7	
Site 4	3.7	1.5	
Site 5	0.0024	1.1	
Site 6	0	0.73	
Site 7	6	0.54	
Site 8	0.0029	0.7	
Site 9	0.0019	0.15	
Site 10	0	0.4	
Site 11	0	1.8	
Site 12	0	1.8	
Site 13	0.11	1.2	
Site 14	15	1.5	
Site 15	0.00004	0.59	
Site 16	0.0004	0.91	

Site-Specific Release Data	Release to Water	Release to Air	Process Volume
	kg/yr	kg/yr	
Site 17	0.021	3.8	
Site 18	2.5	0.23	

Number of Release Days

The site-specific data in the EURAR indicates wastewater discharges occur over 1 to 12 days/year, which are values reported by the sites. Based on these data, EPA estimated wastewater discharges over a range of 1 to 12 days/year. None of these sites reported emission days for air releases. For these sites, the EURAR estimated 42 to 300 air emission days using defaults in the European Communities Technical Guidance Document for industrial use in the polymers industry and processing volume at the individual sites (ECB, 2003). Using this same European guidance and a processing volume of 100,000 pounds HBCD/year (45.4 metric tons), EPA estimated 16 days of emission per year. EPA used 1 day/year for air emissions as the lower bounding estimate, using the same low-end of emission days as that reported by the EU sites for wastewater discharges, and 16 days/year based on the European Communities Technical Guidance Document.

The data sources used to estimate releases in this section are listed in Table 2-17 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-17. Manufacturing of XPS Foam Using HBCD Powder Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECHA, 2008b)	Site-Specific Release Data	See Table 2-16	High
(U.S. EPA, 2017h)	Site-Specific Release Data	See Table 2-20	Medium
(ECHA, 2008b)	Release Days	1 to 12 days/year for wastewater discharges	High
(ECB, 2003)	Release Days	16 days/year for all releases	Medium

Environmental Release Assessment Results

The releases reported by the Dow Chemical Company in the 2017 TRI for sites that manufacture XPS articles with HBCD are presented in Table 2-20. The data in 2017 TRI is reported on an annual basis. EPA calculated daily releases with the TRI data using the same estimates for days per year that is discussed above. EPA also calculated releases using Equation 2-1 and the EURAR data discussed above, and the input variables for this calculation are given in Table 2-18. The results of these calculations are summarized in Table 2-19.

Table 2-18. Input Variables to Equation 2-1 for XPS Foam Manufacturing Using HBCD Powder

Input Variable			
Volume (of HBCD)	**N_S (sites)**	**f (kg HBCD released/kg HBCD processed)**	**N_d (days/yr)**
		Average calculated from EURAR data	
100,000 pounds/year = 45,359 kg/year	1	7.29E-06 to stack air and/or fugitive air 1.02E-05 to surface water, onsite WWT, and/or POTW	1-12 (water), 1-16 (air)
[a] CDR reporting threshold for small manufacturers (U.S. EPA, 2016a)			

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates, high confidence in the assessed range of number of release days per year associated with releases to water, and medium confidence in the assessed range of number of release days per year associated with releases to air that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA is highly confident in this assessment approach, which is a strength of the assessment. EPA implemented this approach using two groups of data:

a) release and processing volume data which EPA assigned an overall confidence rating of high using systematic review
b) data on number of release days which EPA assigned an overall confidence rating of high in the case of data associated with releases to water and an overall confidence rating of medium in the case of data associated with releases to air using systematic review.

EPA also assessed releases using TRI data which EPA assigned an overall confidence rating of medium using systematic review.

The limitations of the assessment are uncertainties about the extents to which the emission factor data, including the emission factors calculated from release and processing volume data, and the data on number of days of release per year are applicable to the HBCD processing that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-19. Summary of HBCD Releases from XPS Foam Manufacturing Using HBCD

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from average emission factor based on EURAR release data [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 1 day/year (water and air)	Number of release days: Over 12 day/year (water) and 16 day/year (air)		
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Stack air or fugitive air	0.331	0.331	0.331	2.07E-02	1	8 hours/day
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Surface Water, Onsite WWT, or POTW	0.463	0.463	0.463	0.039	1	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid HBCD or solid mixtures containing polystyrene and HBCD.

Table 2-20. Summary of HBCD Releases from XPS Foam Manufacturing Using HBCD from 2017 TRI Data

Site identity	2017 TRI			Hours of Release per Day (hr/day)
	Annual Quantities per Site (kg/year)	Daily Release (kg/site-day)		
		Assuming low-end of 1 day/year	Assuming high-end of 16 days/year	
Dow Chemical Company, Pevely MO	Stack air [a]: 1.81 Off-site transfer for Incineration [b]: 30.8 Off-site transfer for disposal to landfill [c]: 123	Stack air [a]: 1.81 Off-site transfer for Incineration [b]: 30.8 Off-site transfer for disposal to landfill [c]: 123	Stack air [a]: 0.113 Off-site transfer for incineration [b]: 1.93 Off-site transfer for disposal to landfill [c]: 7.68	8 hours/day
Dow Chemical Company, Dalton GA	Stack air [a]: 21.3 Off-site transfer for disposal to landfill [c]: 109 Off-site transfer for incineration [d]: 23.1	Stack air [a]: 21.3 Off-site transfer for disposal to landfill [c]: 109 Off-site transfer for incineration [d]: 23.1	Stack air [a]: 1.33 Off-site transfer for disposal to landfill [c]: 6.80 Off-site transfer for incineration [d]: 1.45	8 hours/day

Site identity	2017 TRI			Hours of Release per Day (hr/day)
	Annual Quantities per Site (kg/year)	Daily Release (kg/site-day)		
		Assuming low-end of 1 day/year	Assuming high-end of 16 days/year	

[a] These stack air releases were reported under Section 5.2 of the TRI Form R, which correspond to on-site stack or point air emissions.
[b] This incineration quantity was reported under Section 6.2 of the TRI Form R, which corresponds to code M50, which is off-site transfer for incineration/thermal treatment.
[c] This landfill quantity was reported under Section 6.2 of the TRI Form R, which corresponds to code M64, which is off-site transfer for disposal to other landfills.
[d] This incineration quantity was reported under Section 6.2 of the TRI Form R, which corresponds to code M56, which is off-site transfer for energy recovery. EPA assumes this is to incineration.

2.2.6 Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads

To manufacture EPS, EPS beads are first pre-expanded by heating with steam, which causes the beads to soften and expand to the desired density, as the temperature of the steam exceeds that of the blowing agent (such as pentane) incorporated in the beads (NICNAS, 2012b; ECHA, 2008b). Once pre-expansion is completed, the beads are dried, then placed in shape or block molds. In the molds, the pressure is dropped with a vacuum pump, eliminating air and water and causing the expanded beads to fuse and take the shape of the mold (NICNAS, 2012b). The EPS foam is then removed from the molds and cooled.

Excess foam may be trimmed off, or the shapes or blocks may be cut into smaller sizes (i.e., secondary processing). Any trimmings may be recycled back into the foam production process (i.e., reclamation) (ECHA, 2008b). The EPS foam is then wrapped for transport and shipped either to customers who may further process the foam into SIPs or automobile replacement parts or directly to end users for installation in structures such as buildings and cars. HBCD content in the EPS foam is typically from 0.5 to 0.7 weight percent, with the usual content being 0.7 weight percent (ECHA, 2017c; NICNAS, 2012b; ECHA, 2009b; Thomsen et al., 2007).

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.1, EPA estimates environmental releases based on a processing volume of 100,000 pounds per site per year and estimates a single unidentified site for this condition of use.

Release Sources

Based on the process description, EPA infers that releases may occur from: dust generation during unloading the EPS resin beads from the bags in which they were received; disposal of the bags in which the EPS resin beads are received; and periodic cleaning of process equipment.

Foam manufacturing sites may also generate dust and scraps from cutting or trimming of EPS foam into panels or other shapes for shipment to end users. However, both the EU and Australian risk assessments specify that industry provided information indicating that generated dust and trimmings may be captured and recycled back into the foam molding process, thereby reducing or eliminating waste from the cutting and trimming process (NICNAS, 2012b; ECHA, 2008b). EPA does not know the extent that these practices are used in the United States and assessed these release sources as described below.

Emission Factors

EPA used emission factors given in the 2009 OECD ESD on Plastics Additives, as summarized in Table 2-21.

Per the OECD ESD, unloading of EPS resin beads is not expected to generate dust. However, there may be residual resin in the transport containers. The OECD ESD estimates an emission factor of 1% from the disposal of transport containers, which the OECD ESD indicates are disposed of as solid waste to landfills. Although there is no statistical characterization of this emission factor, EPA believes the 1% emission factor is in the upper end of the distribution based on EPA's experience. The OECD ESD indicates that the converting process may result in dust generation at a loss rate of 0.1 to 0.5%, which is initially released to air, with particles eventually settling and being disposed of as solid waste or discharged as wastewater (OECD, 2009). Per the *EPA/OPPT Solids Transfer Dust Loss Model*, dust releases are similarly estimated with a 0.5% emission factor and initial release to air with subsequent treatment via incineration, disposal to landfill, or discharge as wastewater from wiping and cleaning of surfaces onto which particles have settled (U.S. EPA, 2013a). The method of release, disposal, treatment, or discharge is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. EPA did not find information about the prevalence of dust capture and control technologies at importation sites in the United States. EPA estimated dust releases with a range of release from 0.1 to 0.5%. The method of release, disposal, treatment, or discharge may be some or all of the following: stack air, fugitive air, onsite wastewater, POTW, landfill, or incineration, per the OECD ESD and EPA/OPPT model.

The OECD ESD identifies trimming of produced foam as a release source, estimating a release of 2.5% to solid waste or water from grinding or machining of the foam. EPA also identified foam trimming release of 1% to solid waste for closed-cell spray polyurethane foam (SPF). These data were reported by industry for the development of the draft generic scenario on SPF application (U.S. EPA, 2018c). While this foam is different than that in this condition of use, EPA uses this emission factor of 1% to present a range of potential releases from the trimming of foam. EPA assessed this release via disposal to landfill or treatment via incineration, as the foam scraps are likely disposed of as solid waste (U.S. EPA, 2018c; OECD, 2009). The method of release, disposal, treatment, or discharge is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. EPA did not find information on waste handling procedures at these sites. HBCD may be disposed of to landfill and/or treated via incineration.

Based on the process description for this condition of use, EPA expects that equipment cleaning may be another source of release. EPA estimated this release using the OECD ESD, which estimates an emission factor of 1% for all other operations than previously discussed, which EPA assumes includes equipment cleaning (OECD, 2009). In addition, the *EPA/OPPT Solid Residuals in Transport Containers Model* also estimates a loss of 1% of processed material . Although there is no statistical characterization of this emission factor, EPA believes the 1% emission factor is in the upper end of the distribution based on EPA's experience. The method of release, disposal, treatment, or discharge is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. EPA did not identify information on waste handling procedures at these sites. The method of release, disposal, treatment, or discharge may include some or all of the following depending on site-specific conditions: surface water, POTW, onsite WWT, POTW, landfill, or incineration.

Table 2-21. Summary of HBCD Releases During Manufacturing of EPS Foam from the 2009 OECD ESD on Plastics Additives and Standard EPA/OPPT Models

Release Source	Emission factor used in this Risk Evaluation	Method of Release, Disposal, Treatment, or Discharge Assessed in this Risk Evaluation [a]	Basis or Source
Dust generation from unloading EPS resin beads from transport containers	N/A – HBCD dust generation from unloading EPS resin beads is expected to be minimal. Additionally, HBCD is entrained within the polymer matrix.		(NICNAS, 2012b; ECHA, 2008b)
Disposal of transport containers (bags) containing solid HBCD residual	0.01 kg HBCD released/kg HBCD in containers	Landfill	(OECD, 2009)
Dust / volatilization releases at elevated temperatures during converting process	0.001-0.005 kg HBCD released/kg HBCD processed	Uncertain: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, Incineration	(OECD, 2009)
Equipment cleaning losses of residual HBCD solids from compounding equipment	0.01 kg HBCD released/kg HBCD processed	Uncertain – Surface water, onsite WWT, POTW, Landfill, Incineration	(OECD, 2009)
Trimming of foam [a]	0.01 to 0.025 kg HBCD released/kg HBCD processed	Uncertain Incineration, Landfill	(U.S. EPA, 2018c; OECD, 2009)

N/A = Not applicable
[a] Trimmed foam may be reintroduced into the process and not disposed of based on the information in the EURAR and Australian risk assessment (NICNAS, 2012b; ECHA, 2008b). EPA includes this release to present a range if release estimates.

EPA's method of assessing emission factors and the methods of assessing the emission factors pertaining to releases from the manufacture of EPS foam from EPS resin beads as reported in EURAR and NICNAS (NICNAS, 2012b; ECHA, 2008b) are similar because in all cases emission factors were obtained from an OECD ESD or other similar method. The EURAR and NICNAS only assessed dust releases during the converting process, and did not assess releases from unloading, disposal of transport containers and equipment cleaning. Accordingly, EPA's overall emission factor is considerably greater than the emission factors used in these assessments, and EPA's assessment may be conservative.

Number of Release Days

EPA estimated the number of release days based on information given in the European Communities Technical Guidance Document (ECB, 2003) and in the Australian risk assessment. EPA estimated 16 release days per year using the European Communities Technical Guidance Document for industrial use in the polymers industry and a processing volume of 100,000 pounds HBCD/year (45.4 metric tons), The Australian risk assessment includes one estimate of the number of operational days per year at an EPS foam production plant. This plant reports producing EPS products containing HBCD 8 to 10 times per year, with each production lasting up to 14 days. This results in production for 112 to 140 days per year. In conclusion, EPA estimated a range of 16 to 140 days/year.

The data sources used to estimate releases in this section are listed in Table 2-22 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-22. Manufacturing of EPS Foam from Imported EPS Resin Beads Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(NICNAS, 2012b)	Release Days	112 to 140 days/year for all releases	High
(ECB, 2003)	Release Days	16 days/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-23.

Table 2-23. Input Variables to Equation 2-1 for EPS Foam Manufacturing from EPS Resin Beads

Input Variable				
V (of HBCD)	N_S (sites)	f (kg HBCD released/kg HBCD processed)		N_d (days/yr)
		Lower value of emission factors	Upper value of emission factors	
100,000 pounds/year = 45,359 kg/year	1	0.01 to landfill 0.001 to stack air, fugitive air, surface water, onsite WWT, POTW, landfill, and/or incineration 0.01 to surface water, onsite WWT, POTW, landfill, and/or incineration 0.001 to incineration and/or landfill	0.01 to landfill 0.005 to stack air, fugitive air, surface water, onsite WWT, POTW, landfill, and/or incineration 0.01 to surface water, onsite WWT, POTW, landfill, and/or incineration 0.025 to incineration and/or landfill	16-140

[a] CDR reporting threshold for small manufacturers (U.S. EPA, 2016a)

The daily amount of HBCD released per site from EPS foam manufacturing from EPS resin beads was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-24.

Strengths, Limitations, and Confidence in Assessment Results

EPA did not find release data in 2017 TRI or the EURAR that are applicable to this condition of use. EPA estimated releases at EPS foam production sites using emission factors from the 2009 OECD ESD on Plastic Additives (OECD, 2009), the draft generic scenario on SPF application (U.S. EPA, 2018c), and an EPA/OPPT model available in ChemSTEER (U.S. EPA, 2013a). As noted previously, the higher emission factor in the ESD for dust releases corresponds to the same factor used in the EPA/OPPT Solids Transfer Dust Loss Model, which is based on U.S. release data (U.S. EPA, 2013a). Additionally, the emission factor from the draft generic scenario on SPF application (U.S. EPA, 2018c) is based on industry input. The representativeness of these data toward the true distribution of environmental releases for this use is uncertain. However, EPA has a medium to high confidence that these emission factors are representative, but notes that those from the ESD and EPA/OPPT model are likely on the higher end of the distribution of real-world values.

EPA estimated a range of release days using the European Communities Technical Guidance Document (ECB, 2003), which has an overall confidence rating of medium from EPA's systematic review process, and industry data include in the Australian risk assessment (NICNAS, 2012b). EPA estimated release days with the Technical Guidance Document using the polymer industry category, which includes molding operations. The data from the Australian risk assessment is not correlated to an HBCD throughput, so EPA could not adjust the number of days by the assessed production volume (i.e., 100,000 pounds HBCD/year). However, EPA estimated a range of release days in order to capture variability and address uncertainty. EPA has a medium to high confidence that the estimated range of release days encompasses the actual range of release days at these sites.

Considering the overall strengths and limitations of the data, EPA has an overall medium to high confidence that the range of estimated daily releases encompasses the actual range of the daily releases.

Table 2-24. Summary of HBCD Releases from EPS Foam Manufacturing from EPS Resin Beads

Release Source	Method of Release, Disposal, Treatment, or Disposal [a]	Releases calculated from lower value of range of emission factors [b]				Releases calculated from upper value of range of emission factors [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 16 days/year	Number of release days: 140 days/year			Number of release days: 16 days/year	Number of release days: 140 days/year		
Dust release during converting process	May go to one or more: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, or Incineration	45.4	45.4	2.83	0.324	227	227	14.17	1.62	1	8 hours/day
Equipment cleaning	May go to one or more: surface water, onsite WWT, POTW, landfill, or Incineration	454	454	28.3	3.24	454	454	28.3	3.24	1	8 hours/day
Disposal of transport containers	Landfill	454	454	28.3	3.24	454	454	28.3	3.24	1	8 hours/day
Trimming foam scrap	May go to one or more: Incineration or landfill	454	454	28.35	3.24	1134	1134	70.87	8.10	1	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.

2.2.7 Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam

After XPS and EPS foam is produced, the foam may be subsequently sent to specialty fabricators to produce structural insulated panels (SIPs) or automobile replacement parts.

To manufacture SIPs, the XPS and EPS foam is cut into the desired size panel, either with saws or thermal wires (NICNAS, 2012b). The panels are then adhered to steel, plastic, concrete, plasterboard, or other sheathing material on either side, forming a sandwich, which is why these panels are also referred to as sandwich panels (NICNAS, 2012b). Once the SIPs are produced, they are shipped to construction sites for installation.

Major automobile manufacturers have phased out use of HBCD in U.S. production but continue to use it in replacement parts, according to information provided by the Alliance of Automotive Manufacturers (Alliance of Automobile Manufacturers, 2018b; Rege, 2017; Tatman, 2017). Manufacturers identified 155 replacement parts containing HBCD: these include absorbers (front roof rail energy) and two types of insulator panels (Tatman, 2017). For the purpose of this risk evaluation, EPA assumes that EPS and XPS foam containing HBCD is used in these replacement parts (U.S. EPA, 2018e, f).

EPA did not identify specific information regarding the process for manufacturing of automobile parts containing XPS or EPS foam. EPA believes this process likely involves the molding and cutting of parts, similar to the manufacturing of panels and boards for construction purposes. Additionally, this process may include the bonding of the insulation with metal or plastic surfaces. After fabrication, the automotive replacement parts containing foam are likely shipped to automobile assemblers who install the parts without further cutting, shaping, or other handling of the parts.

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.1, EPA estimates environmental releases based on a processing volume of 100,000 pounds per site per year. This processing volume is for any one site, and this section covers two conditions of use, Manufacturing of SIPs and Automotive Replacement Parts, so EPA developed estimates for two modeled sites, one that processes EPS and XPS foam to produce SIPs and one that processes XPS and EPS foam to produce automotive replacement parts, with 100,000 pounds HBCD/year at each site.

Release Sources

Based on the process description, EPA infers that releases likely occur at SIPs and automotive replacement part manufacturing shops from the cutting of EPS and XPS foam to produce parts of specific dimensions. Specifically, release would occur during the formation of dust during the fabrication process and from the disposal of foam scraps. Once the parts are fabricated and shipped to end-users, they are not likely to be further processed or handled in such a way that subsequent release would occur. EPA estimated releases during this condition of use from the cutting or sawing of foam and the subsequent disposal of foam scraps.

Emission Factors

The EURAR includes information from a study on the cutting of XPS and EPS foam containing HBCD in the construction industry, including both thermal cutting with hot wires and cutting with mechanical saws (ECHA, 2008b). This study provides emission factors for the quantity of particles generated per

quantity of foam cut (Klatt, 2003). A summary is presented in Table 2-25 below. Note that no emission factor was available for the thermal cutting of XPS boards. EPA calculated an emission factor assuming the same ratio between hot wire cutting and sawing as that for EPS foam.

Table 2-25. Particle Generation Factors Reported in the EURAR for Cutting of EPS/XPS Foam

Foam Type	Activities	Particle Generation Factor
XPS boards	Sawing	5.0 g XPS particles/metric ton XPS sawed
XPS boards	Hot wire cutting	1.12 g XPS particles/metric ton XPS cut [a]
EPS boards	Sawing	445 g EPS particles/metric ton EPS sawed
EPS boards	Hot wire cutting	100 g EPS particles/metric ton EPS cut

[a] Calculated by EPA using the same ratio as that for EPS foam. Particle generation factor for cutting = 5.0 g XPS particles/metric ton XPS sawed x (100 g EPS particles/metric ton EPS cut ÷ 445 g EPS particles/metric ton EPS sawed) = 1.12 g XPS particles/metric ton XPS cut.

A supporting document for the EURAR indicates that the proportions of HBCD used for XPS and EPS are similar (ECHA, 2009b). EPA estimates 50 percent of the HBCD processing volume is used for XPS applications and 50 percent for EPS applications and, using this split with the emission factors for XPS and EPS foams in Table 2-25, EPA calculated weighted emission factors for the thermal cutting and sawing of foam containing HBCD and used these to estimate a range of releases from this condition of use. The calculated emission factors are listed in Table 2-26. Note that these emission factors assume that the composition of the generated particulates is equal to that of the foam being cut.

The method of release, disposal, treatment, or discharge for generated particles containing HBCD during sawing and cutting is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. EPA did not identify information on waste handling procedures at these sites. The method of release, disposal, treatment, or discharge may include some or all of the following depending on site-specific conditions: stack air, fugitive air, surface water, POTW, onsite WWT, landfill, and/or incineration.

EPA used the same emission factors for the trimming of XPS and EPS foam that were used in Section 2.2.6 for the manufacturing of EPS foam from EPS resin beads. Specifically, EPA uses a range of loss fractions of 1 to 2.5% of foam containing HBCD to estimate disposal of foam scrap to landfill or treatment via incineration, depending on the site's disposal practices. EPA did not identify information on waste handling procedures at these sites. Part or all of this release could be disposed of to landfill or treated via incineration. Refer to Section 2.2.6 for additional information on this release.

Table 2-26. Summary of HBCD Release Sources During the Manufacturing of SIPs and Automotive Replacement Parts from XPS/EPS Foam

Release Source	Emission factor used in this Risk Evaluation (kg HBCD released/kg HBCD processed)		Method of Release, Disposal, Treatment, or Discharge Assessed in this Risk Evaluation	Basis or Source
	Lower value of emission factors	Upper value of emission factors		
Dust generation from thermal cutting of XPS (50%) and EPS (50%)	5.06E-05	2.25E-04	Uncertain: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, and/or Incineration	(ECHA, 2008b)
Trimming disposal	0.01	0.025	Uncertain: Incineration and/or landfill [a]	(OECD, 2009) (lower fraction); (U.S. EPA, 2018c) (upper fraction)
[a] EPA assumed solid trimming waste disposal is to incineration and/or landfill.				

Number of Release Days

EPA estimated range of emission days per year based on the European Communities Technical Guidance Document for industrial use in the polymer industry (ECB, 2003). Specifically, EPA determined a range of potential emission days by calculating the lowest and highest possible emission days from the applicable defaults for industrial use in the polymer industry. With this method and the HBCD processing volume for each condition of use (100,000 pounds [45.4 metric tons]/site), EPA estimated 16 days/year. The highest number of emission days for industrial use in the polymer industry is 300 days/year. Based on these values, EPA estimated a range of 16 to 300 emission days/year.

The data sources used to estimate releases in this section are listed in Table 2-27 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-27. Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECHA, 2008b)	Particle Generation Factor	See Table 2-25	High
(ECB, 2003)	Release Days	16 to 300 days/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-28.

Table 2-28. Input Variables to Equation 2-1 for the Manufacturing of SIPs and Automotive Replacement Parts from XPS/EPS Foam

Input Variable				
V (of HBCD)	N_S (sites)	F (kg HBCD released/kg HBCD processed)		N_d (days/yr)
		Lower value of emission factors	Upper value of emission factors	
200,000 pounds/year = 90,718 kg/year[a]	2 (1 for SIPs and 1 for auto parts)	5.06E-05 to Stack air, Fugitive Air, surface water, onsite WWT, POTW, landfill, and/or incineration 0.01 to landfill and/or incineration	2.25E-04 to Stack air, Fugitive Air, surface water, onsite WWT, POTW, landfill, and/or incineration 0.025 to landfill and/or incineration	16-300

[a] CDR reporting threshold volume for small manufacturers were used for each condition of use.

The daily amount of solid HBCD released per site from cutting of XPS and EPS foam to manufacture SIPs and automobile replacement parts was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-29.

Strengths, Limitations, and Confidence in Assessment Results

EPA has an overall medium to high confidence in the assessed range of daily release rates. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA has high confidence in this assessment approach, which is a strength of the assessment. EPA used emission factor data from the EURAR and the draft GS on SPF application. The data from the EURAR has an overall confidence rating of high and the data from the technical guidance document has an overall confidence rating of medium; these ratings were assigned using EPA's systematic review process, as discussed in Section 1.5. EPA determined a range of release days per year using the European Communities Technical Guidance Document (ECB, 2003), which has an overall confidence rating of medium. However, EPA estimated a range of release days to capture variability and has a high confidence that the estimated range encompasses the actual range of release days, which is another strength of the assessment. The limitations of the assessment are uncertainties regarding the extent to which the emission factor data and the data on number of release days are applicable to the HBCD use activities that would occur in the U.S. Based on the strengths and limitations of the assessment, EPA has an overall medium to high confidence in the assessment results.

Table 2-29. Summary of HBCD Releases from the Manufacturing of SIPs and Automotive Replacement Parts from XPS/EPS Foam

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from lower value of range of emission factors [b]				Releases calculated from upper value of range of emission factors [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 16 days/year	Number of release days: 300 days/year			Number of release days: 16 days/year	Number of release days: 300 days/year		
Dust release during sawing / cutting of foam	May go to one or more: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, or Incineration	4.59	2.29	0.143	7.64E-03	20.4	10.21	0.638	3.40E-02	2	8 hours/day
Trimming foam scrap	May go to one or more: Incineration or landfill	907	454	28.3	1.512	2268	1134	70.9	3.78	2	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.

2.2.8 Use: Installation of Automotive Replacement Parts

EPA did not identify specific process information regarding the installation of automotive replacement parts containing HBCD. Manufacturers identified 155 replacement parts containing HBCD, these include absorbers (front roof rail energy) and insulator panels (Alliance of Automobile Manufacturers, 2018b). For the purpose of this risk evaluation, based on CDR reporting that showed the vast majority of use of HBCD was for XPS and EPS, EPA assumes that HBCD in these replacement parts is incorporated into XPS and EPS foam and that the XPS and EPS foam containing HBCD is used to make the replacement parts.

EPA estimated releases and exposures for the manufacturing of automotive replacement parts from XPS and EPS foam in Section 2.2.7. Once manufactured, the foam automotive replacement parts are shipped to automobile assemblers who likely install the parts without further cutting, shaping, or other handling of the parts. The installation of automotive replacement parts is likely to involve removal of old parts and insertion of the replacement parts within the vehicle, which EPA does not expect to generate dusts or other sources of release. Thus, EPA does not expect releases or exposures will occur at automobile repair sites.

2.2.9 Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures

Fabricated SIPs or XPS and EPS foam from XPS and EPS foam manufacturing sites are installed at construction sites for continuous insulation applications such as in walls and roofs on the exterior of buildings, ceilings and subfloor systems insulation (U.S. EPA, 2018e). Specifically, these materials are used for insulation within the walls of buildings, as exterior sheathing, and in ceilings, roofs, and subfloors (NICNAS, 2012b). The building and construction industry use XPS and EPS foam thermal insulation boards and laminates for sheathing products. EPS foam prevents freezing, provides a stable fill material and creates high-strength composites in construction applications (U.S. EPA, 2018e). XPS foam board is used mainly for roofing applications and architectural molding. HBCD is used in both types of foams because it is highly effective at levels less than 1% and maintains the insulation properties of XPS and EPS foam (Morose, 2006b).

During installation of the SIPs and XPS and EPS foam that was not previously formed into SIPs, these materials may be cut or sawed at the construction site to fit into the building structure. Cutting is likely to be done manually but may be done with thermal wires at large construction sites or by professional insulation installation contractors (NICNAS, 2012b). The EURAR assumes that one in every ten foam boards is cut at construction sites (i.e., 10%). Due to lack of additional information, EPA estimated releases and exposures from the cutting of 10% of the amount of HBCD used for construction purposes.

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.1, EPA evaluated this condition of use assuming an import volume of 100,000 pounds/year (45,359 kg/year) (U. S. EPA, 2016). EPA does not estimate releases and exposures for one site for this condition of use, as EPA expects this condition of use is more widespread. EPA calculates a range of 34 to 2,696 construction sites for this condition of use based on 100,000 pounds/year import volume, as described below.

The Chemical Safety Report on HBCD prepared by the European Chemicals Agency (ECHA) assesses XPS and EPS foam use rate at a large construction site as approximately 2,440 m^3 of foam (ECHA,

2017b), which equates to an applied surface area of 40,733 m^2 based on an insulation thickness of 0.06 meters (ECHA, 2008b). With this use volume, and assuming an average foam density of 40 kg/m^3 based on the average of XPS density (35 kg/m^3) and EPS density (45 kg/m^3), and an HBCD content of approximately 1.35 wt% based on the average of HBCD concentration in XPS (2 wt%) and EPS (0.7 wt%) (ECHA, 2008b), this results in a use rate by a professional contractor of 1,320 kg HBCD/job site. EPA assumed this HBCD use rate at large construction sites based on ECHA data is representative of large construction sites in the United States and uses this use rate for this risk evaluation. With this use rate of 1,320 kg HBCD/job site and a total construction use volume of 100,000 pounds/year (45,359 kg/year), EPA calculates 34 sites. EPA used 34 sites as the lower value in a range of the number of potential affected construction sites.

EPA also calculated the number of potential smaller residential construction sites by assuming a floor surface area of 2,169 ft^2 from U.S. Census Bureau data (https://www.census.gov/const/C25Ann/sftotalmedavgsqft.pdf). EPA calculated the total applied surface area to be 519 m^2 and the total volume of insulation to be 31.2 m^3, assuming a square house with one layer of insulation on three 10-foot tall stories (including basement and two above ground stories) and a foam thickness of 0.06 meters (ECHA, 2008b). Using the same density and HBCD concentration as described above, EPA calculated a use rate of 16.82 kg HBCD/job site. With this use rate of 16.82 kg HBCD/job site and a total construction use volume of 45,359 kg/year, EPA calculates 2,696 sites. EPA uses 2,696 sites as the upper value in a range of the number of potential affected construction sites. EPA provides an estimated range of construction sites depending on the use of HBCD-containing XPS and EPS foam between commercial and residential sites.

Release Sources

Based on the process description, EPA infers that there are releases from sawing or thermal cutting of XPS or EPS foam and disposal of trimmings at construction sites. EPA does not expect dust generation during travel and unloading of the foam slabs at the construction sites (OECD, 2009).

Emission Factors

Due to lack of specific information on releases from sites that install XPS and EPS foam insulation in buildings, EPA estimated releases from this condition of use consistent with the methodology used to estimate releases from the Manufacture of SIPs and Automobile Replacement Parts from XPS /EPS Foam. Refer to section 2.2.7 for additional explanation of this methodology and Table 2-26 in Section 2.2.7 for a summary of the emission factors used in this assessment.

As described in facility estimates, EPA uses an HBCD use volume for this condition of use of 100,000 pounds/year (45,359 kg/year). The EURAR assumes that one in every ten foam boards is cut at construction sites (i.e., 10%). EPA uses this same assumption and assessed that 10% of the amount of HBCD used for construction purposes is cut (i.e., 10,000 pounds/year [4,536 kg HBCD/year]). EPA multiplied this volume by the emission factors discussed in this section to estimate releases.

EPA expects that construction sites are not likely to implement dust controls that would result in releases to stack air. EPA expects that dust releases are initially to fugitive air, with the possibility that the particles may settle and be discharged in wastewater to surface water or sewers (which lead to either surface water or POTWs). EPA does not expect that these dust releases will end up in landfills or be incinerated.

Number of Release Days

Based on the Draft Application of Spray Polyurethane Foam (SPF) generic Scenario (U.S. EPA, 2018c), EPA estimated that workers install insulation over one day per residential job site and three days for commercial job sites. These estimates are based on the length of time for application of foam, the size of the building in which foam is installed, and judgement on additional time needed for set-up, tear-down, and maintenance activities at the job site.

The data sources used to estimate releases in this section are listed in Table 2-30 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-30. Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECHA, 2008b)	Particle Generation Factor	See Table 2-25	High

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-31.

Table 2-31. Input Variables to Equation 2-1 for the Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

Input Variable					
V (of HBCD)	N_S (sites)		f (kg HBCD released/kg HBCD processed)		N_d (days/yr)
	Lower value (Commercial sites)	Upper value (Residential sites)	Lower value of emission factors (residential)	Upper value of emission factors (commercial)	
100,000 pounds/year = 45,359 kg/year (with 10% of boards assumed to be cut)	34	2,696	5.06E-05 to Fugitive Air, surface water, and/or POTW 0.01 to landfill and/or incineration	2.25E-04 to Fugitive Air; surface water, and/or POTW 0.025 to landfill and/or incineration	1 (residential) to 3 (commercial sites)

The daily amount of solid HBCD released per site from cutting of XPS and EPS foam at construction sites was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-32. EPA presents the lower and upper values of the range of release estimates calculated from varying the emission factors (lower and upper emission factors), number of sites (residential and commercial), and number of days per year (one day/year for residential sites and 3 days/year for commercial sites).

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA has high confidence in this

assessment approach, which is a strength of the assessment. EPA used emission factor data from the EURAR and the draft GS on SPF application. The data from the EURAR has an overall confidence rating of high, assigned using EPA's systematic review process, as discussed in Section 1.5.EPA used data on the number of release days from the draft GS on SPF application. The data from the draft GS on SPF application was not evaluated because it is from a GS. EPA has a medium confidence that the estimated range of release days encompasses the actual range of release days at these sites. The limitations of the assessment are uncertainties regarding the extent to which the emission factor data and the data on number of release days are applicable to the HBCD use activities that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-32. Summary of HBCD Releases from Installation of XPS/EPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from lower value of range of emission factors [b]					Releases calculated from upper value of range of emission factors [b]					Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)	Days of Release (day/year)	Number of Sites	Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)	Days of Release (day/year)	Number of Sites	
Dust release during sawing / cutting of foam	May go to one or more: Fugitive Air, surface water, or POTW	0.2	8.5E-05	8.5E-05	1	2,696	1.0	3.0E-02	1.0E-02	3	34	8 hours/day
Trimming foam scrap	May go to one or more: Incineration or landfill	45.4	1.7E-02	1.7E-02	1	2,696	113	3.3	1.1	3	34	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.

2.2.10 Demolition and Disposal of XPS/EPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures

At the end of the use life of XPS and EPS foam insulation products, they are removed from buildings through demolition or remodeling of buildings. The demolition may be accomplished with many methods, including the use of explosives, a wrecking ball, or manual deconstruction (ECHA, 2008b). EPA expects the demolition process is likely to involve the breaking of XPS and EPS foam insulation products into smaller pieces for subsequent disposal or recycling.

Environmental Release Assessment Methodology

Facility Estimates

EPA estimated environmental releases for this condition of use based on the volume of HBCD that is disposed of annually. EPA estimated this volume as a fraction of the amount of HBCD currently in use in buildings the United States. The Environmental Health Strategy Center estimated that about 100 million pounds of HBCD existed in use in the "built environment" (EPA interprets this to mean in

buildings) in the United States as of 2010 (comment on Docket ID Number: EPA-HQ-OPPT-2016-0735-0008, (Safer Chemicals, 2017)). EPA estimated environmental releases of HBCD during demolition of XPS and EPS foam insulation in buildings using a fraction of these 100 million pounds of HBCD, as discussed below.

(Managaki et al., 2009) estimates that approximately 1.7 percent of the in-service volume of HBCD in Japan is disposed of each year. These data have an overall confidence rating of High from EPA's systematic review process, which takes into consideration the country of origin of the data. EPA did not find data related to the disposal of in-service volume of HBCD in the United States. EPA used the estimate from (Managaki et al., 2009), 1.7 percent, of the in-service volume of HBCD in the United States (100 million pounds), is demolished each year. This results in 1.7 million pounds/year (771,107 kg/year) for this condition of use.

EPA estimated the number of demolition sites to be proportional to the number of installation sites. As discussed in Section 2.2.9, EPA estimated a lower value of 34 commercial sites and an upper value of 2,696 residential sites had EPS or XPS foam insulation containing HBCD installed based on a processing volume of 100,000 pounds HBCD/year. Scaling for the larger demolition volume of 1.7 million pounds HBCD/year, EPA estimated a lower value of 578 commercial sites and an upper value of 45,832 residential sites with HBCD-containing insulation are demolished each year. The following is a sample calculation:

> Low-end number of demolition sites = 34 installation sites X (1.7 million lbs of HBCD /100,000 lb/yr of HCBD) = 578 sites.

Disposal wastes from demolition sites are ultimately to construction waste landfills and municipal incinerators.

Release Sources

During demolition, releases are likely to occur from the breaking apart of XPS and EPS insulation boards and subsequent disposal. The subsequent recycling/reuse of these boards are assessed separately in Section 2.2.11.

Emission Factors

Of the amount of XPS/EPS building insulation containing HBCD that is removed from buildings, (Managaki et al., 2009) estimates that 4% of this amount is recycled, 53% is disposed of to landfill (emission factor = 0.53 kg HBCD to landfill/kg HBCD in demolished foam), and 43% is treated via incineration (emission factor = 0.43 kg HBCD to incineration/kg HBCD in demolished foam). EPA did not find data specifically related to the disposal of in-service volume of HBCD in the United States. EPA applied these estimates from Japan described above from (Managaki et al., 2009) for disposal mechanisms in the United States. These releases from demolition sites are ultimately to construction and demolition landfills and municipal incinerators.

In addition to the above releases from disposal of demolition wastes, a smaller amount of HBCD is released at the actual demolition sites from the demolition process (i.e., dust generation from the breaking of insulation). EPA estimated this fraction based on methodology from the EURAR. The EURAR assessed releases from demolition activities using a particle emission rate of 90 g particles/metric ton EPS for the manual breaking of EPS boards (ECHA, 2008b). This particle generation rate is based on a study in which EPS boards were manually broken to determine the particle

generation rate by weighing the quantity of particles formed during these activities. EPA estimated releases from demolition assuming all material is manually deconstructed, using the emission rate for manual breaking of EPS boards of 90 g EPS particles/metric ton EPS boards broken, which is equal to an emission factor of 9.0E-05 kg HBCD released/kg HBCD in demolished foam. The EURAR determined that there is no release of XPS particles from manual breaking based on the same study. The difference between XPS and EPS particle generation from manual breaking is due to the difference in structure between XPS and EPS foam (ECHA, 2008b).

Buildings being demolished may contain either XPS or EPS insulation. A supporting document for the EURAR indicates that the proportions of HBCD used for XPS and EPS are similar (ECHA, 2009b). Hence, EPA assessed a split of 50 percent XPS foam and 50 percent EPS foam. With this split, EPA calculated a weighted emission factor based on the particle emission rate for EPS and that no particles are generated from breaking XPS, as described above from the EURAR. This weighted emission factor is presented in Table 2-34. Demolition sites are not likely to implement dust controls. With no dust controls to capture generated dust, EPA expects that dust generated during demolition is released to fugitive air. While these dust releases are initially to fugitive air, the particles may subsequently settle and be released in wastewater to surface water or sewers (which lead to either surface water or POTWs). EPA does not expect that these dust releases will end up in landfills or be incinerated.

The data sources used to estimate releases in this section are listed in Table 2-33 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-33. Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(Managaki et al., 2009)	Emission Factors	0.53 to landfill and 0.43 to incineration	High
(ECHA, 2008b)	Particle Generation Factor	See Table 2-25	High

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-34.

Table 2-34. Input Variables to Equation 2-1 for Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

Input Variable			
V (of HBCD)	**N_S (sites)**	**f (kg HBCD released/kg HBCD processed)**	**N_d (days/yr)**
1.7 million pounds/year = 771,107 kg/year	Releases occur at demolition sites, construction waste landfills, and municipal incinerators.	4.50E-05 to fugitive air, surface water, and/or POTW 0.53 to landfill 0.43 to incineration	EPA did not estimate the number of release days.

The amount of solid HBCD released from demolition was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-35.

Table 2-35. Summary of HBCD Releases from Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Total Annual Release for All Sites (kg/yr) [b]
Dust release during breaking of foam	May go to one or more: Fugitive Air, Surface Water, or POTW	34.7
Disposal of demolition waste (foam)	Landfill	408,687
Disposal of demolition waste (foam)	Incineration	331,576

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium confidence in the assessed range of annual releases that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. EPA implemented this approach using emission factor data from the EURAR and (Managaki et al., 2009). The data from these sources both have overall confidence ratings of high, assigned using EPA's systematic review process, as discussed in Section 1.5. The limitations of the assessment are uncertainties regarding the extent to which the emission factor data is applicable to the demolition activities that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium confidence in the assessment results.

2.2.11 Processing: Recycling of EPS Foam and Reuse of XPS Foam

Schlummer et al. (Schlummer et al., 2017) notes that XPS and EPS foam in construction insulation materials are rarely recycled for numerous reasons, including that insulation waste is typically not separated from mixed waste stream and most insulation containing HBCD is still in place.

To recycle EPS foam, the EPS boards are grinded, melted, and introduced into the EPS molding process with virgin EPS (ECHA, 2008b). Thus, EPS recycling is likely to occur at sites with similar operations to those described for EPS foam manufacturing in Section 2.2.6. XPS insulation may be reused but is rarely recycled due to the specialized equipment needed to do so (U.S. EPA, 2018e). Reuse of XPS may involve the cutting of the XPS insulation into different sizes, as needed. Based on reasonably available information, as discussed in the 2018 HBCD Problem Formulation Document, EPA assessed the reuse of XPS, but not the recycling of XPS (U.S. EPA, 2018f).

Environmental Release Assessment Methodology

Facility Estimates

EPA identified two companies in the 2018 HBCD Problem Formulation Document that directly reuse (e.g., reuse without reforming) and recycle (e.g., melting and inserting into the manufacturing process) XPS and EPS foam insulation (U.S. EPA, 2018f). One of these companies indicated that they recycle EPS roofing material at a rate of 10,000 pounds/year of EPS and reuse XPS roofing material at an unknown rate (but does not recycle it due the special equipment needed to recycle XPS). Details on the operations of the other recycling / reuse company were not provided (U.S. EPA, 2018e), but EPA expects this company may perform both recycling and reuse of XPS and EPS foam.

EPA estimated releases for two EPS recycling and XPS reuse sites (one site per company identified in the 2015 HBCD Problem Formulation document (U.S. EPA, 2015) for this condition of use and uses the same known throughput (10,000 pounds of EPS insulation recycled per year) for both sites. EPA did not identify data to characterize the statistical representativeness of this assessment. With a typical HBCD concentration of 0.7 weight percent in EPS insulation (ECHA, 2017c; INEOS Styrenics, 2017; U.S. EPA, 2015; ECHA, 2009a, 2008b; Thomsen et al., 2007), each company processes 70 pounds HBCD/year in EPS insulation (31.8 kg HBCD/site-year, or 63.5 kg HBCD/year for both sites).

One of the above companies estimates that 10-20% of EPS roofing material is recycled nationally (U.S. EPA, 2018f), thus the number of sites that perform EPS recycling in the United States is likely greater than the two sites.

Release Sources

Based on the process description, EPA infers that releases for recycling of EPS foam for this condition of use are similar to those for Manufacturing of EPS Foam from Imported EPS Resin Beads, as described in Section 2.2.6, with the removal of the trimming release, as EPA does not expect that there will be waste disposal due to trimming at a EPS recycling site.

Emission Factors

EPA expects that EPS foam is likely to be transported in trucks or other bulk containers for this condition of use, as opposed to the transport of EPS resin beads in bags for the Manufacturing of EPS Foam from Imported EPS Resin Beads. For this condition of use, EPA estimates releases from the cleaning of bulk containers used to transport the EPS foam to the converting site. The method of release, disposal, treatment, or discharge is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. The method of release, disposal, treatment, or discharge may include some or all of the following depending on site-specific conditions: surface water, POTW, onsite WWT, POTW, landfill, or incineration.

EPA additionally estimated releases from dust and equipment cleaning residue in accordance with the methodology described in Section 2.2.6 for the Manufacturing of EPS Foam from Imported EPS Resin Beads.

Number of Release Days

Using the European Communities Technical Guidance Document for industrial use in the polymers industry and a processing volume of 140 pounds HBCD/year (<1 metric ton), EPA estimated 1 day of emission per year (ECB, 2003). Based on these data, EPA used a lower bounding estimate of one day/year, as the number of emission days cannot be lower than this estimate. Because EPS recycling

occurs at the similar sites as EPS foam manufacturing from EPS resin, EPA uses the same upper value of the range of days determined in Section 2.2.6, which is 140 days/year, to account for variability in the amount of foam that is recycled at a time.

The data sources used to estimate releases in this section are listed in Table 2-36 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-36. Recycling of EPS Foam Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(NICNAS, 2012b)	Release Days	140 days/year for all releases	High
(ECB, 2003)	Release Days	1 day/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-37.

Table 2-37. Input Variables to Equation 2-1 for the Recycling of EPS Foam

Input Variable				
V (of HBCD)	N_S (sites)	f (kg HBCD released/kg HBCD processed)		N_d (days/yr)
		Lower value of emission factors	Upper value of emission factors	
20,000 pounds of EPS foam/year = 140 pounds HBCD/yr (0.7% HBCD in foam) = 63.5 kg HBCD/year	2	Container cleaning: 0.01 to uncertain (could go to surface water, onsite WWT, POTW, landfill, and/or incineration) Equipment cleaning: 0.01 to uncertain (could go to surface water, onsite WWT/POTW, landfill, and/or incineration) Dust: 0.001 to uncertain (could go to stack air, fugitive air, surface water, onsite WWT, POTW, landfill, and/or incineration)	Container cleaning: 0.01 to uncertain (could go to surface water, onsite WWT, POTW, landfill, and/or incineration) Equipment cleaning: 0.01 to uncertain (could go to surface water, onsite WWT/POTW, landfill, and/or incineration) Dust: 0.005 to uncertain (could go to stack air, fugitive air, surface water, onsite WWT, POTW, landfill, and/or incineration)	1-140

The amount of solid HBCD released annually was calculated with Equation 2-1 by multiplying the processing volume of HBCD by the emission factors. The daily amount of HBCD released from recycling was calculated by dividing this annual release by the number of days of emission. The results of these calculations are summarized in Table 2-38.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA has high confidence in this assessment approach, which is a strength of the assessment. EPA used emission factor data from the 2009 OECD ESD on Plastic Additives and other EPA/OPPT models. The emission factor data were not evaluated because these data were obtained from an ESD or GS. EPA used data on the number of release days from the European Communities Technical Guidance Document (ECB, 2003) and Australian risk assessment (NICNAS, 2012b). The data from the technical guidance document has an overall confidence rating of medium and the data from the Australian risk assessment has an overall confidence rating of high; these ratings were assigned using EPA's systematic review process, as discussed in Section 1.5. EPA estimated a range of release days in order to capture variability and address uncertainty. EPA has a medium to high confidence that the estimated range of release days encompasses the actual range of release days at these sites. The limitations of the assessment are uncertainties regarding the extent to which the emission factor data and the data on number of release days are applicable to the HBCD recycling activities that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-38. Summary of HBCD Releases from the Recycling of EPS Foam

Release Source	Method of Release, Disposal, Treatment, or Disposal [a]	Releases calculated from lower value of range of emission factors [b]				Releases calculated from upper value of range of emission factors [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 1 day/year	Number of release days: 140 days/year			Number of release days: 1 day/year	Number of release days: 140 days/year		
Dust release from grinding of foam	May go to one or more: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, or Incineration	6.35E-02	3.18E-02	3.18E-02	2.27E-04	0.318	0.159	0.159	1.13E-03	2	8 hours/day
Container cleaning residual	May go to one or more: surface water, onsite WWT, POTW, Landfill, or Incineration	1.270	0.635	0.635	4.54E-03	1.27	0.635	0.635	4.54E-03	2	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.

2.2.12 Processing: Formulation of Flux/Solder Pastes

EPA identified from the 2017 TRI results one site that processed HBCD as a formulation component. As discussed in Section 1.2, communication with this company indicates that this site formulates HBCD into flux/solder pastes. The TRI data does not specify the physical form of HBCD that is processed as a formulation component. Based on the process description below, EPA expects HBCD powder is likely used for this condition of use. This condition of use represents only the incorporation of HBCD into formulations of soldering materials.

In communication with EPA, the flux and solder paste formulation company explained that flux/solder paste components are processed in the U.S. and sent to China for final formulation and sale. The final solder flux formulations containing HBCD are sold to both international and U.S. customers who use the formulations primarily for electronics, such as circuit boards.

Incorporation into a formulation, mixture, or reaction product refers to the process of mixing or blending several raw materials to obtain a single product or preparation (OECD, 2010b). First, the components of the product formulation are unloaded from transport containers, either directly into the mixing equipment or into an intermediate storage vessel (OECD, 2010b). Transfer from transport containers may be manual or automated using a pumping system. An automated dispenser may be used to feed components into the mixing vessel to ensure that precise amounts are added at the proper time during the mixing process. Once in the mixing vessel, the components are then mixed in either a batch or continuous system. Depending on the specific product, the formulation may be further processed through filtering. Once the formulation is completed, it is sampled for quality control. The final formulation is then filled into containers, either through manual dispensing from transfer lines or through an automatic system. Automatic filling systems are generally used for the filling of smaller containers that are intended for consumer and commercial applications, whereas manual filling is done for larger containers (e.g., tank trucks, totes, drums) which are typically used in an industrial setting (OECD, 2010b).

Environmental Release Assessment Methodology

Facility Estimates

EPA expects that the amount of HBCD used in flux/solder paste is significantly less than the amount used for insulation in buildings, as these uses were not reported by the former manufacturers and importers of HBCD to the 2016 CDR. Use in EPS and XPS foam has accounted for 95 percent of all HBCD applications in the past decade (U.S. EPA, 2014d; UNEP, 2010). Due to lack of additional information, for the purposes of this risk evaluation, EPA estimated that the remaining five percent of HBCD applications are in solder flux formulations. With an importation volume equal to the CDR threshold of 100,000 pounds/year and 5 percent, EPA used a throughput of 5,000 pounds HBCD/year (2,268 kg/year) to estimate releases and exposures for this condition of use. EPA assessed one solder formulation site based on 2017 TRI data (U.S. EPA, 2017h).

Release Sources

Based on the process description, EPA infers releases may occur from dust generation during the transfer of HBCD powder from transport containers into blending vessels, residual HBCD in the emptied transport containers from the direct disposal of the emptied containers, and the periodic cleaning of blending equipment.

Emission Factors

EPA estimated releases from this condition of use using release information reported by the solder/flux formulation site to the 2017 TRI.

Number of Release Days

EPA estimated a range of emission days per year based on the European Communities Technical Guidance Document for formulation in the electronics industry, as the flux/solder formulations in this condition of use are used for electronics applications (ECB, 2003). Specifically, EPA determined a range of potential emission days by calculating the lowest and highest possible emission days from the applicable defaults for formulation within the electronics industry. With this method and the HBCD processing volume for this condition of use (5,000 pounds or 2.25 metric tons), EPA estimated 5 days/year. The highest number of emission days for formulation within the electronics industry is 300 days/year. Based on this, EPA estimated a range of 5 to 300 emission days/year.

The data sources used to estimate releases in this section are listed in Table 2-39 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-39. Formulation of Flux/Solder Pastes Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(U.S. EPA, 2017h)	Site-Specific Release Quantities	See Table 2-40	Medium
(ECB, 2003)	Release Days	5 to 300 days/year for all releases	Medium

Environmental Release Assessment Results

The releases, as they were reported to 2017 TRI, are summarized in Table 2-40. The flux/solder paste formulation site reports off-site transfers to a waste broker for disposal (disposal as defined at 40 CFR 372.3 is 'any underground injection, placement in landfills/surface impoundments, land treatment, or other intentional land disposal'.) and for treatment via solidification/stabilization (EPA assumes this disposal is to landfill).

Table 2-40. Summary of HBCD Releases from Flux/Solder Paste Formulation Sites from 2017 TRI Data

Site identity	Condition of Use	2017 TRI			Hours of Release per Day (hr/day)
		Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)[a]		
			Over 5 day/year	Over 300 day/year	
INDIUM CORP OF AMERICA, Clinton, NY	Formulation of Solder	Fugitive air [a]: 0.454 Stack air [b]: 6.350 Unknown disposal [c]: 0.454 Off-site landfill [d]: 6.350	Fugitive air [a]: 0.091 Stack air [b]: 1.27 Unknown disposal [c]: 0.091 Off-site landfill [d]: 1.27	Fugitive air [a]: 0.0015 Stack air [b]: 0.021 Unknown disposal [c]: 0.0015 Off-site landfill [d]: 0.021	8 hours/day

[a] These fugitive air releases were reported under Section 5.1 of the TRI Form R, which correspond to on-site fugitive or non-point air emissions.
[b] These stack air releases were reported under Section 5.2 of the TRI Form R, which correspond to on-site stack or point air emissions.
[c] This unknown disposal quantity was reported under Section 6.2 of the TRI Form R, which corresponds to code M94, which is off-site transfer to waste broker for disposal. Disposal (as defined at 40 CFR 372.3) is 'any underground injection, placement in landfills/surface impoundments, land treatment, or other intentional land disposal'.
..
[d] This off-site landfill quantity was reported under Section 6.2 of the TRI Form R, which corresponds to code M40, which is off-site transfer for treatment via solidification/stabilization. No additional details were provided. EPA assumes the final method of disposal is landfill.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using reported annual release quantities and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA has high confidence in this assessment approach, which is a strength of the assessment. EPA used release data from 2017 TRI data, which has an overall confidence rating of medium, assigned using EPA's systematic review process, as discussed in Section 1.5. EPA used data on number of release days from the European Communities Technical Guidance Document (ECB, 2003), which has an overall confidence rating of medium. However, EPA estimated a range of release days in order to capture variability and address uncertainty in this method. EPA has a high confidence that the estimated range of release days encompasses the actual range of release days at these sites, which is a strength of this assessment. The limitations of the assessment are uncertainties regarding the extent to which the annual release data is reflective of the full distribution of release rates and the extent to which the data on number of release days are applicable to the HBCD processing activities that would occur in the U.S. Based on the strengths and limitations of the assessment, EPA has medium to high confidence in the assessment results.

2.2.13 Use of Flux/Solder Pastes

As described in Section 1.2.5.3, EPA identified that HBCD is used specifically in solder/flux pastes that are used in electronics manufacturing. The solder/flux paste formulator indicated that the final formulations are used both overseas for electronics manufacturing and domestically. EPA did not find

information on the fraction of the solder/flux pastes that are used domestically. EPA assumes that the entire amount is used in the United States. Additionally, for the purpose of this risk evaluation, EPA assumes that they are used similarly as they are used overseas, specifically in electronics manufacturing. Within the electronics industry, solder/flux pastes are used to attach components to printed circuit boards. EPA expects that the use of solder in other industries involve similar release sources and quantities as those assessed in this risk evaluation.

Solder pastes are comprised of solder, which is a metal alloy, predominantly tin mixed with other metals such as lead and silver, suspended within flux pastes that typically contains rosin, wetting agents, viscosity modifiers, and other fluxing aids (OECD, 2010a). Soldering is a process in which two or more substrates, or parts (usually metal), are joined together by melting solder paste into the joint and allowing it to cool, thereby joining the independent parts. Solder paste is first applied in the area between the substrates to be joined, then heat is applied to the solder paste, which causes the solder to melt and join the two substrates together once cooled. The solder has a lower melting point than the adjoining metal substrates, allowing it to be melted during the soldering process without melting the substrates. The function of flux within the solder paste is to prevent oxidation during the soldering process, which ensures that soldered joints are secure (OECD, 2010a). Soldering differs from welding in that soldering does not involve melting the substrates being joined.

Solder paste can be applied to metal substrates with a variety of methods. The website of the site that processes HBCD as a formulation component, identified from 2017 TRI, depicts solder paste formulations as syringe/bead applied to circuits to be soldered. Based on this information, EPA expects the use of syringe application on circuit boards during this condition of use.

Solder pastes are largely made up of metal solder (at least 90 percent), flux (around 5 percent), with the remainder as solvent and other additives (these specialty chemicals are generally less than one percent of the composition of the solder paste) (OECD, 2010a). HBCD serves as a fluxing aid within solder/flux paste formulations.

Environmental Release Assessment Methodology

Facility Estimates

As discussed in Section 2.2.12, EPA estimated a throughput of 5,000 pounds HBCD/year (2,268 kg/year) for the formulation of solder flux. EPA uses this same HBCD volume for this condition of use. EPA estimated that the entire throughput is used in the United States, as the portion that is used internationally is unknown, as discussed above.

EPA uses the OECD ESD on Chemicals Used in the Electronics Industry (OECD, 2010a). To calculate the number of solder use sites as described below. Since the OECD ESD estimates other additives are generally less than one percent of the composition of the solder paste, EPA used an HBCD composition of one weight percent for this condition of use.

The OECD ESD includes default annual facility use rates for non-aqueous (paste) solder paste formulations of less than 1,000 kg/site-year for small scale use sites and greater than 1,000 kg/site-year for large scale use sites. To calculate the number of sites for this condition of use, EPA uses a throughput of 1,000 kg solder formulation/site-year. The number of sites is equal to the HBCD use volume (2,268 kg/year), divided by the solder paste formulation use rate (1,000 kg/site-year) and HBCD content in the formulation (0.01). This calculation results in 227 sites.

Release Sources

Based on information in the OECD ESD, EPA infers that releases may occur from: disposal of containers used to ship the flux/solder paste formulations containing HBCD, cleaning of soldering equipment and soldered components, and overapplied solder (OECD, 2010a).

EPA estimated releases from this condition of use using the 2010 OECD ESD on Chemicals used in the Electronics Industry (OECD, 2010a), as the formulator of the solder and flux pastes containing HBCD indicates that these formulations are used for circuits and other electrical components. Table 2-41 summarizes the release sources assessed by EPA. Explanation of the methodology used for this assessment is explained below.

Emission Factors

The OECD ESD on Chemicals Used in the Electronics Industry indicates that the total loss from use of flux and solder in the electronics industry is typically 10 percent (OECD, 2010a). The OECD ESD specifies that releases contributing to this overall loss may include washing of equipment used for soldering, washing of components that have been soldered, and from disposal of unused solder by either solvent washings that occur throughout the electronics manufacturing process or disposal of scrap components containing solder formulations.

While the OECD ESD does not specifically call out releases from disposal of containers used to ship the flux and solder paste formulations, EPA expects this release is a part of the total 10 percent loss estimated by the OECD ESD. The website of the flux and solder formulator identified in 2017 TRI indicates that these formulations are frequently supplied in small containers, such as syringes, from which application onto substrates may be conducted directly from the containers, without unloading into separate application equipment. EPA expects that these containers are most likely disposed of as solid waste to landfill or treated via incineration, as opposed to being cleaned (which may result in liquid wastes). Thus, EPA estimated release from container residual disposed of to landfill or treated via incineration, using the *EPA/OPPT Small Container Residual Model*, which indicates a loss of 0.6 percent from residue inside containers (U.S. EPA, 2013a). The method of release, disposal, treatment, or discharge is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. EPA did not find information on waste handling procedures at these sites. The method of release, disposal, treatment, or discharge may include disposal to landfill, treatment via incineration, or both.

The OECD ESD on Chemicals Used in the Electronics Industry indicates that release may occur from cleaning of equipment or components (such as solder equipment, which is distinguished from application equipment) (OECD, 2010a). The OECD ESD estimates that this release is up to 2 percent of the use volume discharged in wastewater to on-site WWT or POTW.

The final release that is defined in the OECD ESD is loss of unused flux and solder paste formulations. This may occur when unused formulation on soldered components (i.e., overapplied solder) is washed off components in some of the solvent washings that are customary in the electronics manufacturing process (OECD, 2010a). This release may also occur from the disposal of scrap components that have been soldered or that contain unused flux and solder formulation. While the OECD ESD does not specify an exact loss percentage for this release, it does estimate a total loss of 10 percent, which EPA used to determine this release fraction by subtracting the upstream losses of container disposal (0.6%) and equipment cleaning (1 to 2%). Thus, EPA estimated a loss of 7.4 to 8.4 percent for this release. The

OECD ESD indicates that generated process solvents are disposed of as hazardous waste (which EPA assumes includes incineration or hazardous waste landfill disposal) and that scrap components are disposed of as solid waste. Thus, EPA assessed disposal to landfill or treatment via incineration. The method of release, disposal, treatment, or discharge is dependent on any pollution controls that are implemented at that site, as well as other factors such as the equipment used and size of the site. EPA did not identify information on waste handling procedures at these sites. The method of release, disposal, treatment, or discharge may include disposal to landfill, treatment via incineration, or both.

The total loss from this condition of use is 10% per the OECD ESD, with variation in the amount of release for each method of release, disposal, treatment, or discharge (wastewater, landfill, or incineration).

Table 2-41. Summary of HBCD Release Sources During Use of Flux and Solder Pastes

Release Source	Emission Factor used in this Risk Evaluation	Method of Release, Disposal, Treatment, or Discharge Assessed in this Risk Evaluation	Basis or Source
Disposal of used transport container containing solid HBCD residuals	0.006 kg HBCD released/kg HBCD in containers	Uncertain: landfill, incineration Due to the small container size (syringes), EPA assumes containers are disposed of from the sites as solid waste to either landfill or incineration	*EPA/OPPT Small Container Residual Model* (U.S. EPA, 2013a)
Equipment Cleaning release of solid HBCD residuals	0.01 to 0.02 kg HBCD released/kg HBCD used	100% to Onsite WWT/ POTW	(OECD, 2010a). – The OECD ESD indicates that up to 2% of total releases may be to wastewater from cleaning of equipment or components.
Unused flux remaining on components, which are likely removed in subsequent solvent washes	0.084 to 0.074 (10% minus upstream losses, see above) kg HBCD released/kg HBCD used	Uncertain: landfill, incineration Solvent washings treated as hazardous waste. EPA assessed to incineration or landfill.	(OECD, 2010a). – Per the OECD ESD a total of 10% loss is expected; accounting for upstream losses, this loss is 7.4%

Number of Release Days

EPA estimated a range of emission days per year based on the European Communities Technical Guidance Document for use in the electronics industry, as the solder formulations in this condition of use are used for electronics applications (ECB, 2003). Specifically, EPA determined a range of potential emission days by calculating the lowest and highest possible emission days from the applicable defaults for use within the electronics industry. With this method and the HBCD processing volume for this condition of use (5,000 pounds or 2.25 metric tons), EPA estimated 4 days/year. The highest number of emission days for use within the electronics industry is 300 days/year. Based on these values, EPA estimated a range of 4 to 300 emission days/year.

The data sources used to estimate releases in this section are listed in Table 2-42 along with the data quality score. See Appendix D for more details about data source evaluation.

Table 2-42. Use of Flux and Solder Pastes Release Data Source Evaluation

Source Reference	Data Type	Value	Overall Confidence Rating of Data
(ECB, 2003)	Release Days	4 to 300 days/year for all releases	Medium

Environmental Release Assessment Results

The variables used for calculating releases with Equation 2-1 are summarized in Table 2-43.

Table 2-43. Input Variables to Equation 2-1 for Use of Flux and Solder Pastes

Input Variable				
V (kg HBCD imported/yr)	N_S (sites)	f (kg HBCD released/kg HBCD used)		N_d (days/yr)
		Lower values of emission factors	Upper values of emission factors	
5,000 pounds/yr = 2,268 kg/yr	227	0.09 to landfill and/or incineration 0.01 to Onsite WWT and/or POTW	0.08 to landfill and/or incineration 0.02 to Onsite WWT and/or POTW	4-300

The amount of solid HBCD released from use of flux and solder pastes was calculated with Equation 2-1. The results of these calculations are summarized in Table 2-44. The use of flux and solder pastes results in releases to wastewater, municipal landfill, and incineration. The largest source of release is from unused formulations that are disposed of to landfill or incineration.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed range of daily release rates that are presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence.

To estimate the range of daily release rates, EPA calculated minimum and maximum daily release rates using the assessed HBCD processing volume, a range of emission factors, and a range of number of release days per year as discussed in detail in Section 2.2.1 and above. EPA has high confidence in this assessment approach, which is a strength of the assessment. EPA used emission factor data from the 2010 OECD ESD on Chemicals Used in the Electronics Industry. The quality of the emission factor data was not evaluated because this data was obtained from an ESD. EPA used data on number of release days from the European Communities Technical Guidance Document (ECB, 2003), which has an overall confidence rating of medium, assigned using EPA's systematic review process, as discussed in Section 1.5. However, EPA estimated a range of release days in order to capture variability and address uncertainty in this method. EPA has a high confidence that the estimated range of release days encompasses the actual range of release days at these sites, which is a strength of this assessment. The limitations of the assessment are uncertainties regarding the extent to which the emission factor data and the data on number of release days are applicable to the HBCD use activities that would occur in the U.S. Based on the strength and limitations of the assessment, EPA has medium to high confidence in the assessment results.

Table 2-44. Summary of HBCD Releases from Use of Flux and Solder Pastes

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Higher landfill and incineration releases [b]				Higher onsite wastewater, POTW releases [b]				Number of Sites	Hours of Release per Day (hr/day)
		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)		Total Annual Release for All Sites (kg/yr)	Annual Release Per Site (kg/site-yr)	Daily Release (kg/site-day)			
				Number of release days: 4 day/year	Number of release days: 300 day/year			Number of release days: 4 day/year	Number of release days: 300 day/year		
Equipment cleaning release of solid HBCD residuals	May go to one or more: Onsite WWT or POTW	22.7	0.100	2.50E-02	3.33E-04	45.4	0.200	5.00E-02	6.66E-04	227	8 hours/day
Disposal of transport containers containing solid HBCD residual and overapplied/unused solder	May go to one or more: Incineration or landfill	204	0.899	2.25E-01	3.00E-03	181	0.799	0.200	2.66E-03	227	8 hours/day

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.

[b] Release estimates are quantities of HBCD. The physical form of these releases is solid or paste mixtures containing HBCD and other solder / flux formulation components.

2.2.14 Sensitivity Analysis- Process Volume

In Section 2.2.2 through Section 2.2.7, EPA provided release estimates using the CDR reporting threshold volume of 100,000 lbs/yr-site. EPA selected 100,000 lbs/yr as a conservative process volume in an effort to account for the uncertainty in the current HBCD import volume. As discussed in Section 1.2.5, EPA determined that the previously high volume HBCD importers (as identified by the 2016 CDR) have permanently stopped importing HBCD. EPA's review of a widely used import database (Datamyne) identified 5 sites in 2016 importing a total of 399,315 lbs/yr of HBCD, and 1 site importing 46,096 lbs/yr in 2017. As of October 2018, there were no imports reported for 2018. The import of HBCD has been steadily declining since the Stockholm Convention on Persistent Organic Pollutants (POPs) has caused many processors to shift to alternative flame retardants. Due to the uncertainty with the imported volume, EPA performed a targeted sensitivity analysis of process volume for select conditions of use.

EPA performed the sensitivity analyses for three conditions of use at the per site process volumes of 50,000 lbs/yr and 25,000 lbs/yr to examine the effect of process volume on environmental releases and subsequently the resulting general population and environmental exposures. EPA selected 50,000 lbs/yr based on the most recent import volume reported for HBCD (2017), and to account for the declining use of HBCD, EPA also considered a lower volume of 25,000 lbs/yr. The conditions of use considered in the sensitivity analysis represent the conditions of use that resulted in the highest estimates of releases on a daily basis and include scenarios that rely on both industry data and OECD ESDs. As shown in equation 2.1, the daily releases of HBCD are estimated based on four parameters: process volume(V), number of sites (Ns), emission factor (f), and number of release days (Nd). The last parameter, number of release days (Nd), was estimated by either using industry data, days provided in relevant ESDs/GSs or European Communities Technical Guidance Document (ECB, 2003). Depending on the source, the selected range of release days may vary based on the expected process volume and was adjusted accordingly. The determination of release days for each condition of use is discussed in their respective sections: Section 2.2.2, Section 2.2.4, and Section 2.2.6. For all of the selected conditions of use, the estimated total annual release per site decreased by the same factor as the decrease in the process volume (i.e. annual releases based on 50,000 lbs/yr decreased by a factor of 2; annual releases based 25,000 lbs/yr decreased by a factor of 4).

Processing: Repackaging of Import Containers

For repackaging of import containers, quantities of releases are estimated from dust emissions during the transfer of HBCD powder from import containers into new containers and from residual HBCD in the emptied import containers that are disposed. The quantities of releases at the different process volumes are presented in Table 2-45. An explanation of the emission factors for this condition of use are presented in Section 2.2.2. The daily quantities of releases into the environment at different process volumes are relatively unchanged as the range of the daily throughput volume (process volume per site/operating days) for this condition of use did not significantly change. The lower value of the number of release days (i.e., operating days for this condition of use) were estimated using B-tables from the basic chemicals industry category in the European Communities Technical Guidance Document (ECB, 2003), which calculates a number of release days using the total import volume of the chemical substance. The changes in process volumes adjusted the number of release days proportionally to the decrease in process volume, the effect was similar daily releases. For this specific condition of use, EPA also deemed that the higher value of release days, 300 days, would be adjusted to stay within a reasonable range of daily throughputs based on the expected repackaging process and the reported daily

throughput given by a repackaging site in NICNAS. The higher value of release days was scaled by the same factor as the change in annual import volume.

Processing: Manufacturing of XPS foam from XPS Masterbatch

For the manufacturing of XPS foam from XPS Masterbatch, releases are estimated from: dust generation during unloading the HBCD powder from the bags in which they were received; disposal of the bags in which the HBCD powder is received; and periodic cleaning of process equipment. An explanation of the emission factors for this condition of use are presented in Section 2.2.4. The releases at the different process volumes are presented in Table 2-46. The decrease in daily releases into the environment between process volume is directly proportional to the decrease in the process volume. The release days specified by site-specific emission data in the EURAR are used for the range of release days.

Processing: Manufacturing of EPS foam from EPS resins

For Manufacturing of EPS foam from EPS resins, releases are estimated from dust generation during unloading the EPS resin beads from the bags in which they were received and from the converting process; disposal of the bags in which the EPS resin beads are received; and periodic cleaning of process equipment. An explanation of the emission factors for this condition of use are presented in Section 2.2.6. The releases at the different process volumes are presented in Table 2-47. The changes in daily release into the environment vary depending on number of release days estimate. For the lower value of release days that were generated using the EU TGD- Polymer Industry (ECB, 2003), the adjustment to the release days was proportional to the decrease in process volume. This results in little change between the daily releases at the lower value of release days. The higher value of release days was reported by a EPS foam manufacturer in NICNAS (NICNAS, 2012b). The process volume of the reported site was not included, so it is uncertain if the lower process volume is applicable to the reported release days. However, EPA believes given the small percentage of HBCD in EPS resins beads (<1%), 140 days is still within a reasonable range of release days for EPS foam manufacturing for both 50,000 lbs/yr and 25,000 lbs/yr of HBCD.

Table 2-45. Summary of HBCD Releases from Sensitivity Analysis of Repackaging of Import Containers

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from lower value of range of emission factors [b]			Releases calculated from upper value of range of emission factors [b]		
		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)	
			Lower Number of release days [d]	Upper Number of release days [e]		Lower Number of release days [d]	Upper Number of release days [e]
Annual import volume = 100,000 pounds HBCD/year							
Dust release during unloading of HBCD	May go to one or more: Stack air, Fugitive Air, on-site WWT, POTW, landfill, or incineration	45.4	1.56	0.15	227	7.82	0.756
Disposal of transport bags	Landfill	454	15.64	1.51	454	15.64	1.51
Annual import volume = 50,000 pounds HBCD/year							
Dust release during unloading of HBCD	May go to one or more: Stack air, Fugitive Air, on-site WWT, POTW, landfill, Incineration	22.7	1.51	0.15	113	7.56	0.756
Disposal of transport bags	Landfill	227	15.12	1.51	227	15.12	1.51
Annual import volume = 25,000 pounds HBCD/year							
Dust release during unloading of HBCD	May go to one or more: Stack air, Fugitive Air, on-site WWT, POTW, landfill, Incineration	11.3	1.62	0.15	57	8.10	0.756
Disposal of transport bags	Landfill	113	16.20	1.51	113	16.20	1.51

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid HBCD.
[c] Based on the assumption of one given site.
[d] The lower number of release days is 29 days/yr (100,000 lb/yr), 15 days/yr (50,000 lb/yr), 7 days/yr (25,000 lb/yr). Release days were calculated using the new process volume using EU TGD B-tables (ECB, 2003), which required rounding to the nearest integer for release days. Note: While the process volumes were scaled by 2, due to rounding, the daily releases are not directly scaled by the same factor.
[e] The upper number of release days is 300 days/yr (100,000 lb/yr), 150 days/yr (50,000 lb/yr), 75 days/yr (25,000 lb/yr).

Table 2-46. Summary of HBCD Releases from Sensitivity Analysis of XPS Foam Manufacturing Using XPS Masterbatch

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from lower value of range of emission factors [b]			Releases calculated from upper value of range of emission factors [b]		
		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)	
			Lower Number of release days [d]	Upper Number of release days [e]		Lower Number of release days [d]	Upper Number of release days [e]
Annual import volume = 100,000 pounds HBCD/year							
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Stack air or fugitive air	2.63	2.63	0.164	2.63	2.63	0.164
Unknown – these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Surface Water, Onsite WWT, or POTW	0.486	0.486	3.24E-02	1.19	1.19	0.080
Annual import volume = 50,000 pounds HBCD/year							
Unknown - these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Stack air, fugitive air	1.31	1.31	0.082	1.31	1.31	0.082
Unknown - these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Surface Water, Onsite WWT, POTW	0.243	0.243	1.62E-02	0.60	0.60	0.040
Annual import volume = 25,000 pounds HBCD/year							
Unknown - these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Stack air, fugitive air	0.66	0.66	0.041	0.66	0.66	0.041
Unknown - these data were reported by EU sites in the EURAR as total annual release per site	May go to one or more: Surface Water, Onsite WWT, POTW	0.121	0.121	8.10E-03	0.30	0.30	0.020

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.
[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.
[c] Based on the assumption of one given site.
[d] The lower number of release days is 1 day/year (for all releases and all annual import volumes).
[e] The upper number of release days is 15 day/year (wastewater discharges) and 16 day/year (air releases) for all annual import volumes.

Table 2-47. Summary of HBCD Releases from Sensitivity Analysis of EPS Foam Manufacturing from EPS Resin Beads

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from lower value of range of emission factors [b]			Releases calculated from upper value of range of emission factors [b]		
		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)	
			Lower Number of release days [d]	Upper Number of release days [e]		Lower Number of release days [d]	Upper Number of release days [e]
Annual import volume = 100,000 pounds HBCD/year							
Dust release during converting process	May go to one or more: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, or Incineration	45.4	2.83	0.324	227	14.17	1.62
Equipment cleaning	May go to one or more: surface water, onsite WWT, POTW, landfill, or Incineration	454	28.3	3.24	454	28.3	3.24
Disposal of transport containers	Landfill	454	28.3	3.24	454	28.3	3.24
Trimming foam scrap	May go to one or more: Incineration or landfill	454	28.35	3.24	1134	70.87	8.10
Annual import volume = 50,000 pounds HBCD/year							
Dust release during converting process	May go to one or more: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, Incineration	22.7	2.83	0.162	113	14.17	0.81
Equipment cleaning	May go to one or more: surface water, onsite WWT, POTW, landfill, Incineration	227	28.3	1.62	227	28.3	1.62
Disposal of transport containers	Landfill	227	28.3	1.62	227	28.3	1.62
Trimming foam scrap	May go to one or more: Incineration; landfill	227	28.35	1.62	567	70.87	4.05
Annual import volume = 25,000 pounds HBCD/year							
Dust release during converting process	May go to one or more: Stack air, Fugitive Air, surface water, onsite WWT, POTW, Landfill, Incineration	11.3	2.83	0.081	57	14.17	0.40
Equipment cleaning	May go to one or more: surface water, onsite WWT, POTW, landfill, Incineration	113	28.3	0.81	113	28.3	0.81
Disposal of transport containers	Landfill	113	28.3	0.81	113	28.3	0.81
Trimming foam scrap	May go to one or more: Incineration; landfill	113	28.35	0.81	283	70.87	2.02

[a] The method of release, disposal, treatment, or discharge may include some or all of those listed depending on site-specific conditions, including type of equipment use, size of the site, and waste handling practices, including any pollution controls used.

[b] Release estimates are quantities of HBCD. The physical form of these releases is solid mixtures containing polystyrene and HBCD.

[c] Based on the assumption of one given site.

[d] The lower number of release days is 16 days/yr (100,000 lb/yr), 8 days/yr (50,000 lb/yr), 4 days/yr (25,000 lb/yr).

Release Source	Method of Release, Disposal, Treatment, or Discharge [a]	Releases calculated from lower value of range of emission factors [b]			Releases calculated from upper value of range of emission factors [b]		
		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)		Annual Release Per Site (kg/site-yr) [c]	Daily Release (kg/site-day)	
			Lower Number of release days [d]	Upper Number of release days [e]		Lower Number of release days [d]	Upper Number of release days [e]
[e] The upper number of release days is 140 days/year (all annual import volumes).							

2.2.15 Assumptions and Key Sources of Uncertainties for Environmental Releases

Processing Volume and Number of Sites

This evaluation estimates a processing volume and number of sites for each condition of use of HBCD based on information provided by industry, information from literature or maximum import volume set at the CDR reporting threshold. For the conditions of use involving processing of HBCD into XPS and EPS foam (discussed in Section 2.2.2 to Section 2.2.7), EPA utilizes a processing volume of up to 100,000 pounds per year for an unknown site as discussed in Section 2.2.1. There are uncertainties with the number of possible small firms currently importing HBCD and their import volumes. This could lead to an overestimation of total annual releases at any given site, if HBCD is imported, processed, or used at a lower volume. The impact of the processing volume on daily releases can vary with site-specific variables such as the number of batches (if it's not a continuous process), the frequency of cleaning or the number of release days also influenced by the annual process volume of the chemical substance. EPA evaluated the conditions of use related to XPS and EPS foam manufacturing only at the reporting volume threshold under CDR, however, EPA used a range of release days and emission factors to develop a reasonable range of daily releases to the environment.

For the use of XPS and EPS foam as insulation building materials, EPA used the total HBCD import volume of 100,000 pounds for all sites that install XPS and EPS foam insulation (Sections 2.2.9). As discussed above, there is uncertainty as to the number of small firms importing HBCD and their import volumes, which leads to uncertainty in the overall volume of HBCD that may be used for XPS and EPS foam insulation in buildings. To determine the number of sites that install XPS and EPS foam in buildings, EPA used XPS and EPS foam properties (i.e., density, thickness, and HBCD concentration in the foam) and assumed building sizes to calculate an HBCD throughput at each construction site, from which the number of sites could be determined. For this HBCD throughput calculation, EPA used averaged foam properties between XPS and EPS foam insulation. However, these properties may vary depending on the type of insulation (i.e., interior wall, exterior wall, or roofing), which results in uncertainty in this throughput and number of sites estimates. In addition, EPA used assumed building sizes for residential and commercial sites to develop lower and upper estimates of HBCD throughput and number of sites. In reality, the actual building size and associated HBCD throughput is expected to vary widely, resulting in additional uncertainty in this estimate. The lower and upper estimates of HBCD throughput and number of sites may underestimate and overestimate releases, respectively. However, EPA developed these upper and lower estimates in an effort to capture the possible range of number of sites and associated releases.

EPA used data from an HBCD life cycle assessment in Japan (Managaki et al., 2009) to estimate the amount of insulation materials containing HBCD that are disposed of from demolition sites and the method of disposal. There is uncertainty in the extent to which the disposal practices in Japan are reflective of those in the United States. For the recycling of EPS foam (Section 2.2.11), EPA estimated HBCD processing volume and number of sites based on information identified from industry in the HBCD Problem Formulation document (U.S. EPA, 2018f). There is uncertainty in the extent to which this information captures the full number of sites that recycle or reuse XPS/EPS building insulation containing HBCD. This could lead to underestimation of total annual releases for all sites for this condition of use; however, EPA believes the estimates of releases on a per site basis are reasonable because the HBCD processing volume per site is based on industry data.

For the use of flux/solder pastes containing HBCD (Section 2.2.13), EPA assumed that 5% of 100,000 pounds of HBCD was used for this condition of use based on historical data that indicated 95% or more of HBCD is used in building insulation. As described above, the use of 100,000 pounds is a source of

uncertainty. In addition, there is uncertainty as to whether this historical proportion is still reflective of the current usage of HBCD in United States. Using this total HBCD volume, EPA calculated the number of sites and processing volume at each site using the 2010 OECD ESD on Chemicals Used in the Electronics Industries (OECD, 2010a). The basis of these calculations is an assumed solder paste throughput (and associated HBCD content) reported in the OECD ESD to distinguish small scale from large scale sites that conduct soldering. In reality, the solder throughput and HBCD content likely vary between sites and the use rate in the United States may differ from that reported in the OECD ESD. A major electronics site may utilize more HBCD-containing flux/solder paste than the assumed solder paste throughput, which could lead to an underestimation of releases at the site. The uncertainties in these estimates may result in either underestimation or overestimation of releases on a total and per site basis.

EPA did not estimate the number of sites for the installation of automotive replacement parts (Section 2.2.8) or demolition and disposal of XPS/EPS foam insulation (Section 2.2.10). EPA used 2017 TRI data to estimate the number of sites and associated releases for the formulation of HBCD into solder/flux pastes (Section 2.2.11), rather than estimating these values.

Emission Factors

This report uses existing release data from 2017 TRI data, the EURAR, or modeling approaches from relevant ESDs or GSs to estimate emission factors during each conditions of use. For certain conditions of use (Section 2.2.3 through Section 2.2.5), discrete HBCD release quantities provided in the EURAR were used; however, the EURAR did not provide HBCD throughput (i.e., HBCD processing volumes) for the specific sites from which emission factors could be calculated. The EURAR only provided combined HBCD processing volumes for all the sites for which release data were available. EPA calculated emission factors from EURAR data by dividing the total annual HBCD release quantities for all sites by the total HBCD processing volume for all sites. There is uncertainty from using the total HBCD release quantities and total HBCD throughput to calculate emission factors, as this does not account for variability in the actual HBCD throughput at the site (higher or lower), which would result in different emission factors for each site.

In some instances, EPA used the reported emission factors in the EURAR. Although EPA expects that activities described in risk assessments performed by the EURAR are similar to those performed in the United States, EPA could not verify these values, so this is a source of uncertainty.

As discussed in the Analysis of Exposure Monitoring Data section, uncertainty also arises from the geographic origin of the release data. The data reported in the EURAR pertains to HBCD releases at sites in Europe and the extent to which this data is applicable to HBCD releases in the U.S. is uncertain. Also discussed in the Analysis of Exposure Monitoring Data section, there is uncertainty about the extent to which the release data in the EURAR is applicable to the evaluated conditions of use in this risk evaluation. Despite potential differences in practices of the European sites from which data was collected in the EURAR and sites in the United States, these data still have an overall confidence rating of High from the systematic review process.

In cases where there was no release data in the EURAR for the condition of use in this risk assessment, EPA used modeling approaches from relevant ESDs or GSs, specifically the 2009 OECD ESD on Plastic Additives, and the 2010 OECD ESD on Chemicals Used in the Electronics Industry. While these ESDs or GSs are applicable to the industries of the conditions of use, they are not necessarily specific to the use of HBCD within these industries. In some cases, OECD ESDs or GSs use modeling approaches

listed in EPA ChemSTEER User Guide (U.S. EPA, 2013a). Although there is no statistical characterization of the emission factors that these models, EPA believes the emission factors are in the upper end of the distribution based on EPA's experience. For dust releases in Sections 2.2.2, 2.2.6, and 2.2.11, EPA used emission factors from the 2009 OECD ESD on Plastic Additives, which provides two discrete emission factors, one for particulates <40 µm and one for particles >40 µm. EPA expects a distribution of particle sizes and associated emission factors but does not have these data. The use of the two discrete emission factors from the ESD is a source of uncertainty.

Release Days

EPA estimated the number of release days using industry data from the EURAR, information from ESDs or GSs, and from the European Communities Technical Guidance Document (ECB, 2003). Where available, EPA used the number of release days reported in the EURAR for sites with specific release data. The EURAR did not report site-specific HBCD processing volume from which EPA could scale these release days to account for differences in HBCD throughput at the sites in the EURAR and that assessed by EPA in this report. There is uncertainty in the extent to which the HBCD throughput and HBCD processing activities and frequency is similar to that assessed by EPA. EPA also estimated release days using GSs and ESDs. There is uncertainty whether the GSs and ESDs are reflective of the sites and operations that are included in this risk evaluation. As stated earlier, while ESDs or GSs are applicable to the industries of the conditions of use, they are not necessarily specific to the use of HBCD within these industries. EPA evaluated potential environmental releases using a range of release days in an effort to address the uncertainty and variability in release days.

Additionally, EPA estimated release days from the European Communities Technical Guidance Document (ECB, 2003). There is uncertainty in the applicability of this methodology for HBCD use in the United States. However, EPA evaluated potential environmental releases using a range of release days in an effort to address the large variability in release days.

2.3 Environmental Exposures

2.3.1 Approach and Methodology

HBCD is highly persistent and bioaccumulative and these properties influence its potential for exposure over time. HBCD has been detected in a wide variety of environmental and biological media. Current and recent localized releases to the environment from industrial facilities, releases from indoor sources (building materials and dust), and long-range transport all contribute to levels of HBCD in the outdoor and indoor environment. However, source attribution and temporal trends from these disparate sources is complex as discussed in Section 2.3.7. EPA used the full range of release estimates based on a 100,000 pounds production volume assumption from Section 2.2 of this draft risk evaluation to characterize potential environmental concentrations near facilities. EPA also incorporated variability in other (non-release) inputs used for exposure modeling to further describe the range of potential exposures.

Models used in this assessment include: the Exposure Fate Assessment and Screening Tool (E-FAST), the Variable Volume Water Model Point Source Calculator (VVWM-PSC), and the Integrated Indoor-Outdoor Air Calculator (IIOAC). E-FAST is a peer-reviewed model for estimating total chemical surface water concentrations based on their environmental releases from facilities that manufacture, process, and/or dispose them. As E-FAST does not consider chemical partitioning into various media due to a physico-chemical properties (Kow, Koc), it tends to over-estimate total surface water

concentrations and under estimate the chemical concentration that is sorbed to soil. As HBCD's physico-chemical properties lends it to potentially partitioning into various media (Section 2.1), a tiered modeling approach was conducted for estimating HBCD surface water concentrations using E-FAST in conjunction with the VVWM-PSC model. Thus scenarios with E-FAST-derived exposures that were greater than the most conservative environmental- or human health- relevant PoD, were triaged for further modeling using the VVWM-PSC model. Table 2-48 summarizes the overall approaches used in assessing environmental exposures due to HBCD.

EPA screened, evaluated, and extracted specified monitoring data for surface water, sediment, soil, and targeted wildlife biota. All studies with available monitoring data and passing evaluation scores were considered for determining overall trends. Monitoring data with relevant contextualizing information, indicating the monitored location was near a point source, was considered when selecting central tendency and high-end near-facility concentrations. All remaining monitoring data was compiled and evaluated, and these concentrations were considered to be further away from point sources and more applicable to the overall environment.

Some studies were particularly discussed based on having a large sample size, recent publication date, being conducted in the U.S. (or similar countries), and having additional discussion or interpretation of their results such as noting trends, potential sources, exposure pathways, and/or variability within or across sampling locations.

EPA considered available biomonitoring data in wildlife and dietary patterns across trophic levels as part of its exposure assessment. EPA also conducted modeling to estimate concentrations of HBCD in surface water and sediment. These approaches were considered together to determine central tendency and high-end HBCD concentrations in surface water, sediment, soil, and targeted wildlife biota. Finally, EPA also estimated modification of soils through addition of biosolids and estimated air deposition from point sources and notes that this could contribute to elevated levels of HBCD in soils and ponds near industrial sources. This is discussed semi-quantitatively in Section 2.3.3.

EPA characterized exposure estimates by proximity to industrial facilities. Modeled estimates are specific to different kinds of facilities for specific conditions of use, while monitoring data was more generally classified as being closer to or further away from facilities. There are several exposure assessments completed by other government organizations in the open literature. These exposure assessments were also considered alongside monitored and modeled values.

Table 2-48. Overview of Approaches Used in HBCD Environmental Exposure Assessment

TYPE OF EXPOSURE ESTIMATE	SUMMARY OF APPROACHES USED				
	Direct Use of Reported Monitoring Data	Interpretation, Scaling of Reported Monitoring Data or Completed Assessments	E-FAST Modeling	VVWM-PSC Modeling	IIOAC Modeling
Surface water (river) near industrial facilities emitting HBCD under conditions of use	Yes		Yes	Yes	
Sediment (river) near industrial facilities emitting HBCD under conditions of use	Yes			Yes	
Surface water and Sediment (lakes) near industrial facilities emitting HBCD under conditions of use	Yes	Yes			Yes
Soil near industrial facilities with amended sludge or deposition	Yes	Yes			Yes
Surface water away from industrial sources	Yes				
Sediment away from industrial sources	Yes				
Soil away from industrial sources	Yes				
Exposures to wildlife (variable proximity)	Yes	Yes			

E-FAST = Exposure – Fate Assessment Screening Tool (U.S. EPA, 2014c)
VVWM-PSC = Variable Volume Water Model– Point Source Calculator (U.S. EPA, 2019p)
IIOAC = Integrated Indoor-Outdoor Air Calculator (U.S. EPA, 2019q)

EPA used scenarios described in Section 2.2 for both environmental and human exposure assessment. Each scenario was evaluated for various types of environmental releases. Scenarios identified as having the potential for one or more release types (i.e., surface water, on-site WWT, or POTW) were treated as sub-scenarios when combined with the upper and lower limits of the number of release days and total daily releases. Table 2-49 summarizes the scenarios and sub-scenarios that are relevant for water modeling that were used in the E-Fast and VVWM-PSC models. Surface water modeling was used to estimate surface water concentrations, sediment concentrations, and fish-tissue concentration for human consumption. Water modeling and fish-tissue concentrations are further described in Sections 2.3.2 and 2.4.2.3.

Table 2-49. Summary of Scenarios Used Across Conditions of Use for Water Releases of HBCD

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
1.1	Repackaging of import containers	On-site WWT	90	Lower Value	Dust emissions factor for coarse particles (>40 µm)	Lower Value	29	1.6E+00

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
		[Plastic Resins]						
1.2	Repackaging of import containers	On-site WWT [Plastic Resins]	90	Lower Value	Dust emissions factor for coarse particles (>40 µm)	Higher Value	300	1.5E-01
1.3	Repackaging of import containers	On-site WWT [Plastic Resins]	90	Higher Value	Dust emissions factor for fine particles (<40 µm)	Lower Value	29	7.8E+00
1.4	Repackaging of import containers	On-site WWT [Plastic Resins]	90	Higher Value	Dust emissions factor for fine particles (<40 µm)	Higher Value	300	7.6E-01
1.5	Repackaging of import containers	POTW [Ind POTW]	90	Lower Value	Dust emissions factor for coarse particles (>40 µm)	Lower Value	29	1.6E+00
1.6	Repackaging of import containers	POTW [Ind POTW]	90	Lower Value	Dust emissions factor for coarse particles (>40 µm)	Higher Value	300	1.5E-01
1.7	Repackaging of import containers	POTW [Ind POTW]	90	Higher Value	Dust emissions factor for fine particles (<40 µm)	Lower Value	29	7.8E+00
1.8	Repackaging of import containers	POTW [Ind POTW]	90	Higher Value	Dust emissions factor for fine particles (<40 µm)	Higher Value	300	7.6E-01
2.1	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Surface Water	0	Lower Value	Average calculated emission factor from EURAR data	Lower Value	10	1.5E-01
2.2	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Surface Water	0	Lower Value	Average calculated emission factor from EURAR data	Higher Value	60	2.4E-02
2.3	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Surface Water	0	Higher Value	EURAR's 'worst-case' emission factor	Lower Value	10	3.4E-01
2.4	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Surface Water	0	Higher Value	EURAR's 'worst-case' emission factor	Higher Value	60	5.6E-02
2.5	Compounding of Polystyrene Resin to Produce XPS Masterbatch	On-site WWT [Plastic Resins]	90	Lower Value	Average calculated emission factor from EURAR data	Lower Value	10	1.5E-01

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
2.6	Compounding of Polystyrene Resin to Produce XPS Masterbatch	On-site WWT [Plastic Resins]	90	Lower Value	Average calculated emission factor from EURAR data	Higher Value	60	2.4E-02
2.7	Compounding of Polystyrene Resin to Produce XPS Masterbatch	On-site WWT [Plastic Resins]	90	Higher Value	EURAR's 'worst-case' emission factor	Lower Value	10	3.4E-01
2.8	Compounding of Polystyrene Resin to Produce XPS Masterbatch	On-site WWT [Plastic Resins]	90	Higher Value	EURAR's 'worst-case' emission factor	Higher Value	60	5.6E-02
2.9	Compounding of Polystyrene Resin to Produce XPS Masterbatch	POTW [Ind POTW]	90	Lower Value	Average calculated emission factor from EURAR data	Lower Value	10	1.5E-01
2.10	Compounding of Polystyrene Resin to Produce XPS Masterbatch	POTW [Ind POTW]	90	Lower Value	Average calculated emission factor from EURAR data	Higher Value	60	2.4E-02
2.11	Compounding of Polystyrene Resin to Produce XPS Masterbatch	POTW [Ind POTW]	90	Higher Value	EURAR's 'worst-case' emission factor	Lower Value	10	3.4E-01
2.12	Compounding of Polystyrene Resin to Produce XPS Masterbatch	POTW [Ind POTW]	90	Higher Value	EURAR's 'worst-case' emission factor	Higher Value	60	5.6E-02
3.1	3. Manufacturing of XPS Foam using XPS Masterbatch	Surface Water	0	Lower Value	Average calculated emission factor from EURAR data	Lower Value	1	4.9E-01
3.2	3. Manufacturing of XPS Foam using XPS Masterbatch	Surface Water	0	Lower Value	Average calculated emission factor from EURAR data	Higher Value	15	3.2E-02
3.3	3. Manufacturing of XPS Foam using XPS Masterbatch	Surface Water	0	Higher Value	EURAR's 'worst-case' emission factor	Lower Value	1	1.2E+00

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
3.4	3. Manufacturing of XPS Foam using XPS Masterbatch	Surface Water	0	Higher Value	EURAR's 'worst-case' emission factor	Higher Value	15	8.0E-02
3.5	3. Manufacturing of XPS Foam using XPS Masterbatch	On-site WWT [Plastic Resins]	90	Lower Value	Average calculated emission factor from EURAR data	Lower Value	1	4.9E-01
3.6	3. Manufacturing of XPS Foam using XPS Masterbatch	On-site WWT [Plastic Resins]	90	Lower Value	Average calculated emission factor from EURAR data	Higher Value	15	3.2E-02
3.7	3. Manufacturing of XPS Foam using XPS Masterbatch	On-site WWT [Plastic Resins]	90	Higher Value	EURAR's 'worst-case' emission factor	Lower Value	1	1.2E+00
3.8	3. Manufacturing of XPS Foam using XPS Masterbatch	On-site WWT [Plastic Resins]	90	Higher Value	EURAR's 'worst-case' emission factor	Higher Value	15	8.0E-02
3.9	3. Manufacturing of XPS Foam using XPS Masterbatch	POTW [Ind POTW]	90	Lower Value	Average calculated emission factor from EURAR data	Lower Value	1	4.9E-01
3.10	3. Manufacturing of XPS Foam using XPS Masterbatch	POTW [Ind POTW]	90	Lower Value	Average calculated emission factor from EURAR data	Higher Value	15	3.2E-02
3.11	3. Manufacturing of XPS Foam using XPS Masterbatch	POTW [Ind POTW]	90	Higher Value	EURAR's 'worst-case' emission factor	Lower Value	1	1.2E+00
3.12	Manufacturing of XPS Foam using XPS Masterbatch	POTW [Ind POTW]	90	Higher Value	EURAR's 'worst-case' emission factor	Higher Value	15	8.0E-02
4.1	Manufacturing of XPS Foam using HBCD Powder	Surface Water	0	-	Average calculated emission factor from EURAR data	Lower Value	1	4.6E-01
4.2	Manufacturing of XPS Foam using HBCD Powder	Surface Water	0	-	Average calculated emission factor from EURAR data	Higher Value	12	3.9E-02

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
4.3	Manufacturing of XPS Foam using HBCD Powder	On-site WWT [Plastic Resins]	90	-	Average calculated emission factor from EURAR data	Lower Value	1	4.6E-01
4.4	Manufacturing of XPS Foam using HBCD Powder	On-site WWT [Plastic Resins]	90	-	Average calculated emission factor from EURAR data	Higher Value	12	3.9E-02
4.5	Manufacturing of XPS Foam using HBCD Powder	POTW [Ind POTW]	90	-	Average calculated emission factor from EURAR data	Lower Value	1	4.6E-01
4.6	Manufacturing of XPS Foam using HBCD Powder	POTW [Ind POTW]	90	-	Average calculated emission factor from EURAR data	Higher Value	12	3.9E-02
5.1	Manufacturing of EPS Foam from Imported EPS Resin beads	Surface Water	0	Lower Value	Dust emissions during converting process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	16	3.1E+01
5.2	Manufacturing of EPS Foam from Imported EPS Resin beads	On-site WWT [Plastic Resins]	90	Lower Value	Dust emissions during converting process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	16	3.1E+01
5.3	Manufacturing of EPS Foam from Imported EPS Resin beads	POTW [Ind POTW]	90	Lower Value	Dust emissions during converting process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	16	3.1E+01
5.4	Manufacturing of EPS Foam from Imported EPS Resin beads	Surface Water	0	Lower Value	Dust emissions during converting process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	3.6E+00
5.5	Manufacturing of EPS Foam from Imported EPS Resin beads	On-site WWT [Plastic Resins]	90	Lower Value	Dust emissions during converting process emission factor (lower) and EPA/OPPT Solid	Higher Value	140	3.6E+00

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
					Residuals in Transport Containers Model emission factor			
5.6	Manufacturing of EPS Foam from Imported EPS Resin beads	POTW [Ind POTW]	90	Lower Value	Dust emissions during converting process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	3.6E+00
5.7	Manufacturing of EPS Foam from Imported EPS Resin beads	Surface Water	0	Higher Value	Dust emissions during converting process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	16	4.2E+01
5.8	Manufacturing of EPS Foam from Imported EPS Resin beads	On-site WWT [Plastic Resins]	90	Higher Value	Dust emissions during converting process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	16	4.2E+01
5.9	Manufacturing of EPS Foam from Imported EPS Resin beads	POTW [Ind POTW]	90	Higher Value	Dust emissions during converting process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	16	4.2E+01
5.10	Manufacturing of EPS Foam from Imported EPS Resin beads	Surface Water	0	Higher Value	Dust emissions during converting process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	4.9E+00
5.11	Manufacturing of EPS Foam from Imported EPS Resin beads	On-site WWT [Plastic Resins]	90	Higher Value	Dust emissions during converting process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	4.9E+00

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
5.12	Manufacturing of EPS Foam from Imported EPS Resin beads	POTW [Ind POTW]	90	Higher Value	Dust emissions during converting process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	4.9E+00
6.1	Manufacturing of SIPs and Automotive Replacement Parts	Surface Water	0	Lower Value	Dust release during cutting of foam	Lower Value	16	1.4E-01
6.2	Manufacturing of SIPs and Automotive Replacement Parts	On-site WWT [Plastic Resins]	90	Lower Value	Dust release during cutting of foam	Lower Value	16	1.4E-01
6.3	Manufacturing of SIPs and Automotive Replacement Parts	POTW [Ind POTW]	90	Lower Value	Dust release during cutting of foam	Lower Value	16	1.4E-01
6.4	Manufacturing of SIPs and Automotive Replacement Parts	Surface Water	0	Lower Value	Dust release during cutting of foam	Higher Value	300	7.6E-03
6.5	Manufacturing of SIPs and Automotive Replacement Parts	On-site WWT [Plastic Resins]	90	Lower Value	Dust release during cutting of foam	Higher Value	300	7.6E-03
6.6	Manufacturing of SIPs and Automotive Replacement Parts	POTW [Ind POTW]	90	Lower Value	Dust release during cutting of foam	Higher Value	300	7.6E-03
6.7	Manufacturing of SIPs and Automotive Replacement Parts	Surface Water	0	Higher Value	Dust release during sawing of foam	Lower Value	16	6.4E-01
6.8	Manufacturing of SIPs and Automotive Replacement Parts	On-site WWT [Plastic Resins]	90	Higher Value	Dust release during sawing of foam	Lower Value	16	6.4E-01
6.9	Manufacturing of SIPs and Automotive Replacement Parts	POTW [Ind POTW]	90	Higher Value	Dust release during sawing of foam	Lower Value	16	6.4E-01

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
6.1	Manufacturing of SIPs and Automotive Replacement Parts	Surface Water	0	Higher Value	Dust release during sawing of foam	Higher Value	300	3.4E-02
6.11	Manufacturing of SIPs and Automotive Replacement Parts	On-site WWT [Plastic Resins]	90	Higher Value	Dust release during sawing of foam	Higher Value	300	3.4E-02
6.12	Manufacturing of SIPs and Automotive Replacement Parts	POTW [Ind POTW]	90	Higher Value	Dust release during sawing of foam	Higher Value	300	3.4E-02
8.1	Installation of Insulation in Buildings	surface water	0	Lower Value	Dust release during cutting of foam	Lower Value	1	8.5E-05
8.2	Installation of Insulation in Buildings	POTW [Ind POTW]	90	Lower Value	Dust release during cutting of foam	Lower Value	1	8.5E-05
8.3	Installation of Insulation in Buildings	surface water	0	Higher Value	Dust release during sawing of foam	Higher Value	3	1.0E-02
8.4	Installation of Insulation in Buildings	POTW [Ind POTW]	90	Higher Value	Dust release during sawing of foam	Higher Value	3	1.0E-02
10.1	Recycling of EPS Foam	surface water	0	Lower Value	Dust emissions during recycling process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	1	6.7E-01
10.2	Recycling of EPS Foam	On-site WWT [Plastic Resins]	90	Lower Value	Dust emissions during recycling process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	1	6.7E-01
10.3	Recycling of EPS Foam	POTW [Ind POTW]	90	Lower Value	Dust emissions during recycling process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	1	6.7E-01

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
10.4	Recycling of EPS Foam	surface water	0	Lower Value	Dust emissions during recycling process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	4.8E-03
10.5	Recycling of EPS Foam	On-site WWT [Plastic Resins]	90	Lower Value	Dust emissions during recycling process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	4.8E-03
10.6	Recycling of EPS Foam	POTW [Ind POTW]	90	Lower Value	Dust emissions during recycling process emission factor (lower) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	4.8E-03
10.7	Recycling of EPS Foam	surface water	0	Higher Value	Dust emissions during recycling process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	1	7.9E-01
10.8	Recycling of EPS Foam	On-site WWT [Plastic Resins]	90	Higher Value	Dust emissions during recycling process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	1	7.9E-01
10.9	Recycling of EPS Foam	POTW [Ind POTW]	90	Higher Value	Dust emissions during recycling process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Lower Value	1	7.9E-01
10.1	Recycling of EPS Foam	surface water	0	Higher Value	Dust emissions during recycling process emission factor (higher) and EPA/OPPT Solid Residuals in Transport	Higher Value	140	5.7E-03

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
					Containers Model emission factor			
10.11	Recycling of EPS Foam	On-site WWT [Plastic Resins]	90	Higher Value	Dust emissions during recycling process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	5.7E-03
10.12	Recycling of EPS Foam	POTW [Ind POTW]	90	Higher Value	Dust emissions during recycling process emission factor (higher) and EPA/OPPT Solid Residuals in Transport Containers Model emission factor	Higher Value	140	5.7E-03
12.1	Use of Solder	On-site WWT [Plastic Resins]	90	Lower Value	Equipment cleaning emission factor (lower) (OECD, 2010a)	Lower Value	4	2.5E-02
12.2	Use of Solder	POTW [Ind POTW]	90	Lower Value	Equipment cleaning emission factor (lower) (OECD, 2010a)	Lower Value	4	2.5E-02
12.3	Use of Solder	On-site WWT [Plastic Resins]	90	Lower Value	Equipment cleaning emission factor (lower) (OECD, 2010a)	Higher Value	300	3.3E-04
12.4	Use of Solder	POTW [Ind POTW]	90	Lower Value	Equipment cleaning emission factor (lower) (OECD, 2010a)	Higher Value	300	3.3E-04
12.5	Use of Solder	On-site WWT [Plastic Resins]	90	Higher Value	Equipment cleaning emission factor (higher) (OECD, 2010a)	Lower Value	4	5.0E-02
12.6	Use of Solder	POTW [Ind POTW]	90	Higher Value	Equipment cleaning emission factor (higher) (OECD, 2010a)	Lower Value	4	5.0E-02
12.7	Use of Solder	On-site WWT [Plastic Resins]	90	Higher Value	Equipment cleaning emission factor (higher) (OECD, 2010a)	Higher Value	300	6.7E-04
12.8	Use of Solder	POTW [Ind POTW]	90	Higher Value	Equipment cleaning emission factor (higher) (OECD, 2010a)	Higher Value	300	6.7E-04

Note: [a]For each release source, water releases were modeled depending on the potential for the release to go directly to surface water, to an on-site wastewater treatment or publicly owned treatment works. [b] Where identified in literature, EPA utilized a range

Scenario Label	Condition of Use	Type of Water Release[a] [SIC]	WWTP %	Emission Factor[b]	Characterization of Emission Factor	Number of Release Days[c]	Release Days	Daily Release (kg/site/day)
of emission factors with the characterization of those emission factor described in further details in Section 2.2. [c]Where identified in literature, EPA utilized a range of release days based on the specific condition of use as discussed further in Section 2.2.								

Table 2-50 summarizes indoor and outdoor air modeling scenarios and sub-scenarios derived from Section 2.2 that were used in the IIOAC model. A sub-scenario was created based on combinations of fugitive, stack, or incineration releases with upper and lower values for release days and daily releases. Air modeling is further described in Section 2.4.2. to estimate surface water concentration.

Table 2-50. Summary of Scenarios Across Conditions of Use for Modeled HBCD Air Concentrations

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
1.1	Import/Repackaging	Fugitive	Dust release during unloading of HBCD	lower value	lower value	29	1.6E+00	Dust release during unloading of HBCD
1.2	Import/Repackaging	Fugitive	Dust release during unloading of HBCD	lower value	higher value	300	1.5E-01	Dust release during unloading of HBCD
1.3	Import/Repackaging	Fugitive	Dust release during unloading of HBCD	upper value	lower value	29	7.8E+00	Dust release during unloading of HBCD
1.4	Import/Repackaging	Fugitive	Dust release during unloading of HBCD	upper value	higher value	300	7.6E-01	Dust release during unloading of HBCD
1.5	Import/Repackaging	Stack	Dust release during unloading of HBCD	lower value	lower value	29	1.6E+00	Dust release during unloading of HBCD
1.6	Import/Repackaging	Stack	Dust release during unloading of HBCD	lower value	higher value	300	1.5E-01	Dust release during unloading of HBCD
1.7	Import/Repackaging	Stack	Dust release during unloading of HBCD	upper value	lower value	29	7.8E+00	Dust release during unloading of HBCD
1.8	Import/Repackaging	Stack	Dust release during unloading of HBCD	upper value	higher value	300	7.6E-01	Dust release during unloading of HBCD
1.9	Import/Repackaging	Incineration	Dust release during unloading of HBCD	lower value	lower value	29	1.6E+00	Dust release during unloading of HBCD

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
1.10	Import/Repackaging	Incineration	Dust release during unloading of HBCD	lower value	higher value	300	1.5E-01	Dust release during unloading of HBCD
1.11	Import/Repackaging	Incineration	Dust release during unloading of HBCD	upper value	lower value	29	7.8E+00	Dust release during unloading of HBCD
1.12	Import/Repackaging	Incineration	Dust release during unloading of HBCD	upper value	higher value	300	7.6E-01	Dust release during unloading of HBCD
2.1	Compounding of Polystyrene Resin to Produce XPS Masterbatch	fugitive	Average calculated emission factor from EURAR data	lower value	lower value	10	2.8E-02	Average calculated emission factor from EURAR data
2.2	Compounding of Polystyrene Resin to Produce XPS Masterbatch	fugitive	Average calculated emission factor from EURAR data	lower value	higher value	60	4.6E-03	Average calculated emission factor from EURAR data
2.3	Compounding of Polystyrene Resin to Produce XPS Masterbatch	fugitive	Average calculated emission factor from EURAR data	upper value	lower value	10	3.3E-02	Average calculated emission factor from EURAR data
2.4	Compounding of Polystyrene Resin to Produce XPS Masterbatch	fugitive	Average calculated emission factor from EURAR data	upper value	higher value	60	5.5E-03	Average calculated emission factor from EURAR data
2.5	Compounding of Polystyrene Resin to Produce XPS Masterbatch	stack	Average calculated emission factor from EURAR data	lower value	lower value	10	2.8E-02	Average calculated emission factor from EURAR data
2.6	Compounding of Polystyrene Resin to Produce XPS Masterbatch	stack	Average calculated emission factor from EURAR data	lower value	higher value	60	4.6E-03	Average calculated emission factor from EURAR data
2.7	Compounding of Polystyrene Resin to Produce XPS Masterbatch	stack	Average calculated emission factor from EURAR data	upper value	lower value	10	3.3E-02	Average calculated emission factor from EURAR data
2.8	Compounding of Polystyrene Resin to Produce XPS Masterbatch	stack	Average calculated emission factor from EURAR data	upper value	higher value	60	5.5E-03	Average calculated emission factor from EURAR data

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
3.1	Manufacturing of XPS Foam using XPS Masterbatch	fugitive	Average calculated emission factor from EURAR data	central value	lower value	1	2.6E+00	Average calculated emission factor from EURAR data
3.2	Manufacturing of XPS Foam using XPS Masterbatch	fugitive	Average calculated emission factor from EURAR data	central value	higher value	16	1.6E-01	Average calculated emission factor from EURAR data
3.3	Manufacturing of XPS Foam using XPS Masterbatch	stack	Average calculated emission factor from EURAR data	central value	lower value	1	2.6E+00	Average calculated emission factor from EURAR data
3.4	Manufacturing of XPS Foam using XPS Masterbatch	stack	Average calculated emission factor from EURAR data	central value	higher value	16	1.6E-01	Average calculated emission factor from EURAR data
4.1	Manufacturing of XPS Foam using HBCD Powder	fugitive	Average calculated emission factor from EURAR data	central value	lower value	1	3.3E-01	Average calculated emission factor from EURAR data
4.2	Manufacturing of XPS Foam using HBCD Powder	fugitive	Average calculated emission factor from EURAR data	central value	higher value	16	2.1E-02	Average calculated emission factor from EURAR data
4.3	Manufacturing of XPS Foam using HBCD Powder	stack	Average calculated emission factor from EURAR data	central value	lower value	1	3.3E-01	Average calculated emission factor from EURAR data
4.4	Manufacturing of XPS Foam using HBCD Powder	stack	Average calculated emission factor from EURAR data	central value	higher value	16	2.1E-02	Average calculated emission factor from EURAR data
4.5	Manufacturing of XPS Foam using HBCD Powder	stack	TRI data	empirical value	lower value	1	1.8E+00	TRI data
4.6	Manufacturing of XPS Foam using HBCD Powder	stack	TRI data	empirical value	higher value	16	1.1E-01	TRI data
4.7	Manufacturing of XPS Foam using HBCD Powder	incineration	TRI data	empirical value	lower value	1	3.1E+01	TRI data

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
4.8	Manufacturing of XPS Foam using HBCD Powder	incineration	TRI data	empirical value	higher value	16	1.9E+00	TRI data
4.9	Manufacturing of XPS Foam using HBCD Powder	stack	TRI data	empirical value	lower value	1	2.1E+01	TRI data
4.10	Manufacturing of XPS Foam using HBCD Powder	stack	TRI data	empirical value	higher value	16	1.3E+00	TRI data
4.11	Manufacturing of XPS Foam using HBCD Powder	incineration	TRI data	empirical value	lower value	1	2.3E+01	TRI data
4.12	Manufacturing of XPS Foam using HBCD Powder	incineration	TRI data	empirical value	higher value	16	1.5E+00	TRI data
5.1	Manufacturing of EPS Foam from Imported EPS Resin beads	stack	Dust release during converting process	lower value	lower value	16	2.8E+00	Dust release during converting process
5.2	Manufacturing of EPS Foam from Imported EPS Resin beads	stack	Dust release during converting process	lower value	higher value	140	3.2E-01	Dust release during converting process
5.3	Manufacturing of EPS Foam from Imported EPS Resin beads	stack	Dust release during converting process	upper value	lower value	16	1.4E+01	Dust release during converting process
5.4	Manufacturing of EPS Foam from Imported EPS Resin beads	stack	Dust release during converting process	upper value	higher value	140	1.6E+00	Dust release during converting process
5.5	Manufacturing of EPS Foam from Imported EPS Resin beads	fugitive	Dust release during converting process	lower value	lower value	16	2.8E+00	Dust release during converting process
5.6	Manufacturing of EPS Foam from Imported EPS Resin beads	fugitive	Dust release during converting process	lower value	higher value	140	3.2E-01	Dust release during converting process

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
5.7	Manufacturing of EPS Foam from Imported EPS Resin beads	fugitive	Dust release during converting process	upper value	lower value	16	1.4E+01	Dust release during converting process
5.8	Manufacturing of EPS Foam from Imported EPS Resin beads	fugitive	Dust release during converting process	upper value	higher value	140	1.6E+00	Dust release during converting process
5.9	Manufacturing of EPS Foam from Imported EPS Resin beads	incineration	Dust release during converting process	lower value	lower value	16	6.0E+01	Dust release during converting process
5.10	Manufacturing of EPS Foam from Imported EPS Resin beads	incineration	Dust release during converting process	lower value	higher value	140	6.8E+00	Dust release during converting process
5.11	Manufacturing of EPS Foam from Imported EPS Resin beads	incineration	Dust release during converting process	upper value	lower value	16	1.1E+02	Dust release during converting process
5.12	Manufacturing of EPS Foam from Imported EPS Resin beads	incineration	Dust release during converting process	upper value	higher value	140	1.3E+01	Dust release during converting process
6.1	Manufacturing of SIPs and Automotive Replacement Parts	fugitive	Dust release during sawing / cutting of foam	lower value	lower value	16	1.4E-01	Dust release during sawing / cutting of foam
6.2	Manufacturing of SIPs and Automotive Replacement Parts	fugitive	Dust release during sawing / cutting of foam	lower value	higher value	300	7.6E-03	Dust release during sawing / cutting of foam
6.3	Manufacturing of SIPs and Automotive Replacement Parts	fugitive	Dust release during sawing / cutting of foam	upper value	lower value	16	6.4E-01	Dust release during sawing / cutting of foam
6.4	Manufacturing of SIPs and Automotive Replacement Parts	fugitive	Dust release during sawing / cutting of foam	upper value	higher value	300	3.4E-02	Dust release during sawing / cutting of foam

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
6.5	Manufacturing of SIPs and Automotive Replacement Parts	stack	Dust release during sawing / cutting of foam	lower value	lower value	16	1.4E-01	Dust release during sawing / cutting of foam
6.6	Manufacturing of SIPs and Automotive Replacement Parts	stack	Dust release during sawing / cutting of foam	lower value	higher value	300	7.6E-03	Dust release during sawing / cutting of foam
6.7	Manufacturing of SIPs and Automotive Replacement Parts	stack	Dust release during sawing / cutting of foam	upper value	lower value	16	6.4E-01	Dust release during sawing / cutting of foam
6.8	Manufacturing of SIPs and Automotive Replacement Parts	stack	Dust release during sawing / cutting of foam	upper value	higher value	300	3.4E-02	Dust release during sawing / cutting of foam
6.9	Manufacturing of SIPs and Automotive Replacement Parts	incineration	Dust release during sawing / cutting of foam	lower value	lower value	16	2.8E+01	Dust release during sawing / cutting of foam
6.10	Manufacturing of SIPs and Automotive Replacement Parts	incineration	Dust release during sawing / cutting of foam	lower value	higher value	300	1.5E+00	Dust release during sawing / cutting of foam
6.11	Manufacturing of SIPs and Automotive Replacement Parts	incineration	Dust release during sawing / cutting of foam	upper value	lower value	16	7.2E+01	Dust release during sawing / cutting of foam
6.12	Manufacturing of SIPs and Automotive Replacement Parts	incineration	Dust release during sawing / cutting of foam	upper value	higher value	300	3.8E+00	Dust release during sawing / cutting of foam
8.1	Installation of Insulation in Buildings	fugitive	Dust release during sawing / cutting of foam	lower value	lower value	1	8.5E-05	Dust release during sawing / cutting of foam
8.2	Installation of Insulation in Buildings	fugitive	Dust release during sawing / cutting of foam	upper value	higher value	3	1.0E-02	Dust release during sawing / cutting of foam
8.3	Installation of Insulation in Buildings	incineration	Dust release during sawing / cutting of foam	lower value	lower value	1	1.7E-02	Dust release during sawing / cutting of foam
8.4	Installation of Insulation in Buildings	incineration	Dust release during sawing / cutting of foam	upper value	higher value	3	1.1E+00	Dust release during sawing / cutting of foam

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
10.1	Recycling of EPS Foam	fugitive	Dust release from grinding of foam	lower value	lower value	1	3.2E-02	Dust release from grinding of foam
10.2	Recycling of EPS Foam	fugitive	Dust release from grinding of foam	lower value	higher value	140	2.3E-04	Dust release from grinding of foam
10.3	Recycling of EPS Foam	fugitive	Dust release from grinding of foam	upper value	lower value	1	1.6E-01	Dust release from grinding of foam
10.4	Recycling of EPS Foam	fugitive	Dust release from grinding of foam	upper value	higher value	140	1.1E-03	Dust release from grinding of foam
10.5	Recycling of EPS Foam	stack	Dust release from grinding of foam	lower value	lower value	1	3.2E-02	Dust release from grinding of foam
10.6	Recycling of EPS Foam	stack	Dust release from grinding of foam	lower value	higher value	140	2.3E-04	Dust release from grinding of foam
10.7	Recycling of EPS Foam	stack	Dust release from grinding of foam	upper value	lower value	1	1.6E-01	Dust release from grinding of foam
10.8	Recycling of EPS Foam	stack	Dust release from grinding of foam	upper value	higher value	140	1.1E-03	Dust release from grinding of foam
10.9	Recycling of EPS Foam	incineration	Dust release from grinding of foam	lower value	lower value	1	6.7E-01	Dust release from grinding of foam
10.10	Recycling of EPS Foam	incineration	Dust release from grinding of foam	lower value	higher value	140	4.8E-03	Dust release from grinding of foam
10.11	Recycling of EPS Foam	incineration	Dust release from grinding of foam	upper value	lower value	1	7.9E-01	Dust release from grinding of foam
10.12	Recycling of EPS Foam	incineration	Dust release from grinding of foam	upper value	higher value	140	5.7E-03	Dust release from grinding of foam
11.1	Formulation of solder	fugitive	TRI data	empirical value	lower value	5	9.1E-02	TRI data
11.2	Formulation of solder	fugitive	TRI data	empirical value	higher value	300	1.5E-03	TRI data
11.3	Formulation of solder	stack	TRI data	empirical value	lower value	5	1.3E+00	TRI data
11.4	Formulation of solder	stack	TRI data	empirical value	higher value	300	2.1E-02	TRI data
12.1	Use of Solder	incineration	Disposal of transport containers and overapplied/unused solder-incineration	higher value	lower value	4	2.2E-01	Disposal of transport containers and overapplied/unused solder-incineration
12.2	Use of Solder	incineration	Disposal of transport	higher value	higher value	300	3.0E-03	Disposal of transport

Scenario Label	Conditions of Use	Type of Air Release	Characterization of Emission Factor	Emission Factor	Release Days	Number of Release Days	Daily Release (kg/site/day)	Type of Air Release
			containers and overapplied/unused solder-incineration					containers and overapplied/unused solder-incineration
12.3	Use of Solder	incineration	Disposal of transport containers and overapplied/unused solder-incineration	lower value	lower value	4	2.0E-01	Disposal of transport containers and overapplied/unused solder-incineration
12.4	Use of Solder	incineration	Disposal of transport containers and overapplied/unused solder-incineration	lower value	higher value	300	2.7E-03	Disposal of transport containers and overapplied/unused solder-incineration

Note: [a]For each release source, air releases were modeled depending on whether the releases were from fugitive, stack or incineration emissions. [b] Where identified in literature, EPA utilized a range of emission factors with the characterization of those emission factor described in further details in Section 2.2. [c]Where identified in literature, EPA utilized a range of release days based on the specific condition of use as discussed further in Section 2.2

2.3.2 Aquatic Environment - Surface Water and Sediment

EPA identified and extracted measured concentrations of HBCD in surface water in fourteen studies. There were also three modeled estimates of HBCD in surface water from other government agencies.

For surface water concentrations near facilities, concentrations were generally higher, with values greater than 0.1 µg/L. Reported surface water monitoring data are typically below 10 µg/L. For example, reports from the UK, South Africa, and Japan and range from 1.52 to 2.1 µg/L (Chokwe et al., 2015; Oh et al., 2014; EC, 2008). Despite the different sampling locations and years, there is a tight range of maximum values reported across these three studies.

A risk assessment from Canada estimated HBCD concentrations ranging from 0.1 to 15 µg/L at 100 meters from a discharge pipe using a fugacity based surface water model (EC/HC, 2011). These modeled estimates best approximate EPA's modeled estimates in surface water, which are discussed later in this section.

Values of surface water concentrations from areas far from facilities are generally low, with values less than 0.1 µg/L. For example, (Venier et al., 2014) measured HBCD in surface water samples from the Great Lakes with HBCD detected in 14 out of 24 samples. Overall concentrations ranged from 2.0E-7 ug/L to 4.4E-6 µg/L, with an average across detected samples of 1.2E-6 µg/L. (Ichihara et al., 2014) measured HBCD in surface water samples from 19 sampling locations in the Yodo River basin in Japan. Multiple samples were collected per sampling location and the mean values were reported by sampling location and by river. Across all 19 sampling locations, surface water concentrations ranged from 1.9E-4 µg/L to 1.4E-2 µg/L with an average concentration of 3.3E-3 µg/L. Average concentrations in the Kanski River, Yodo River, and Yamato River were 9.1E-4, 7.6E-4, and 6.7E-3 µg/L. The authors also reported flow rates and estimated pollutant loads. It is noteworthy, that the lowest flow river, the Yamato River, had the highest HBCD concentration.

EPA identified over fifty monitoring studies that contained information on HBCD in sediment. The relatively large number of studies likely due to the high K_{OC} of HBCD which drives partitioning to sediment. Reported concentrations in sediment span orders of magnitude and range from <1 µg/kg dw to <1,000 µg/kg dw, with the highest concentrations recorded near industrial areas or downstream of facilities that are associated with the manufacture, processing, use of brominated flame retardants (BFRs) or BFR containing materials. This overall trend suggests that some facilities or industries likely serve as point sources for the release of HBCD to the environment.

Two studies by Guerra et al were identified as key studies to characterize near-facility sediment concentrations. These studies noted the same trend with higher sediment concentrations located near point sources, decreasing sediment concentrations downstream from point sources, and non-detects upstream or further away from point sources. (Guerra et al., 2009) identified a sampling site near a point source with HBCD concentrations in surficial sediment ranging from 514-2,430 µg/kg. Concentrations of HBCD decreased to 90-866 µg/kg 27-30 km downstream. HBCD was not detected 60 km downstream or at upstream locations. Similarly, (Guerra et al., 2010) identified a sampling site near a point source with HBCD concentration of 1,873 µg/kg. Other downstream sites had HBCD concentrations of 64.6 to 91 µg/kg.

For central tendency sediment concentrations, the (EC, 2008) assessment characterized sediment concentrations both near point sources and away from point sources. Their meta-analysis across 16 studies reported a range from 0.05 to 511 µg/kg. Overall the data set is skewed with median HBCD concentration of 1.5 µg/kg, lower than the mean HBCD concentration of 31 µg/kg. The 90th percentile HBCD concentration was estimated as 100 µg/kg .

For this assessment, when looking across all sediment studies, the overall results show that most data falls within the range of 1 and 10,000 µg/kg with some data points in a small subset of studies falling below and above this range. Charts and tables that provide additional details for sediment data are presented in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment. (U.S. EPA, 2019d).*

EPA also used the E-FAST and PSC models to estimate surface water and sediment concentrations. E-FAST was used a first tier to identify where modeled surface water column concentrations did and did not exceed aquatic hazard values. The PSC model was then used to identify 1-day and 21-day average dissolved and suspended sediment water concentration as well as 28-day sediment concentrations EPA's Exposure and Fate Assessment Screening Tool (E-FAST) , Version 2.0, was developed to support EPA assessments of potential environmental exposures. For exposure characterization, the E-FAST model was used to estimate HBCD surface water concentrations based on estimated water releases from facilities that manufacture or process HBCD. The exposure scenarios included in the E-FAST model contain default parameter values that allow for exposure estimations considering dilution.

There are a variety of other surface water models that consider additional processes that occur such as partitioning, volatilization, and degradation. Variable flow throughout a river and differences in river characteristics, turbidity, channel characteristics, meteorology can also be considered. As these additional processes are considered, complexity of modeling increases.

Water dilution models can be used to determine the concentration of a chemical in the surface water after a source emits the chemical into a water body. The volume of a river varies over time with different

flows expected seasonally and from year to year. Simple dilution models can take this into account but do not account for partitioning between compartments within a surface water body or degradation over time in different media.

E-FAST includes a Probabilistic Dilution Model (PDM) which predicts the number of days per year in which a designated exposure, or effect level (*i.e.*, concentration of concern) will be exceeded in ambient waters as a result of chemical discharges (effluents) released from a facility. PDM analyses can be performed on stream reaches with measured flow data or stream reaches that incorporate estimated streamflow values. The PDM model provides chronic risk estimates that are derived from a simple mass balance approach of chemical dilution/emulsion into stream water; however, the input parameters are not single point estimates.

In reality, streams exhibit highly variable seasonal flow patterns. In addition, industrial processes include various operating procedures that can change intermittently, thereby affecting effluent flow rates and the total amount of chemical released to the environment over a given time interval. The PDM incorporates probability distributions from Monte Carlo simulations as analysis inputs for calculating the resulting probability distribution for the chemical concentration that may be seen in stream waters. Ultimately it predicts the number of days per year in which the modeled stream concentrations are expected to exceed the designated effect levels (i.e., COCs) identified for aquatic organisms based on the total amounts of chemical released per day (U.S. EPA, 2007)

The limitations associated with use of the E-FAST model relate to the assumptions made regarding use of sector-based flow information as a surrogate for site-specific flow information, as well as lack of partitioning and degradation parameters that were employed in the PSC model.

Since the E-FAST model incorporates defaults that encompass either a combination of upper percentile and mean exposure parametric values, or all upper percentile parametric values, the resulting model predictions represent high-end exposures estimates. EPA acknowledges the conservative nature of this approach, and used the Point Source Calculator, to further describe environmental exposures as described later in this section. Table 2-51 provides flow values used as inputs for the E-FAST model.

Table 2-51. Flow Values Used for the E-FAST Model

	Harmonic Mean Flow Million Liters per Day (MLD) (50th percentile)	Harmonic Mean Flow MLD (10th percentile)	7Q10 Flow MLD (50th percentile)	7Q10 Flow MLD (10th percentile)
SIC Code- Plastic Resins	1.3E+03	4.5E+01	4.0E+02	8.0E+00
SIC Code- Industrial POTW	2.9E+02	4.0E+01	7.8E+01	7.8E+00
SIC Code- All POTW	1.3E+02	1.1E+01	2.7E+01	1.1E+00

The flow of rivers is highly variable and is dependent on many factors such as weather patterns and effluent released from different facilities. Harmonic mean flow values represent long-term average flow conditions and 7Q10 flow values represent the lowest expected weekly flow over a ten-year period. Note, surface water and sediment concentrations based on 7Q10 flows were considered for ecological exposure assessment. Surface water concentrations based on Harmonic Mean flows from 21-day averages were considered for estimates of fish tissue concentrations. Note, 50th percentile values and

10^{th} percentile flow values are available for the SIC codes noted in Table 2-51. In general, the 10^{th} percentile flow values are approximately at factor of ten lower than 50^{th} percentile flows. The probabilistic dilution model estimates the number of days that the time-varying surface water concentration is above the concentration of concern as it varies around these 50^{th} and 10^{th} percentile values.

EPA uses the following equation to estimate surface water concentrations in E-FAST.

$$SWC = \frac{R \times CF1 \times \left(1 - \frac{T}{100}\right)}{SF \times CF2}$$

Where:

SWC = surface water concentration in µg/L
R = release kg/site/day
CF1 = Conversion factor (10^9 µg/kg)
T= Percent removal, typically from wastewater treatment
SF = Flow of receiving river (million liters per day)
CF2 = Conversion factor (10^6 L/day/MLD)

EPA assumed that direct releases to water did not receive removal during wastewater treatment. This is a conservative assumption that results in the total amount of HBCD released to wastewater treatment at a direct discharging site being released to surface water. This assumption reflects the uncertainty of the type of wastewater treatment that may be in use at a direct discharging facility and the HBCD removal efficiency in that treatment.

EPA assumed that primary treatment occurs on-site with 90% removal during treatment; these were assigned to the Plastic Resins SIC code. EPA assumed that on-site WWTP did receive 90% removal during treatment. These were assigned to the Plastic Resins SIC code. EPA assumed that releases to POTW received 90% removal during treatment. These were assigned to the Industrial POTW SIC code. EPA assumed the POTW all SIC code for only the installation of insulation into building scenario. Note, due to the range of release estimates and types reported in Section 2.2 there are multiple sub-scenarios within each overall exposure scenario. E-FAST was used to estimate surface water concentrations for estimated releases as shown in Table 2-49. It should be noted that these estimates are based on dilution and incorporate HBCD in both the dissolved and particulate phase. However, low-flow stream inputs combined with high-release estimates may yield overly conservative surface water concentrations. See Table 2-52 for modeled surface water estimates.

Table 2-52. Estimated HBCD Surface Water (µg/L) Concentrations Using E-FAST

Scenario Label	Harmonic Mean SWC 50th Percentile	Harmonic Mean SWC 10th Percentile	7Q10 SWC 50th percentile	7Q10 SWC 10th percentile
1.1	1.2E-01	3.5E+00	3.9E-01	1.9E+01
1.2	1.1E-02	3.4E-01	3.7E-02	1.9E+00
1.3	5.9E-01	1.8E+01	1.9E+00	9.8E+01
1.4	5.7E-02	1.7E+00	1.9E-01	9.4E+00
1.5	5.4E-01	3.9E+00	2.0E+00	2.0E+01
1.6	5.2E-02	3.8E-01	1.9E-01	1.9E+00

Scenario Label	Harmonic Mean SWC 50th Percentile	Harmonic Mean SWC 10th Percentile	7Q10 SWC 50th percentile	7Q10 SWC 10th percentile
1.7	2.7E+00	2.0E+01	1.0E+01	1.0E+02
1.8	2.6E-01	1.9E+00	9.7E-01	9.7E+00
2.1	1.1E-01	3.4E+00	3.7E-01	1.9E+01
2.2	1.9E-02	5.5E-01	6.1E-02	3.0E+00
2.3	2.5E-01	7.6E+00	8.4E-01	4.2E+01
2.4	4.2E-02	1.3E+00	1.4E-01	7.0E+00
2.5	1.1E-02	3.4E-01	3.7E-02	1.9E+00
2.6	1.9E-03	5.5E-02	6.1E-03	3.0E-01
2.7	2.6E-02	7.6E-01	8.4E-02	4.2E+00
2.8	4.2E-03	1.3E-01	1.4E-02	7.0E-01
2.9	5.2E-02	3.8E-01	1.9E-01	1.9E+00
2.10	8.5E-03	6.2E-02	3.1E-02	3.1E-01
2.11	1.2E-01	8.5E-01	4.3E-01	4.3E+00
2.12	2.0E-02	1.4E-01	7.2E-02	7.2E-01
3.1	3.7E-01	1.1E+01	1.2E+00	6.1E+01
3.2	2.5E-02	7.3E-01	8.0E-02	4.0E+00
3.3	9.0E-01	2.7E+01	3.0E+00	1.5E+02
3.4	6.1E-02	1.8E+00	2.0E-01	1.0E+01
3.5	3.7E-02	1.1E+00	1.2E-01	6.1E+00
3.6	2.5E-03	7.0E-02	1.0E-02	4.0E-01
3.7	9.0E-02	2.7E+00	3.0E-01	1.5E+01
3.8	6.1E-03	1.8E-01	2.0E-02	1.0E+00
3.9	1.7E-01	1.2E+00	6.2E-01	6.3E+00
3.10	1.1E-02	8.2E-02	4.1E-02	4.2E-01
3.11	4.1E-01	3.0E+00	1.5E+00	1.5E+01
3.12	2.8E-02	2.0E-01	1.0E-01	1.0E+00
4.1	3.5E-01	1.0E+01	1.2E+00	5.8E+01
4.2	3.0E-02	8.8E-01	9.7E-02	4.9E+00
4.3	3.5E-02	1.0E+00	1.2E-01	5.8E+00
4.4	3.0E-03	8.8E-02	9.7E-03	4.9E-01
4.5	1.6E-01	1.2E+00	5.9E-01	6.0E+00
4.6	1.4E-02	9.9E-02	5.0E-02	5.0E-01
5.1	2.4E+01	7.0E+02	7.7E+01	3.9E+03
5.2	2.4E+00	7.0E+01	7.7E+00	3.9E+02
5.3	1.1E+01	7.9E+01	4.0E+01	4.0E+02
5.4	2.7E+00	8.0E+01	8.8E+00	4.4E+02
5.5	2.7E-01	8.0E+00	8.8E-01	4.4E+01
5.6	1.2E+00	9.0E+00	4.6E+00	4.6E+01
5.7	3.2E+01	9.5E+02	1.1E+02	5.3E+03
5.8	3.2E+00	9.5E+01	1.1E+01	5.3E+02

Scenario Label	Harmonic Mean SWC 50th Percentile	Harmonic Mean SWC 10th Percentile	7Q10 SWC 50th percentile	7Q10 SWC 10th percentile
5.9	1.5E+01	1.1E+02	5.4E+01	5.5E+02
5.1	3.7E+00	1.1E+02	1.2E+01	6.1E+02
5.11	3.7E-01	1.1E+01	1.2E+00	6.1E+01
5.12	1.7E+00	1.2E+01	6.2E+00	6.3E+01
6.1	1.1E-01	3.2E+00	3.5E-01	1.8E+01
6.2	1.1E-02	3.2E-01	3.5E-02	1.8E+00
6.3	5.0E-02	3.6E-01	1.8E-01	1.8E+00
6.4	5.8E-03	1.7E-01	1.9E-02	9.5E-01
6.5	5.8E-04	1.7E-02	1.9E-03	9.5E-02
6.6	2.7E-03	1.9E-02	9.8E-03	9.9E-02
6.7	4.8E-01	1.4E+01	1.6E+00	8.0E+01
6.8	4.8E-02	1.4E+00	1.6E-01	8.0E+00
6.9	2.2E-01	1.6E+00	8.2E-01	8.3E+00
6.1	2.6E-02	7.6E-01	8.4E-02	4.2E+00
6.11	2.6E-03	7.6E-02	8.4E-03	4.2E-01
6.12	1.2E-02	8.6E-02	4.4E-02	4.4E-01
8.1	6.8E-04	7.7E-03	3.2E-03	8.0E-02
8.2	6.8E-05	7.7E-04	3.2E-04	8.0E-03
8.3	8.0E-02	9.0E-01	3.7E-01	9.4E+00
8.4	8.0E-03	9.0E-02	3.7E-02	9.4E-01
10.1	5.0E-01	1.5E+01	1.7E+00	8.3E+01
10.2	5.0E-02	1.5E+00	1.7E-01	8.3E+00
10.3	2.3E-01	1.7E+00	8.5E-01	8.6E+00
10.4	3.6E-03	1.1E-01	1.2E-02	5.9E-01
10.5	3.6E-04	1.1E-02	1.2E-03	5.9E-02
10.6	1.7E-03	1.2E-02	6.1E-03	6.2E-02
10.7	6.0E-01	1.8E+01	2.0E+00	9.9E+01
10.8	6.0E-02	1.8E+00	2.0E-01	9.9E+00
10.9	2.8E-01	2.0E+00	1.0E+00	1.0E+01
10.1	4.3E-03	1.3E-01	1.4E-02	7.1E-01
10.11	4.3E-04	1.3E-02	1.4E-03	7.1E-02
10.12	2.0E-03	1.4E-02	7.3E-03	7.3E-02
12.1	1.9E-03	5.5E-02	6.2E-03	3.1E-01
12.2	8.7E-03	6.3E-02	3.2E-02	3.2E-01
12.3	2.5E-05	7.5E-04	8.3E-05	4.2E-03
12.4	1.2E-04	8.4E-04	4.3E-04	4.3E-03
12.5	3.8E-03	1.1E-01	1.2E-02	6.2E-01
12.6	1.7E-02	1.3E-01	6.4E-02	6.4E-01
12.7	5.0E-05	1.5E-03	1.7E-04	8.3E-03
12.8	2.3E-04	1.7E-03	8.5E-04	8.6E-03

Water dilution models can be used to determine the concentration of a chemical in the surface water column after a source emits the chemical into a water body. The volume of a river varies over time with different flows expected seasonally and from year to year. The E-FAST model does not account for partitioning between dissolved and suspended sediment within the water column or between the water column and the benthic environment. The benthic environment is made up of pore water and settled sediments.

Site-specific parameters influence how partitioning occurs over time. For example, the concentration of suspended sediments, water depth, and weather patterns all influence how a chemical may partition between compartments. Physical-chemical properties of the chemical itself also influence partitioning and half-lives into environmental media. HBCD has a K_{OC} of 100,000, indicating a high potential to sorb to suspended particles in the water column and settled sediment in the benthic environment.

Canada considered these parameters when estimating surface water and sediment concentrations of HBCD in rivers receiving HBCD from point sources. Surface water and sediment concentrations were estimated at 100 m from the facility and 5,000 m from the facility using a 10 box fugacity-based model (EC/HC, 2011). These modeled estimates ranged from 0.03 to 15 µg/L in surface water and from 230 to 108,2000 µg/kg in sediment. It is noteworthy that this modeling was conducted when releases to surface water from uses of HBCD were likely higher than they are today.

EPA also modeled dissolved water and settled sediment concentrations using surface water release estimates tailored for this assessment. EPA used the Variable Volume Waterbody Model (VVWM) - Point Source Calculator (PSC) to complete this modeling (U.S. EPA, 2019p). The PSC is a tool designed to estimate time-varying surface water concentrations of a chemical directly applied to a water body, including but not limited to river segments. Loading into the river can be varied daily, set up to be discrete one-time events, or repetitive events over most or all of the year. The PSC is a graphical user interface which gathers the user's inputs and runs USEPA's VVWM. Required inputs are the same as those for the VVWM, but the PSC graphical interface facilitates user interaction for the direct-application and allows model inputs to be defined by the user. Time-varying surface water concentrations can be averaged over variable time periods for comparison to concentrations of concern. For example, 21-day average surface water concentrations and 28-day average sediment concentrations were used for EPA's modeling assessment.

More information on the equations used to estimate surface water and sediment concentrations are available in the PSC user guide (U.S. EPA, 2019p). In short, daily releases and daily flow values are used along with other model inputs to solve mass-balance equations for the water column and for the benthic region.

Surface water flow can be set up to be constant flow or use time-varying flows. Since site-specific information is not available for these facilities, constant flows matching the SIC-based flow values used in E-FAST were selected. Suspended sediment values are highly variable and are influenced by stream flow, land cover, and river conditions. A K_{OC} value of 100,000 was chosen based on measured data. Note, a weather file is also needed to run VVWM-PSC. This incorporates variable flow volume through precipitation events. However, variation through precipitation alters stream flow much less than variations in stream flow from other factors. Use of a constant flow which varied across scenarios was chosen. Table 2-53 displays the inputs used to run the VVWM-PSC for HBCD.

Table 2-53. Inputs for Modeling HBCD Sediment Concentration using VVWM-PSC

Input	Type of Input	Value	Units, Comments	Reference
Sorption Coefficient (Koc)	Chemical	100,000	ml/g	**(ECHA 2017)**
Water Column, Hydrolysis, and Photolysis Half-lives	Chemical	365	Days	
Benthic Half-Live	Chemical	11 to 128	Days	(Davis et al., 2005) (Davis et al., 2006)
Molecular weight	Chemical	641.7	g/mol	
Henry's Law Constant	Chemical	7.4E-6	atm-m3/mole	(U.S. EPA, 2012c)
Heat of Henry	Chemical	41570	J/mol	(U.S. EPA, 2019p)
Loading schedule	Chemical	Varies can add separate table and/or add combinations here.	Offset, number of days on and off	
River width	Environment	8	Meters	(EC/HC (Environment Canada and Health Canada), 2011)
River depth	Environment	2	Meters	
River length	Environment	100	Meters	
Flow rate	Environment	Varies	See Table 2-51.	(U.S. EPA, 2014c)
DFAC	Environment	1.19	Photolysis parameter: Represents the ratio of vertical path lengths to depth	(U.S. EPA, 2019p)
Water Column Suspended Sediment	Environment	50	mg/L	Dodds et al 2004
Chlorophyll	Environment	0.005	mg/L	(U.S. EPA, 2019p)
Water Column Fraction Organic Content	Environment	0.04	Fraction	
Water Column Dissolved Oxygen Content	Environment	5.0	mg/L	
Water Column Biomass	Environment	0.4	mg/L	
Benthic Depth	Environment	0.05	M	
Benthic Porosity	Environment	0.5		
Bulk Density	Environment	1.35	g/cm3	
Benthic Fraction Organic Content	Environment	0.04		
Benthic Dissolved Oxygen Content	Environment	5.0	mg/L	
Benthic Biomass	Environment	0.006	g/m2	
Mass Transfer Coefficient	Environment	1e-8	m/s	

Table 2-54 depicts the estimated sediment concentrations from VVWM-PSC. Note that the 1-day average overall surface water column concentrations are similar to estimated surface water

concentrations from E-FAST because the same flow values were used. Further, the PSC was only run for scenarios where the estimated surface water concentration from E-FAST exceeded an acute or chronic aquatic hazard value (discussed in Section 3.1). The results from second-tier modeling are provided below. See Section 2.3.7 regarding the qualitative sensitivity analysis associated with these results.

Table 2-54. HBCD Water Concentrations Modeled Using PSC (7Q10 Flow 50th Percentile)

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
1.1	3.8E-01	2.9E-01	5.8E-02	3.7E-02	2.8E-02	5.6E-03	7.7E+01	3.4E+01
1.2	3.7E-02	2.8E-02	5.6E-03	3.0E-02	2.3E-02	4.6E-03	7.7E+01	3.4E+01
1.3	1.9E+00	1.5E+00	2.9E-01	1.8E-01	1.4E-01	2.8E-02	3.9E+02	1.7E+02
1.4	1.9E-01	1.4E-01	2.8E-02	1.5E-01	1.2E-01	2.3E-02	3.9E+02	1.7E+02
1.5	1.9E+00	1.5E+00	2.9E-01	1.9E-01	1.4E-01	2.8E-02	4.0E+02	1.7E+02
1.6	1.9E-01	1.4E-01	2.9E-02	1.6E-01	1.2E-01	2.3E-02	3.9E+02	1.7E+02
1.7	9.7E+00	7.3E+00	1.5E+00	9.4E-01	7.1E-01	1.4E-01	2.0E+03	8.7E+02
1.8	9.6E-01	7.3E-01	1.5E-01	7.8E-01	5.9E-01	1.2E-01	2.0E+03	8.6E+02
2.1	3.7E-01	2.8E-01	5.6E-02	1.8E-02	1.3E-02	2.7E-03	2.8E+01	1.3E+01
2.2	6.0E-02	4.5E-02	9.1E-03	1.6E-02	1.2E-02	2.3E-03	2.6E+01	1.2E+01
2.3	8.3E-01	6.3E-01	1.3E-01	4.0E-02	3.0E-02	6.0E-03	6.3E+01	3.0E+01
2.4	1.4E-01	1.0E-01	2.1E-02	2.6E-02	2.0E-02	4.0E-03	6.0E+01	2.7E+01
2.5	3.7E-02	2.8E-02	5.6E-03	1.8E-03	1.3E-03	2.7E-04	2.8E+00	1.3E+00
2.7	8.3E-02	6.3E-02	1.3E-02	4.0E-03	3.0E-03	6.0E-04	6.3E+00	3.0E+00
2.9	1.9E-01	1.4E-01	2.8E-02	9.0E-03	6.8E-03	1.4E-03	1.4E+01	6.7E+00
2.11	4.2E-01	3.1E-01	6.3E-02	2.0E-02	1.5E-02	3.1E-03	3.2E+01	1.5E+01
3.1	1.2E+00	9.1E-01	1.8E-01	5.7E-02	4.3E-02	8.6E-03	4.8E+01	3.6E+01
3.2	8.0E-02	6.0E-02	1.2E-02	3.8E-03	2.9E-03	5.8E-04	8.9E+00	4.0E+00
3.3	2.9E+00	2.2E+00	4.4E-01	1.4E-01	1.1E-01	2.1E-02	1.2E+02	8.9E+01
3.4	2.0E-01	1.5E-01	3.0E-02	9.4E-03	7.1E-03	1.4E-03	2.2E+01	9.9E+00
3.5	1.2E-01	9.1E-02	1.8E-02	5.7E-03	4.3E-03	8.6E-04	4.8E+00	3.6E+00
3.6	8.0E-03	6.0E-03	1.2E-03	3.8E-04	2.9E-04	5.8E-05	8.9E-01	4.0E-01
3.7	2.9E-01	2.2E-01	4.4E-02	1.4E-02	1.1E-02	2.1E-03	1.2E+01	8.9E+00
3.8	2.0E-02	1.5E-02	3.0E-03	9.4E-04	7.1E-04	1.4E-04	2.2E+00	9.9E-01
3.9	6.0E-01	4.5E-01	9.1E-02	2.9E-02	2.2E-02	4.4E-03	2.4E+01	1.8E+01
3.10	4.0E-02	3.0E-02	6.1E-03	2.0E-03	1.5E-03	3.0E-04	4.5E+00	2.0E+00
3.11	1.5E+00	1.1E+00	2.2E-01	7.1E-02	5.4E-02	1.1E-02	6.0E+01	4.5E+01
3.12	9.9E-02	7.5E-02	1.5E-02	4.8E-03	3.7E-03	7.3E-04	1.1E+01	5.0E+00
4.1	1.1E+00	8.6E-01	1.7E-01	5.4E-02	4.1E-02	8.2E-03	4.6E+01	3.5E+01
4.2	9.6E-02	7.3E-02	1.5E-02	4.6E-03	3.5E-03	6.9E-04	8.2E+00	3.7E+00
4.3	1.1E-01	8.6E-02	1.7E-02	5.4E-03	4.1E-03	8.2E-04	4.6E+00	3.5E+00
4.4	9.6E-03	7.3E-03	1.5E-03	4.6E-04	3.5E-04	6.9E-05	8.2E-01	3.7E-01

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
4.5	5.7E-01	4.3E-01	8.7E-02	2.8E-02	2.1E-02	4.2E-03	2.3E+01	1.8E+01
4.6	4.8E-02	3.6E-02	7.3E-03	2.3E-03	1.8E-03	3.5E-04	4.2E+00	1.9E+00
5.1	7.7E+01	5.8E+01	1.2E+01	3.7E+00	2.8E+00	5.6E-01	8.9E+03	4.1E+03
5.2	7.7E+00	5.8E+00	1.2E+00	3.7E-01	2.8E-01	5.6E-02	8.9E+02	4.1E+02
5.3	3.9E+01	2.9E+01	5.8E+00	1.9E+00	1.4E+00	2.8E-01	4.6E+03	2.1E+03
5.4	8.8E+00	6.6E+00	1.3E+00	2.9E+00	2.2E+00	4.5E-01	7.6E+03	3.3E+03
5.5	8.8E-01	6.6E-01	1.3E-01	2.9E-01	2.2E-01	4.5E-02	7.6E+02	3.3E+02
5.6	4.4E+00	3.4E+00	6.7E-01	1.5E+00	1.1E+00	2.3E-01	3.9E+03	1.7E+03
5.7	1.1E+02	7.9E+01	1.6E+01	5.0E+00	3.8E+00	7.6E-01	1.2E+04	5.5E+03
5.8	1.1E+01	7.9E+00	1.6E+00	5.0E-01	3.8E-01	7.6E-02	1.2E+03	5.5E+02
5.9	5.3E+01	4.0E+01	7.9E+00	2.6E+00	1.9E+00	3.9E-01	6.2E+03	2.8E+03
5.10	1.2E+01	9.1E+00	1.8E+00	4.0E+00	3.0E+00	6.1E-01	1.0E+04	4.6E+03
5.11	1.2E+00	9.1E-01	1.8E-01	4.0E-01	3.0E-01	6.1E-02	1.0E+03	4.6E+02
5.12	6.1E+00	4.6E+00	9.2E-01	2.1E+00	1.6E+00	3.1E-01	5.3E+03	2.3E+03
6.1	3.5E-01	2.7E-01	5.3E-02	1.7E-02	1.3E-02	2.6E-03	4.1E+01	1.9E+01
6.2	3.5E-02	2.7E-02	5.3E-03	1.7E-03	1.3E-03	2.6E-04	4.1E+00	1.9E+00
6.3	1.8E-01	1.3E-01	2.7E-02	8.6E-03	6.5E-03	1.3E-03	2.1E+01	9.4E+00
6.4	1.9E-02	1.4E-02	2.9E-03	1.6E-02	1.2E-02	2.5E-03	4.1E+01	1.8E+01
6.7	1.6E+00	1.2E+00	2.4E-01	7.5E-02	5.7E-02	1.1E-02	1.8E+02	8.3E+01
6.8	1.6E-01	1.2E-01	2.4E-02	7.5E-03	5.7E-03	1.1E-03	1.8E+01	8.3E+00
6.9	7.9E-01	6.0E-01	1.2E-01	3.9E-02	2.9E-02	5.8E-03	9.4E+01	4.2E+01
6.10	8.4E-02	6.4E-02	1.3E-02	7.2E-02	5.5E-02	1.1E-02	1.8E+02	8.0E+01
6.11	8.4E-03	6.4E-03	1.3E-03	7.2E-03	5.5E-03	1.1E-03	1.8E+01	8.0E+00
6.12	4.3E-02	3.3E-02	6.5E-03	3.7E-02	2.8E-02	5.6E-03	9.3E+01	4.0E+01
8.1	2.9E-03	2.2E-03	4.4E-04	1.4E-04	1.1E-04	2.1E-05	1.2E-01	8.9E-02
8.3	3.4E-01	2.6E-01	5.1E-02	1.7E-02	1.3E-02	2.5E-03	1.6E+01	1.1E+01
10.1	1.6E+00	1.2E+00	2.5E-01	7.8E-02	5.9E-02	1.2E-02	6.6E+01	5.0E+01
10.2	1.6E-01	1.2E-01	2.5E-02	7.8E-03	5.9E-03	1.2E-03	6.6E+00	5.0E+00
10.3	8.2E-01	6.2E-01	1.2E-01	4.0E-02	3.0E-02	6.0E-03	3.3E+01	2.5E+01
10.4	1.2E-02	8.9E-03	1.8E-03	3.9E-03	3.0E-03	6.0E-04	1.0E+01	4.5E+00
10.7	2.0E+00	1.5E+00	3.0E-01	9.3E-02	7.1E-02	1.4E-02	9.6E+01	6.0E+01
10.8	2.0E-01	1.5E-01	3.0E-02	9.3E-03	7.1E-03	1.4E-03	9.6E+00	6.0E+00
10.9	9.8E-01	7.4E-01	1.5E-01	4.7E-02	3.6E-02	7.1E-03	4.0E+01	3.0E+01
10.10	1.4E-02	1.1E-02	2.1E-03	4.7E-03	3.5E-03	7.1E-04	1.2E+01	5.3E+00
12.1	6.2E-03	4.7E-03	9.3E-04	2.9E-04	2.2E-04	4.5E-05	2.9E-01	1.9E-01
12.2	3.1E-02	2.3E-02	4.7E-03	1.5E-03	1.1E-03	2.3E-04	1.5E+00	9.5E-01
12.5	1.2E-02	9.3E-03	1.9E-03	5.9E-04	4.4E-04	8.9E-05	5.8E-01	3.8E-01
12.6	6.2E-02	4.7E-02	9.4E-03	3.0E-03	2.3E-03	4.5E-04	2.9E+00	1.9E+00

[a] sediment benthic half-life (days)

Table 2-55. PSC Results 7Q10 Flow 10th percentile

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
1.1	1.5E+01	1.1E+01	2.2E+00	1.7E+00	1.3E+00	2.6E-01	3.6E+03	1.4E+03
1.2	1.7E+00	1.3E+00	2.6E-01	1.5E+00	1.1E+00	2.2E-01	3.6E+03	1.4E+03
1.3	7.4E+01	5.6E+01	1.1E+01	8.6E+00	6.5E+00	1.3E+00	1.8E+04	7.0E+03
1.4	8.7E+00	6.6E+00	1.3E+00	7.4E+00	5.6E+00	1.1E+00	1.8E+04	7.0E+03
1.5	1.5E+01	1.1E+01	2.3E+00	1.8E+00	1.3E+00	2.7E-01	3.7E+03	1.4E+03
1.6	1.8E+00	1.3E+00	2.7E-01	1.5E+00	1.1E+00	2.3E-01	3.7E+03	1.4E+03
1.7	7.6E+01	5.7E+01	1.1E+01	8.9E+00	6.7E+00	1.3E+00	1.9E+04	7.2E+03
1.8	9.0E+00	6.8E+00	1.4E+00	7.6E+00	5.7E+00	1.1E+00	1.9E+04	7.2E+03
2.1	1.4E+01	1.1E+01	2.1E+00	7.9E-01	5.9E-01	1.2E-01	1.3E+03	5.4E+02
2.2	2.4E+00	1.8E+00	3.6E-01	5.4E-01	4.1E-01	8.2E-02	1.2E+03	4.7E+02
2.3	3.1E+01	2.4E+01	4.7E+00	1.8E+00	1.3E+00	2.7E-01	2.9E+03	1.2E+03
2.4	5.4E+00	4.1E+00	8.2E-01	1.3E+00	9.5E-01	1.9E-01	2.8E+03	1.1E+03
2.5	1.4E+00	1.1E+00	2.1E-01	7.9E-02	5.9E-02	1.2E-02	1.3E+02	5.4E+01
2.7	3.1E+00	2.4E+00	4.7E-01	1.8E-01	1.3E-01	2.7E-02	2.9E+02	1.2E+02
2.9	1.4E+00	1.1E+00	2.2E-01	8.1E-02	6.1E-02	1.2E-02	1.3E+02	5.5E+01
2.11	3.2E+00	2.4E+00	4.9E-01	1.8E-01	1.4E-01	2.8E-02	3.0E+02	1.2E+02
3.1	4.5E+01	3.4E+01	6.8E+00	2.3E+00	1.7E+00	3.5E-01	1.9E+03	1.4E+03
3.2	3.0E+00	2.3E+00	4.6E-01	1.8E-01	1.4E-01	2.7E-02	4.1E+02	1.6E+02
3.3	1.1E+02	8.3E+01	1.7E+01	5.7E+00	4.3E+00	8.6E-01	4.7E+03	3.5E+03
3.4	7.5E+00	5.6E+00	1.1E+00	4.5E-01	3.4E-01	6.8E-02	1.0E+03	4.0E+02
3.5	4.5E+00	3.4E+00	6.8E-01	2.3E-01	1.7E-01	3.5E-02	1.9E+02	1.4E+02
3.6	3.0E-01	2.3E-01	4.6E-02	1.8E-02	1.4E-02	2.7E-03	4.1E+01	1.6E+01
3.7	1.1E+01	8.3E+00	1.7E+00	5.7E-01	4.3E-01	8.6E-02	4.7E+02	3.5E+02
3.8	7.5E-01	5.6E-01	1.1E-01	4.5E-02	3.4E-02	6.8E-03	1.0E+02	4.0E+01
3.9	4.6E+00	3.5E+00	7.0E-01	2.4E-01	1.8E-01	3.6E-02	2.0E+02	1.5E+02
3.10	3.1E-01	2.3E-01	4.7E-02	1.9E-02	1.4E-02	2.8E-03	4.3E+01	1.7E+01
3.11	1.1E+01	8.6E+00	1.7E+00	5.8E-01	4.4E-01	8.8E-02	4.8E+02	3.6E+02
3.12	7.7E-01	5.8E-01	1.2E-01	4.6E-02	3.5E-02	7.0E-03	1.1E+02	4.1E+01
4.1	4.3E+01	3.2E+01	6.5E+00	2.2E+00	1.7E+00	3.3E-01	1.8E+03	1.4E+03
4.2	3.6E+00	2.7E+00	5.5E-01	2.1E-01	1.6E-01	3.1E-02	3.9E+02	1.5E+02
4.3	4.3E+00	3.2E+00	6.5E-01	2.2E-01	1.7E-01	3.3E-02	1.8E+02	1.4E+02
4.4	3.6E-01	2.7E-01	5.5E-02	2.1E-02	1.6E-02	3.1E-03	3.9E+01	1.5E+01
4.5	4.4E+00	3.3E+00	6.6E-01	2.3E-01	1.7E-01	3.4E-02	1.9E+02	1.4E+02
4.6	3.7E-01	2.8E-01	5.6E-02	2.1E-02	1.6E-02	3.2E-03	4.0E+01	1.6E+01
5.1	2.9E+03	2.2E+03	4.4E+02	1.7E+02	1.3E+02	2.6E+01	4.2E+05	1.7E+05
5.2	2.9E+02	2.2E+02	4.4E+01	1.7E+01	1.3E+01	2.6E+00	4.2E+04	1.7E+04
5.3	3.0E+02	2.2E+02	4.5E+01	1.8E+01	1.3E+01	2.7E+00	4.3E+04	1.7E+04

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
5.4	3.6E+02	2.7E+02	5.4E+01	1.4E+02	1.1E+02	2.1E+01	3.6E+05	1.4E+05
5.5	3.6E+01	2.7E+01	5.4E+00	1.4E+01	1.1E+01	2.1E+00	3.6E+04	1.4E+04
5.6	3.7E+01	2.8E+01	5.6E+00	1.4E+01	1.1E+01	2.2E+00	3.7E+04	1.4E+04
5.7	4.0E+03	3.0E+03	6.0E+02	2.4E+02	1.8E+02	3.6E+01	5.7E+05	2.3E+05
5.8	4.0E+02	3.0E+02	6.0E+01	2.4E+01	1.8E+01	3.6E+00	5.7E+04	2.3E+04
5.9	4.1E+02	3.1E+02	6.1E+01	2.4E+01	1.8E+01	3.7E+00	5.9E+04	2.3E+04
5.10	4.9E+02	3.7E+02	7.4E+01	1.9E+02	1.4E+02	2.9E+01	4.9E+05	1.9E+05
5.11	4.9E+01	3.7E+01	7.4E+00	1.9E+01	1.4E+01	2.9E+00	4.9E+04	1.9E+04
5.12	5.0E+01	3.8E+01	7.6E+00	2.0E+01	1.5E+01	3.0E+00	5.0E+04	1.9E+04
6.1	1.3E+01	1.0E+01	2.0E+00	7.9E-01	6.0E-01	1.2E-01	1.9E+03	7.6E+02
6.2	1.3E+00	1.0E+00	2.0E-01	7.9E-02	6.0E-02	1.2E-02	1.9E+02	7.6E+01
6.3	1.4E+00	1.0E+00	2.1E-01	8.2E-02	6.2E-02	1.2E-02	2.0E+02	7.8E+01
6.4	8.7E-01	6.6E-01	1.3E-01	7.7E-01	5.8E-01	1.2E-01	1.9E+03	7.4E+02
6.7	6.0E+01	4.5E+01	9.0E+00	3.5E+00	2.7E+00	5.3E-01	8.5E+03	3.4E+03
6.8	6.0E+00	4.5E+00	9.0E-01	3.5E-01	2.7E-01	5.3E-02	8.5E+02	3.4E+02
6.9	6.1E+00	4.6E+00	9.2E-01	3.6E-01	2.8E-01	5.5E-02	8.8E+02	3.5E+02
6.10	3.9E+00	2.9E+00	5.9E-01	3.4E+00	2.6E+00	5.2E-01	8.5E+03	3.3E+03
6.11	3.9E-01	2.9E-01	5.9E-02	3.4E-01	2.6E-01	5.2E-02	8.5E+02	3.3E+02
6.12	4.0E-01	3.0E-01	6.0E-02	3.5E-01	2.7E-01	5.3E-02	8.8E+02	3.4E+02
8.1	2.0E-02	1.5E-02	3.0E-03	1.3E-03	9.8E-04	2.0E-04	1.1E+00	7.6E-01
8.3	2.4E+00	1.8E+00	3.6E-01	1.7E-01	1.3E-01	2.6E-02	2.0E+02	9.0E+01
10.1	6.2E+01	4.7E+01	9.3E+00	3.2E+00	2.4E+00	4.8E-01	2.6E+03	2.0E+03
10.2	6.2E+00	4.7E+00	9.3E-01	3.2E-01	2.4E-01	4.8E-02	2.6E+02	2.0E+02
10.3	6.3E+00	4.8E+00	9.6E-01	3.3E-01	2.5E-01	4.9E-02	2.7E+02	2.0E+02
10.4	4.8E-01	3.6E-01	7.3E-02	1.9E-01	1.4E-01	2.8E-02	4.8E+02	1.8E+02
10.7	7.3E+01	5.5E+01	1.1E+01	3.8E+00	2.8E+00	5.7E-01	3.1E+03	2.3E+03
10.8	7.3E+00	5.5E+00	1.1E+00	3.8E-01	2.8E-01	5.7E-02	3.1E+02	2.3E+02
10.9	7.5E+00	5.7E+00	1.1E+00	3.9E-01	2.9E-01	5.8E-02	3.2E+02	2.4E+02
10.10	5.7E-01	4.3E-01	8.6E-02	2.2E-01	1.7E-01	3.4E-02	5.7E+02	2.2E+02
12.1	2.3E-01	1.7E-01	3.5E-02	1.2E-02	9.2E-03	1.8E-03	1.3E+01	7.4E+00
12.2	2.4E-01	1.8E-01	3.6E-02	1.3E-02	9.5E-03	1.9E-03	1.3E+01	7.6E+00
12.5	4.6E-01	3.5E-01	7.0E-02	2.4E-02	1.8E-02	3.7E-03	2.5E+01	1.5E+01
12.6	4.7E-01	3.6E-01	7.2E-02	2.5E-02	1.9E-02	3.8E-03	2.6E+01	1.5E+01

[a] sediment benthic half-life (days)

2.3.3 Terrestrial Environment – Soil and Deposition from Air

EPA identified 17 studies where concentrations of HBCD in soil were extracted. Wu et al reported soil concentrations ranging from 0.3 to 249 µg/kg that represented a wide variety of land-use types (Wu et al., 2016a). The soil concentration was influenced by the sample depth as well as proximity to facilities, with higher concentrations reported near industrial areas. Tang (Tang et al., 2014a) collected 90 samples across the Ningbo Region of China, including in residential and agricultural areas. The overall range of soil concentrations reported was ND (farmland areas) to 103 µg/kg (industrial areas) with land-use highly influencing the overall magnitude of reported soil concentrations. EPA considers these concentrations suitable for informing actual concentrations of HBCD in the environment.

HBCD may also be deposited to soil through application of biosolids to agricultural lands. Health Canada used a modeling approach that resulted in an estimated soil concentration of 300 µg/kg, however, one of the limitations of Health Canada's modeling approach is that it does not consider air deposition or background soil concentration (EC/HC, 2011). This value is on the high-end of reported soil monitoring data (Table 2-58). The approach used a conservative biosolids concentration of 100,000 µg/kg (10 mg/kg) based on La Guardia (La Guardia et al., 2012). This value remains among the highest values identified by EPA.

Predicted environmental concentrations (PECs) were calculated for tilled agricultural soil and pastureland based on Equation 60 of the European Commission Technical Guidance Document (TGD) (ECB, 2003) as follows:

Equation 2-2

$$PEC_{soil} = \frac{C_{sludge} \times AR_{sludge}}{D_{soil} \times BD_{soil}}$$

where:

PEC_{soil} = PEC for soil (mg/kg)
C_{sludge} = concentration in sludge (mg/kg)
AR_{sludge} = application rate to sludge amended soils (kg/m2/yr); default = 0.5 from Table A-11 of TGD
D_{soil} = depth of soil tillage (m); default = 0.1 m from Table 11 of TGD
BD_{soil} = bulk density of soil (kg/m^3); default = 1700 kg/m^3 from Section 2.3.4 of TGD

The equation assumes no losses from transformation, degradation, volatilization, erosion or leaching to lower soil layers. Additionally, it is assumed there is no input of HBCD from atmospheric deposition and there are no background HBCD accumulations in the soil. To examine potential impacts from long-term application, an application time period of 10 consecutive years was considered. The sludge concentrations reported by La Guardia (La Guardia et al., 2010), 10 mg/kg dw, was used as C_{sludge} in the calculation. Data were converted from ng/g TOC to mg/kg dw using the organic carbon content of the sludge specified in the study.

EPA calculated the resulting soil concentration from air deposition in scenario specific release estimates using the following equations:

Equation 2-3

$$\boldsymbol{AnnDep = TotDep \times AW \times CF}$$

Where

$AnnDep$	=	Total annual deposition to soil catchment area (µg)
$TotDep$	=	Annual deposition flux to water body (g/m^2)
AW	=	Area of soil catchment area (m^2)
CF	=	Conversion of grams to micrograms

Equation 2-4

$$\boldsymbol{SoilConc = \frac{AnnDepC}{AC \times Mix \times Dens}}$$

Where

$SoilConc$	=	Annual-average concentration in catchment soil (µg/kg)
$AnnDepC$	=	Total deposition to soil catchment area (µg)
Mix	=	Mixing depth (m)
AC	=	Area of catchment, removing the area of the water body in it (m^2)
$Dens$	=	Density (1,700 kg/m^3)

EPA provides some additional context for estimated deposition rates from air modeling and empirically from transport. HBCD has potential for transport and this has been measured in many environments. The IIOAC model also estimates deposition rates and the highest deposition rates were:

- **2.28E-05 g/m^2/y** at the hypothetical facility's fenceline; and
- **4.18E-06 g/m^2/y** at "community" receptors beyond the fenceline (82 percent lower than at fenceline).

A recent study near the Great Lakes showed background deposition values of HBCD could range from non-detectable levels up to 82 ng/m^2/d, with an average of 2.3 ng/m^2/d, corresponding to wet deposition of HBCD as detected with automated wet-deposition samplers located at sites ranging from remote to peri-urban (Robson et al., 2013). Observed HBCD deposition values varied by location (perhaps due in part to meteorological conditions) and, to a lesser extent, by time, though sampling time was limited to four years at some sites. For comparison to the modeled values, EPA assumed that the observed per-day fluxes from Robson et al. (2013) were held constant for a year, resulting in:

- **2.99E-05 g/m^2/y** for maximum deposition; and
- **8.40E-07 g/m^2/y** for average deposition

Among the highest deposition scenarios modeled the community receptors are likely more appropriate for typical exposure-assessment purposes, which consider locations where the public would have regular access (the IIOAC community receptors are within 1 kilometer from the facility). The spatial averages provided by the community receptors are also more appropriate to use for deposition to ponds and their catchments since they cover a larger surface area. The highest IIOAC-modeled deposition at the community receptors near a hypothetical facility is nearly a factor of 5 above the average "background" value observed in the monitoring study of Robson et al. (Robson et al., 2013). Differences in concentrations in environmental media are proportional to differences in deposition. It is logical that the

high-end modeled values of deposition and media concentrations near a facility, averaged over a year, are substantially higher than long-term-averaged values resulting from general transport. Remaining IIOAC deposition rates are comparable with the reported by Robson et al. (2013).

The overall magnitude of the contribution of air deposition to soil concentrations is generally low, <1 µg/kg for the highest scenario with releases to air (i.e., manufacturing of SIPs and automotive replacement parts). Further, background soil concentrations based on the soil monitoring data are well below 300 µg/kg and closer to 1-10 µg/kg. Therefore, an estimated high-end soil concentration of HBCD from all sources, including biosolids application (300 µg/kg), air deposition (1 µg/kg), and background (10 µg/kg) would be slightly higher (311 µg/kg) than potential soil concentrations from any of these individual sources.

2.3.4 Assessment of Exposure in Targeted Wildlife

There are several biomonitoring studies examining the occurrence of HBCD in a wide range of wildlife biota across multiple trophic levels. Most of the wildlife biomonitoring samples report HBCD in lipid weight, but some are reported in wet weight. Some studies describe temporal, spatial (Esslinger et al., 2011b), and trophic level (Poma et al., 2014) trends of HBCD concentrations in biota. A summary of occurrence of HBCD in aquatic and terrestrial biota is presented in Sections 4.1.1 and 4.2.1 of the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d)*.

Certain studies demonstrate that wildlife are more highly exposed when they are close to point sources i.e., certain species that live near effluent discharge sites (Haukås et al., 2010b),. Due to HBCD's persistence and potential for long-range transport (UNEP 2010), exposure to wildlife is expected, at some level, to continue even as current releases to the environment decline.

2.3.5 Summary of Results for Environmental Exposure Assessment

For ground truthing of near-facility concentration, HBCD monitoring data was compared with modeled estimates of environmental concentrations based on estimated release data. Monitoring data was also considered when selecting central tendency and high-end concentrations, based on whether they had data both near and away from point (primary) sources. The overall range of data from all studies, range of central tendency, range and central tendency estimates of key studies summarized in previous sections, and sampling locations and sample size were considered. While a meta-analysis using raw data would have provided a more robust approach, raw data was generally not available for most studies.

Table 2-56. Summary of Key Studies for HBCD Environmental Concentrations

References	Environmental Media			Point Source Proximity	Systematic Review Score
	Surface Water Concentration (µg/L)	Sediment Concentration (µg/kg)	Soil Concentration (µg/kg)		
Modeled Estimates from Canada 2011 (100 meters from facility)	**Raw Materials Handling**		NA	Near	NA
	5.0E-01 – 1.5E+01	3.6E+03 – 1.8E+05			
	Compounding				
	1.0E-01 – 1.3E+00	3.3E+02 – 9.9E+03			
Modeled Estimates from Canada 2011 (5 km from facility)	**Raw Materials Handling**		NA	Far	NA
	3.0E-01 – 1.0E+01	2.6E+03 – 7.7E+04			
	Compounding				
	3.0E-02 – 9.0E-01	2.3E+02 – 7.0E+03			
E-FAST modeled estimates[a]	8.3E-05 – 1.1E+02	NA	NA	Near	NA
E-FAST modeled estimates[b]	4.2E-03 – 5.3E+03	NA	NA	Near	NA
VVWM-PSC modeled estimates[a]	**21-Day Average-Dissolved**	**28-Day Average**	NA	Near	NA
	1.1E-04 – 3.8E+00	1.2E-01 – 1.2E+04			
VVWM-PSC modeled estimates[b]	**21-Day Average Dissolved**	**28-Day Average**	NA	Near	NA
	9.8E-04 – 3.8E+00	8.9E-02 – 5.5 E+03			
Range of all Monitoring Data	9.5E-06 – 2.1E+01	2.0E-03 – 8.5E+04	2.0E-3 to 1.3E+03	Near/Far	NA
(EC, 2008) (modeled concentrations)	2.8E-02 – 3.7E+02	NA	1.7E-03 – 9.1E+01	Near	High
	NA	1.3E-02 – 1.7+05	4.5E-04 – 2.2E-03	Far	
(La Guardia et al., 2012)	NA	1.20E+04 – 3.9E+05	NA	Near	Medium
(Guerra et al., 2009)	NA	9.0E+00 – 2.4E+03	NA	Near	Medium
(Guerra et al., 2010)	NA	6.8E+00 – 1.9E+03	NA	Near	High
(Li et al., 2016b)	NA	NA	9.0E-02 – 3.4E+00	Near	High
(Tang et al., 2014a)	NA	NA	6.3E+00 -1.0E+02	Near	High
	NA	NA	1.1E-02 – 3.8E+01	Far	
(Venier et al., 2014)	2.0E-07 - 4.4E-06	NA	NA	Far	Medium

References	Environmental Media			Point Source Proximity	Systematic Review Score
	Surface Water Concentration (µg/L)	Sediment Concentration (µg/kg)	Soil Concentration (µg/kg)		
(Ichihara et al., 2014)	1.9E-04 – 1.4E-02	NA	NA	Far	High

[a] **All mean-flow estimates across scenarios**
[b] **All low-flow estimates across scenarios**

2.3.6 Predicted Environmental Concentration Used in the Environmental Exposure Assessment

Table 2-57 presents the predicted environmental concentrations that were used in the environmental exposure assessment. Note that soil concentrations were also used for the assessment of human exposure and are further discussed in Section 2.4.2.

Table 2-57. Summary of Estimated HBCD Surface Water, Sediment, and Soil Concentrations Based on Scenario Specific Environmental Releases

SCENARIO NAME	7Q10 surface water (river)- 50th µg/L		7Q10 surface water (river)- 10th µg/L		28-day HBCD sediment concentration (river) µg/kg		Soil concentration µg/kg
	1-day	21-day average	1-day	21-day average	7Q10 50th flow µg/kg	7Q10 10th flow µg/kg	
1. Processing: Repackaging of Import Containers	3.7E-02 - 9.7E+00	3.0e-02 - 9.4E-01	1.7E+00 - 7.6E+01	1.5E+00 to 8.9E+00	3.4E+01 - 2.0E+03	1.4E+03 – 1.9 E+04	Not estimated.
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	6.0E-02 - 8.3E-01	1.6E-02 - 4.0E-02	2.4E+00 - 3.1E+01	5.4E-01 to 1.8E+00	3.0E+00 – 6.3E+01	1.2E+02 - 2.9E+03	
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	8.0E-02 - 2.9E+00	3.8E-03 - 1.4E-01	3 - 110	1.8E-01 to 5.7E+00	3.6E+00 - 118	1.4 E+02 - 4. 7E+03	
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	1.1E-01 - 1.1E+00	5.4E-3 - 5.4E-02	4.28 - 42.8	2.2E-01 to 2.2E+00	3.5E+00 - 4.6E+01	1.4E+02 - 1.8E+03	
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	8.8E-01 - 1.1E+02	2.9E-01 - 5.0E+00	35.8 - 3960	1.4E+01 to 2.40E+01	3.34E+02 - 1.2E+04	1.4E+04 - 5.7E+05	
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	8.4E-03 - 1.6E+00	7.2E-03 - 7.5E+00	0.387 - 59.5	3.4E-01 to 3.5E+00	8.0E+00 - 1.8E+02	3.3 E+02 - 8.5E+03	
7. Use: Installation of Automobile Replacement Parts	No water releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	3.18E-04 - 3.4E-01		8.03E-03 - 2.4E+00		1.1E+01 - 1.6E+01	9.0E+01 - 2.0E+02	
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	1.2E-02 - 2.0E+00	3.9E-03 - 9.3E-02	4.8E-01 - 7.3E+01	1.9E-01 - 3.8E+00	4.5E+00 - 9.6E+01	1.8 E+02 - 3.1E+03	
11. Processing: Formulation of Coatings and solder	No water releases						
12. Use of Solder	8.3E-05 - 4.1E-03		6.4E-02 - 6.4E-01		No sediment estimates; expected to be low		
Generic based on Monitoring data (near facility)	1.0E-01 - 1.0E+01 µg/L					5.0E+02 - 1.0E+03 µg/g	3.1E+02
Generic based on Monitoring data (not near facility)	1.0E-04 - 1.0E-01 µg/L					3.0E+01 - 5.0E+03µg/g	1.0E-01 - 1.0E+01

2.3.7 Sensitivity Analysis – Environmental Exposure

For estimated sediment concentrations from VVWM-PSC (Section 2.3.2), the default values, such as suspended sediment concentration, fraction organic content, chlorophyll, and biomass content also influence distribution. A targeted sensitivity analysis showed that K_{OC}, half-life in sediment, fraction organic content, and suspended solids concentration are parameters that tend to have more of an impact on sediment concentrations. EPA considered variation of some of the more sensitive parameters, but found results using different inputs showed similar magnitude and trends as the results presented. This is likely because alteration of multiple parameters many have an off-setting impacts.

Table 2-58 summarizes the sensitivity analysis associated with monitoring data. Potential variability in the assumption that the central tendency estimate of the reported monitoring data represent the geometric mean appear to have a limited impact on the estimate of the high-end (95th percentile) dose. Increasing the geometric mean by 10% over the baseline value increased high-end dose by 4%, while decreasing it by 10% decreased dose by 7%.

Table 2-58. Sensitivity Analysis of Central Tendency Estimate Assumptions in Monitoring Data

	Estimated Dose in mg/kg/day		
	Baseline GM	**Baseline GM + 10%**	**Baseline GM - 10%**
95th Percentile Dose	3.12E-04	3.23E-04	2.91E-04
% Change from Baseline	--	4%	-7%

GM = geometric mean

For fish tissue concentrations (Section 2.4.2), a wide range of BCF and BAF values are available in the literature. Generally, BCF and BAF values are highly sensitive to variability in measured input values (dissolved surface water concentration, lipid weight fish tissue concentration, and fraction lipid-content). Small changes in these input values can result in large changes in associated BCF and BAF values.

As described in Section 2.2.14, EPA performed sensitivity analyses for three conditions of use at the per site process volumes of 50,000 lbs/yr and 25,000 lbs/yr to examine the effect of process volume on the resulting general population and environmental exposures. In addition, EPA chose to perform additional sensitivity analyses by incorporating a higher onsite (direct release) wastewater removal when the removal rates were unknown. For Scenario 1 (Repackaging of Import Containers), based on information provided in Section 2.2.2, EPA applied 90% removal for releases to water. As mentioned in Section 2.3.2, when information regarding pretreatment for direct releases to surface was uncertain, EPA applied a removal rate of 0%. In the sensitivity analysis presented here, a tiered approach was used to assess these releases using both 0% removal and a higher removal rate.

Little information was found on the type or efficiency of onsite treatment used by direct discharging facilities using HBCD. Due to its low water solubility (66 µg/L), high log Kow (5.6) and physical state (solid), HBCD is likely to partition to the organic phase, including organic particulates in wastewater. It is expected to behave as a particulate in aqueous wastewater and be removed with other solids by gravity settling during the wastewater clarification process. The efficiency of removal of HBCD may be reflected in data for total suspended solids (TSS) removal. The EPA Development Document for Effluent Limitations, Guidelines and Standards for Organic Chemicals, Plastics and Synthetic Fibers Point Source Category (U.S. EPA, 1987) reports TSS removal for a commonly used onsite wastewater

treatment, activated sludge treatment. Reported mean (67%), median (81%), minimum (-29%) and maximum (99%) values for TSS removal were reported for thirty nine observations. EPA considered these reported values and uncertainty in extrapolating from performance of the treatment systems surveyed in the Effluent Guidelines document to those facilities using HBCD. EPA also considered uncertainty associated with the use of TSS removal as a surrogate for HBCD removal. EPA selected 75% removal of HBCD in onsite wastewater treatment for direct dischargers. EPA is confident that some removal of HBCD will occur in onsite wastewater treatment. Higher or lower removal of HBCD could occur based on the type of treatment employed and its performance optimization.

EPA acknowledges the downward trend of environmental releases as the production volume of HBCD has decreased over time. To account for this, EPA considered three separate estimates of releases for conditions of use based on three different production volumes: 100,000, 50,000, and 25,000 kilograms per year. EPA estimated surface water and sediment concentrations through the Point Source Calculator for all combinations. EPA inferred that the days of release correlated with kg/site/day releases. For example as total releases decrease, the number of days of release also decrease. For this reason, any 1-day surface water concentrations are approximately equal. Both the overall magnitude of the release and the number of days of release influence estimated concentrations. When the overall magnitude of the release is reduced by a factor of two or four, the corresponding environmental concentration is also reduced by approximately a factor of two or four. When the number of days are reduced by factor of two or four, the corresponding environmental concentration is reduced, however, the trend is not linear and depends on the number of days of release. This is due to uncertainty in the timing of the release days and the selected averaging periods (21-days for surface water and 28 days for sediment). 21-day average water concentrations and 28-day average sediment concentrations are more sensitive to changes in release estimates. EPA inferred that the release days occur intermittently rather than continuously through the year. The timing of these releases, in addition to the number of release days, influence potential exposure concentrations. EPA also varied other parameters in its surface water modeling that have a large impact of estimated results. The selected flow values for mean-flow or low flow are highly sensitive. EPA used a central-tendency and a high-end estimate for each of these flow metrics. estimated sediment concentrations are highly sensitive to the sediment half-life used; hence, EPA used central-tendency and high-end estimates for sediment half-life in calculating sediment concentrations. Because the percent removal of HBCD from different removal processes is likely variable, EPA also varied percent removal expected based on three scenarios: on-site treatment (pre-treatment) [0%], on-site wastewater treatment [75%], and off-site wastewater treatment plants [90%]. Some release estimates already account for treatment while others do not. The efficiency of treatment across different industrial facilities and different wastewater treatment plants will also vary.

Table 2-59. Summary of HBCD Surface Water Concentrations from Sensitivity Analysis: Varying Production Volume and Waste Water Treatment Removal– Environmental Exposures

SCENARIO NAME	Production Volume (lbs / year)	% WWTP Removal for Direct Releases[a]	Surface Water 1-Day Average Concentration Range (ug/L)		Sediment	
			Acute: 50th %-ile	Chronic: 50th %-ile	11-d half-life: 50th %-ile	128-d half-life: 50th %-ile
Scenario 1. Import and Re-packaging/ Processing: Repackaging of Import Containers	100,000	90%	3.7E-02 - 9.7E+00	3.0E-02 - 9.4E-01	3.4E+01 - 8.7E+02	7.7E+01 - 2.0E+03
	50,000	90%	3.7E-02 - 9.4E+00	1.8E-02 - 5.0E-01	1.9E+01 - 5.4E+02	4.1E+01 - 1.2E+03
	25,000	90%	3.7E-02 - 1.0E+01	8.8E-03 - 4.8E-01	8.5E+00 - 3.2E+02	1.9E+01 - 6.3E+02
Scenario 3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	100,000	0%	8.0E-03 - 2.9E+00	3.8E-04 - 1.4E-01	4.0E-01- 8.9E+01	8.9E-01 - 1.2E+02
		75%	8.0E-03 - 1.5E+00	3.8E-04 - 7.1E-02	4.0E-01 - 4.5E+01	8.9E-01 - 6.0E+01
	50,000	0 %	4.0E-03 - 1.5E+00	1.9E-04 - 7.1E-02	2.0E-01 - 4.5E+01	4.4E-01 - 6.0E+01
		75 %	4.0E-03 - 7.4E-01	1.9E-04 - 3.6E-02	2.0E-01 - 2.3E+01	4.4E-01 - 3.0E+01
	25,000	0 %	2.0E-03 - 7.4E-01	3.8E-04 - 1.4E-01	1.0E-01 - 2.3E+01	2.2E-01 - 3.0E+01
		75%	9.5E-05 - 3.5E-02	3.8E-04 - 7.1E-02	1.0E-01 - 1.1E+01	2.2E-01 - 1.5E+01
Scenario 5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	100,000	0 %	8.8E-01- 1.1E+02	2.9E-01 - 5.0E+00	3.3E+02- 5.5E+03	7.6E+02 - 1.2E+04
		75%	8.8E-01 - 5.3E+01	2.9E-01 - 2.6E+00	3.3E+02 - 2.8E+03	7.6E+02 - 6.2E+03
	50,000	0 %	4.4E-01 - 1.1E+02	1.5E-01 - 5.0E+00	1.7E+02 - 3.5E+03	3.8E+02 - 6.9E+03
		75 %	4.4E-01 - 5.3E+01	1.5E-01 - 2.5E+00	1.7E+02 - 1.7E+03	3.8E+02 - 3.4E+03
	25,000	0 %	2.2E-01 - 1.1E+02	7.4E-02 - 5.0E+00	8.4E+01 - 3.2E+03	1.9E+02 - 4.9E+03
		75 %	2.2E-01 - 5.3E+01	7.4E-02 - 2.5E+00	8.4E+01 - 1.6E+03	1.9E+02 - 2.5E+03

[a] Note, there are no predicted direct releases for Scenario 1.

2.3.8 Assumptions and Key Sources of Uncertainty in Environmental Exposure Assessment

Concentrations of HBCD in environmental and biological media are expected to vary. Close proximity to facilities and other sources is likely to lead to elevated concentrations compared to locations which are more remote. A combination of monitoring data from the U.S. and international sources were used in this exposure assessment. In addition, monitoring data were collected in previous years when production volume and associated releases of HBCD into the environment are expected to have been higher than they are currently and expected to be in the future. When considering older monitoring data and monitoring data from international sources, there are uncertainties associated with using these data because it is unknown whether those sampling sites are representative of current sites within the U.S.

In modeling environmental concentrations of HBCD, EPA acknowledges the conservative nature of the E-FAST model and the additional refinement provided by the PSC model. Water dilution models can be used to determine the concentration of a chemical in the surface water after a source emits the chemical into a water body. Since the E-FAST model default values encompass either a combination of upper percentile and mean exposure parametric values, or all upper percentile parametric values, the resulting model predictions represent high-end exposures estimates. A simple dilution model, such as EFAST, provides exposure estimates that are derived from a simple mass balance approach, and does not account for partitioning between compartments within a surface water body or degradation over time in different media, parameters which are relevant to HBCD. For these reasons, EPA utilized a two tier approach by complementing the EFAST modeling with more refined estimates from the PSC model to further describe environmental exposures.

When modeling using E-FAST, EPA assumed that primary treatment removal at POTWs occurred with 90% removal efficiency, however for direct discharges, EPA used 0% removal. EPA recognizes that this is a conservative assumption that results in no removal of HBCD prior to release to surface water. This assumption will give higher surface water and sediment concentrations compared to a removal efficiency of 75 or 90% removal. This assumption reflects both the uncertainty of the type of wastewater treatment that may be in use at a direct discharging facility and the HBCD removal efficiency in that treatment. It is likely that under the COUs for HBCD, a facility's wastewater discharge is required to meet National Pollutant Discharge Elimination System (NPDES) discharge permit limits for total suspended solids, five-day biochemical oxygen demand (BOD_5) and other wastewater treatment parameters. Treatment methods used to meet the limits (such as activated sludge treatment) will likely also remove HBCD from wastewater to an uncertain, but non-zero, extent due to the properties of HBCD.

EPA used a combination of chemical-specific parameters and generic default parameters when estimating surface water, sediment, soil, and fish-tissue concentrations. EPA used both central tendency and high-end values across model inputs to characterize the variability within and across scenarios. EPA also used central tendency and high-end model outputs. Comparison of model outputs with monitored values offers one way to ground-truth the combination of model inputs and outputs used. EPA compared monitoring and modeled surface water, sediment, soil, and fish-tissue concentration estimates. Estimates of fish-tissue concentrations are further discussed in Section 2.4.2. In summary, EPA compared monitored and modeled fish tissue concentrations using modeled 21-day average dissolved water concentrations and low-end BAF values and found overlap and concordance between these values and fish-tissue monitoring data. When modeling the HBCD concentrations in water and sediment, EPA did not consider the potential impact of persistence and longer-term sinks in lake and estuary environments.

Recent and future estimated levels of HBCD in the area may be lower than past levels due to reported reductions in releases over time. EPA assessed more recent releases. The predicted concentrations may be lower than concentrations that consider more years of releases or releases associated with higher production volumes.

2.4 Human Exposures

2.4.1 Occupational Exposures

EPA assessed workplace exposures pertaining to the following HBCD conditions of use:

1. Processing: Repackaging of Import Containers
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch
4. Processing: Manufacturing of XPS Foam using HBCD Powder
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam
7. Use: Installation of Automobile Replacement Parts
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures
9. Demolition and Disposal of EPS/XPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures
10. Processing: Recycling of EPS Foam
11. Processing: Formulation of Flux/Solder Pastes
12. Use of Flux/Solder Pastes

Appendix F includes a crosswalk between the subcategories of use listed in the *Problem Formulation Document for Cyclic Aliphatic Bromide Cluster (HBCD)* and the conditions of use assessed in this risk evaluation.

Components of the Occupational Exposure Assessment

The occupational exposure of each condition of use comprises the following components:

1. **Number of Workers and Occupational Non-Users:** An estimate of the number of workers and occupational non-users(-workers, who do not directly handle the chemical but perform work in an area where the chemical is present) potentially exposed to the chemical for the given condition of use.
2. **Inhalation Exposure:** Central tendency and high-end estimates of inhalation exposure to workers and occupational non-users. Note EPA assumes that all inhaled particulates are absorbed by either the lung or intestine after ingestion as further discussed in Section 4.2.1.
3. **Dermal Exposure:** Estimates of dermal exposure to workers.

The process descriptions and facility estimates are included in Section 2.3 for each condition of use.

2.4.1.1 Occupational Exposures Approach and Methodology

Number of Workers and ONUs

Where available, EPA prefers to use CDR data to provide a basis to estimate the number of workers and occupational non-users (ONUs). However, all companies that have historically reported HBCD manufacturing and importation to CDR have ceased such operations. In lieu of current CDR data, EPA

used U.S. economic data to estimate the number of workers and ONUs using the following method:

1. Identify the North American Industry Classification System (NAICS) codes for the industry sectors associated with each condition of use.
2. Estimate total employment by industry/occupation combination using the Bureau of Labor Statistics' Occupational Employment Statistics (OES) data (U.S. BLS, 2016).
3. Refine the OES estimates where they are not sufficiently granular by using the U.S. Census' (2015) Statistics of U.S. Businesses (SUSB) data on total employment by 6-digit NAICS.
4. Estimate the number of potentially exposed employees per site.
5. Estimate the number of potentially exposed employees within the condition of use, using the number of sites estimated as described in Section 2.2.1.

EPA discussed the estimation of HBCD throughput and number of sites in Section 2.2.1.

EPA's General Approach to the Assessment of Inhalation Exposure

EPA will provide occupational exposure results representative of central tendency conditions and high-end conditions. A central tendency is assumed to be representative of occupational exposures in the center of the distribution for a given condition of use. For risk evaluation, EPA may use the 50th percentile (median), mean (arithmetic or geometric), mode, or midpoint values of a distribution as representative of the central tendency scenario. EPA's preference is to provide the 50th percentile of the distribution. However, if the full distribution is not known, EPA may assume that the mean, mode, or midpoint of the distribution represents the central tendency depending on the statistics reported in the data source for the distribution.

A high-end is assumed to be representative of occupational exposures that occur at probabilities above the 90th percentile but below the exposure of the individual with the highest exposure (U.S. EPA, 1992). For risk evaluation, EPA plans to provide high-end results at the 95th percentile. If the 95th percentile is not available, EPA may use a different percentile greater than or equal to the 90th percentile but less than or equal to the 99.9th percentile, depending on the statistics available for the distribution. If the full distribution is not known and the preferred statistics are not available, EPA may estimate a maximum or bounding estimate in lieu of the high-end.

Exposures are calculated from datasets, comprised of data from one or more sources, depending on the size of the dataset. For datasets with six or more data points, central tendency and high-end exposures were estimated using the 50th percentile and 95th percentile. For datasets with three to five data points, central tendency exposure was calculated using the 50th percentile and the maximum was presented as the high-end exposure estimate. For datasets with two data points, the midpoint was presented as a midpoint value and the higher of the two values was presented as a higher value. Finally, data sets with only one data point presented the value as a what-if exposure. EPA did not have discrete data points for the discussed monitoring data in this section. Only statistical summaries of the data sets were available and EPA did not combine or perform calculations with these reported statistics.

EPA follows the following hierarchy in selecting data and approaches for assessing inhalation exposures:

1. Monitoring data:
    a. Personal and directly applicable
    b. Area and directly applicable
    c. Personal and potentially applicable or similar
    d. Area and potentially applicable or similar

2. Modeling approaches:
    a. Surrogate monitoring data
    b. Fundamental modeling approaches
    c. Statistical regression modeling approaches
3. Occupational exposure limits:
    a. Company-specific occupational exposure limits (OELs) (for site-specific exposure assessments, e.g., there is only one processing site who provides to EPA their internal OEL but does not provide monitoring data)
    b. OSHA permissible exposure limit (PEL)
    c. Voluntary limits (American Conference of Governmental Industrial Hygienists [ACGIH] threshold limit value [TLV], NIOSH recommended exposure limit [REL], Occupational Alliance for Risk Science [OARS] workplace environmental exposure level (WEEL) [formerly by AIHA])

For occupational exposures, EPA used measured air concentrations, estimated air concentrations, or occupational exposure limits to calculate exposure concentration metrics required for risk evaluation. Specifically, EPA used these exposure concentration values to calculate acute exposure dose (AED) and average daily dose (ADD). Additional explanation of the equations used to calculate AED and ADD, and example calculations are located in Appendix E.4 and Appendix E.5, respectively. EPA then multiplied the AED and ADD by the inhalation absorption factor of 100% (discussed in Section 3.2.2) to estimate the acute absorbed dose (AAD) and chronic absorbed dose (CAD), respectively. The AED and AAD are used to assess acute exposure risks. The ADD and CAD are used to assess chronic, non-cancer risks. These calculations require additional parameter inputs, such as years of exposure, exposure duration and frequency, and lifetime years.

For the final exposure result metrics, each of the input parameters (e.g., air concentrations, working years, exposure frequency, lifetime years) may be a point estimate (i.e., a single descriptor or statistic, such as central tendency or high-end) or a full distribution. EPA will consider three general approaches for estimating the final exposure result metrics:

Deterministic calculations: EPA will use combinations of point estimates of each parameter to estimate a central tendency and high-end for each final exposure metric result. EPA will document the method and rationale for selecting parametric combinations to be representative of central tendency and high-end.

Probabilistic (stochastic) calculations: EPA will pursue Monte Carlo simulations using the full distribution of each parameter to calculate a full distribution of the final exposure metric results and selecting the 50th and 95th percentiles of this resulting distribution as the central tendency and high-end, respectively.

Combination of deterministic and probabilistic calculations: EPA may have full distributions for some parameters but point estimates of the remaining parameters. For example, EPA may pursue Monte Carlo modeling to estimate exposure concentrations, but only have point estimates of working years of exposure, exposure duration and frequency, and lifetime years. In this case, EPA will document the approach and rationale for combining point estimates with distribution results for estimating central tendency and high-end results.

EPA's determination of each of the input parameters for calculation of AED and ADD are explained in Appendix E.4.

EPA assessed exposure to male and female workers including female workers of reproductive age of > 16 years to less than 50 years old. Adolescents greater than 16 to less than 21 years old are a small part of the total workforce in the workplace.

EPA's Approach to the Assessment of HBCD Inhalation Exposure

EPA reviewed monitoring data found in published literature (i.e., personal exposure monitoring data and area monitoring data). EPA gathered and evaluated occupational exposure information according to the process described in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a). The key data source resulting from this process that was used to assess occupational exposure is the European Union Risk Assessment Report (EURAR), which has an overall confidence rating of high.

The worker monitoring data that EPA reviewed include HBCD occupational inhalation exposure monitoring data from industrial sites in Europe. These sites processed HBCD to produce XPS masterbatch or XPS foam. EPA used these monitoring data to assess occupational inhalation exposures for the following conditions of use: the compounding of polystyrene resin to produce XPS masterbatch, the manufacturing of XPS foam using XPS masterbatch, and the manufacturing of XPS foam using HBCD powder. EPA also used these monitoring data as surrogate data to assess occupational inhalation exposures for the following conditions of use: repackaging of import containers, manufacturing of EPS foam from EPS resin beads, manufacturing of SIPs and automobile replacement parts, installation of XPS/EPS foam, recycling of EPS foam and reuse of XPS foam, and formulation of flux/solder. EPA selected surrogate monitoring data based on similarity in processes and worker activities. The approaches to the assessment of inhalation exposure for the conditions of use are summarized in Table 2-60.

Table 2-60. Summary of Inhalation Exposure Assessment Approaches

Relevant Report Section	Condition of Use	Approach to the Assessment of HBCD Potential Inhalation Exposure Concentrations
Section 2.4.1.2	Processing: Repackaging of Import Containers	EPA used HBCD inhalation exposure monitoring data pertaining to the manufacture of HBCD at sites in Europe.
Section 2.4.1.3	Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	EPA found monitoring data for this condition of use, however the quality of this data is not adequate for this assessment because the grade of HBCD associated with this data is unknown and the type of sampling is either area sampling or is unknown. Therefore, EPA assessed exposures using data and estimates reported in the EURAR (ECHA, 2008b). The values reported in the EURAR were used by the EU for all polymer processing operations involving standard grade HBCD.
Section 2.4.1.5	Processing: Manufacturing of XPS Foam using HBCD Powder	
Section 2.4.1.4	Processing: Manufacturing of XPS Foam using XPS Masterbatch	EPA found and used monitoring data that are specific to this condition of use.
Section 2.4.1.6	Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	EPA assessed exposure concentrations based on monitoring data pertaining to a similar scenario. Specifically, EPA used HBCD inhalation exposure monitoring data pertaining to the secondary processing of XPS boards at sites in Europe.
Section 2.4.1.7	Processing: Manufacturing of SIPs and Automobile	

Relevant Report Section	Condition of Use	Approach to the Assessment of HBCD Potential Inhalation Exposure Concentrations
	Replacement Parts from XPS/EPS Foam	
Section 2.4.1.9	Use: Installation of XPS/EPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	
Section 2.4.1.10	Demolition and Disposal of XPS/EPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures	EPA assessed exposure concentrations using the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for particulates not otherwise regulated (PNOR), adjusted by the HBCD concentration in the particulates (i.e., in the EPS and XPS foam).
Section 2.4.1.11	Processing: Recycling of EPS Foam and Reuse of XPS foam	EPA assessed exposure concentrations based on monitoring data pertaining to a similar scenario. Specifically, EPA used HBCD potential inhalation exposure monitoring data pertaining to the secondary processing of XPS boards at sites in Europe.
Section 2.4.1.12	Processing: Formulation of Flux/Solder	EPA assessed exposure concentrations based on monitoring data pertaining to a similar scenario. Specifically, EPA used the estimated values reported in the EURAR that pertain to all polymer processing operations involving standard grade HBCD, due to similarity in HBCD unloading processes.
Section 2.4.1.8	Use: Installation of Automobile Replacement Parts	EPA does not expect these conditions of use to result in the generation of dust, hence EPA does not estimate inhalation exposures.
Section 2.4.1.13	Use of Flux/Solder Pastes	

Specific details related to the use of monitoring data for each condition of use are described below. Monitoring data were selected based on overall confidence score and relevance to the occupational exposure scenario. For each condition of use, monitoring data were used to calculate chronic exposures. Equations and sample calculations for chronic exposures can be found in Appendix E.4 and Appendix E.5, respectively. Exposure monitoring data were available for fine grade HBCD, standard grade HBCD, and HBCD granules (refer to Section 2.2.2 for additional information on these physical forms). EPA only assessed the handling of standard grade and granular HBCD, as these are the physical forms expected to be used for the assessed conditions of use (NICNAS, 2012b; ECHA, 2008b).

EPA did not distinguish between respirable and inhalable particulates in this assessment. Respirable particles are estimated to be those that are less than 10 µm. Respirable particulates are able to travel into the deep lung. EPA assumes that any particles inhaled in the respirable range deposit into the deep lung, where they are absorbed. Inhalable particulates are those that are less than 100 µm. Inhalable particles that are not in the respirable range do not travel into the deep lung, but deposit in the upper respiratory tract, where they can be swallowed. EPA assumes that all inhaled particles that are not respirable are deposited in the upper respiratory tract. The European Union Risk Assessment Report (EURAR) assumes that 100% of particulates deposited in the upper respiratory tract are swallowed (ECHA, 2008b). EPA makes this same assumption. Thus, EPA assumes that all inhaled particulates are either absorbed in the lung or in the intestine after ingestion as further discussed in Section 4.2.1. Because of

this assumption, EPA does not distinguish between respirable and inhalable particles in the subsequent inhalation exposure sections of this report.

EPA expects potential inhalation exposure to occupational non-users (ONUs), but EPA did not quantify these exposures due to lack of data. ONUs are workers that do not directly work with HBCD but work in or near areas where HBCD is handled or processed, such as supervisors. EPA expects that dust that is generated during worker activities may be transported via indoor air or ambient air currents to locations in which ONUs are present. EPA expects these potential exposures to be lower than the potential exposures of the workers whose activities generated the dust because the dust dilutes as it transports through indoor or ambient air. The lower HBCD air concentration to which ONUs are potentially exposed would result in lower risk for ONUs as compared to workers, with regards to inhalation exposure.

General Dermal Exposures Approach and Methodology

EPA estimated worker dermal exposures using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model* for the repackaging of import containers, compounding of polystyrene to produce XPS masterbatch, manufacturing of XPS foam using XPS masterbatch, manufacturing of XPS foam using HBCD powder, and formulation of flux/solder pastes (Sections 2.4.1.2 through 2.4.1.5 and2.4.1.12). This model determines a dermal potential dose rate based on an assumed quantity of solids on skin during one contact event per day. Specifically, the model estimates that there are 3,100 mg of chemical on workers' skin per contact event with the solid chemical (U.S. EPA, 2013a). EPA estimated worker dermal exposures for the use of solder/flux pastes (Section 2.2.13) using the *EPA/OPPT Direct 2-Hand Dermal Contact with Container Surfaces (Solids) Model*. Similarly, this model determines a dermal potential dose rate based on an assumed quantity of solids on skin during one contact event per day, using a smaller quantity of 1,110 mg of chemical on workers' skin per contact event with the solid chemical (U.S. EPA, 2013a). These models are routinely used by RAD for engineering assessments (U.S. EPA, 2013a). EPA does not expect dermal exposure for the remaining conditions of use because HBCD is entrained in the EPS and XPS foam (those in Section 2.4.1.6 through 2.4.1.11).

Both models assume a single contact event per day and that the amount of solid on the skin is not expected to be significantly reduced by wiping from the skin or increased from repeated contact with the chemical (i.e., wiping excess solids from the skin does not remove a significant fraction of the small layer of chemical adhering to the skin and additional contacts with the chemical do not add a significant fraction to the layer). EPA calculated the potential dose for a worker with no dermal protection by multiplying the quantity of solids on the skin by the weight fraction of HBCD in the solids and the frequency of exposure events.

In this risk evaluation, EPA provides comparison of the potential worker dermal dose rates calculated by EPA and those estimated in the EURAR (ECHA, 2008b) and Australian Risk Assessment (NICNAS, 2012b). The EURAR and NICNAS both estimate potential dermal exposures using the Estimation and Assessment of Substance Exposure (EASE) model. The EASE model was developed by the UK Health and Safety Executive with the Health and Safety Laboratory. It predicts expected dermal exposures for a wide range of substances and scenarios using situational information related to the chemical (Tickner et al., 2005).

For occupational exposures, EPA used the potential dermal dose rate estimated as described above to calculate exposure concentration metrics required for risk assessment. Specifically, EPA used the potential dermal dose rates and dermal absorption factor of 6.5% (discussed later in Section 3.2.2) to

estimate the AAD and CAD, the AAD calculation entails the multiplication of the dermal potential dose rate by the dermal absorption factor, which is then divided by body weight. The CAD calculation is the same, with the additional multiplication of exposure frequency and working years, followed by division of the averaging time. The values used for body weight, exposure frequency, working years, and averaging time are explained in Appendix E.4. The AAD is used to assess acute exposure risks. The CAD is used to assess chronic risks.

Occupational non-users are workers that do not directly work with HBCD and thus would not perform activities that would require dermal contact with HBCD. However, it is possible that ONUs may be unintentionally exposed through dermal contact with surfaces where HBCD dust has settled. EPA did not quantify these exposures due to lack of data. EPA expects that dermal exposures may be much less likely for this population.

Consideration of Engineering Controls and Personal Protective Equipment

OSHA and NIOSH recommend employers utilize the hierarchy of controls to address hazardous exposures in the workplace. The hierarchy of controls strategy outlines, in descending order of priority, the use of elimination, substitution, engineering controls, administrative controls, and lastly personal protective equipment (PPE). The hierarchy of controls prioritizes the most effective measures first which is to eliminate or substitute the harmful chemical (e.g., use a different process, substitute with a less hazardous material), thereby preventing or reducing exposure potential. Following elimination and substitution, the hierarchy recommends engineering controls to isolate employees from the hazard, followed by administrative controls, or changes in work practices to reduce exposure potential(e.g., source enclosure, local exhaust ventilation systems). Administrative controls are policies and procedures instituted and overseen by the employer to protect worker exposures. As the last means of control, the use of personal protective equipment(e.g., respirators, gloves) is recommended, when the other control measures cannot reduce workplace exposure to an acceptable level.

Respiratory Protection

OSHA's Respiratory Protection Standard (29 CFR § 1910.134) requires employers in certain industries to address workplace hazards by implementing engineering control measures and, if these are not feasible, provide respirators that are applicable and suitable for the purpose intended. Respirator selection provisions are provided in § 1910.134(d) and require that appropriate respirators are selected based on the respiratory hazard(s) to which the worker will be exposed and workplace and user factors that affect respirator performance and reliability. Assigned protection factors (APFs) are provided in Table 1 under § 1910.134(d)(3)(i)(A) (see below in Table 2-61.) and refer to the level of respiratory protection that a respirator or class of respirators is expected to provide to employees when the employer implements a continuing, effective respiratory protection program.

There are no OSHA or NIOSH exposure limits for the HBCD cluster: (CAS #s: 25637-99-4; 3194-55-6; 3194-57-8), however, HBCD is handled in a powdered form with mean particle size ranges from 20 to 150 µm. There is the potential for generation of airborne HBCD dust during different worker activities. Employers should first consider elimination, substitution, engineering, and administrative controls to reduce exposure potential and, if exposures still present workplace, employers are required to institute a respiratory protection program and provide employees with NIOSH-certified respirators. Where other hazardous agents could exist in addition to HBCD, consideration of combination cartridges would be necessary. Table 2-61 can be used as a guide to show the protectiveness of each category of respirator; EPA took this information into consideration as discussed in Section 4.2.2. Based on the APF, inhalation

exposures may be reduced by a factor of 5 to 10,000, assuming workers and occupational non-users are complying with their employer's respiratory protection program.

Table 2-61. Assigned Protection Factors for Respirators in OSHA Standard 29 CFR § 1910.134

Type of Respirator	Quarter Mask	Half Mask	Full Facepiece	Helmet/ Hood	Loose-fitting Facepiece
1. Air-Purifying Respirator	5	10	50	-	-
2. Power Air-Purifying Respirator (PAPR)	-	50	1,000	25/1,000	25
3. Supplied-Air Respirator (SAR) or Airline Respirator					
• Demand mode	-	10	50	-	-
• Continuous flow mode	-	50	1,000	25/1,000	25
• Pressure-demand or other positive-pressure mode	-	50	1,000	-	-
4. Self-Contained Breathing Apparatus (SCBA)					
• Demand mode	-	10	50	50	-
• Pressure-demand or other positive-pressure mode (e.g., open/closed circuit)	-	-	10,000	10,000	-
Source: 1910.134(d)(3)(i)(A)					

Dermal Protection

The Hand Protection section of OSHA's Personal Protective Equipment Standard (29 CFR § 1910.138(b)) requires employers to select and require workers to wear gloves to prevent exposure to harmful substances. As with respirators, gloves are used to prevent employee exposures to hazards. Employers base selection of gloves on the type of hazard encountered, conditions during use, tasks performed and factors that affect performance and wear ability. Gloves, if proven impervious to the hazardous chemical, and if worn on clean hands and replaced when contaminated or compromised, are expected to provide employees with protection from hazardous substances. HBCD is a solid particulate and would not be expected to permeate through gloves. Some examples of impervious gloves are nitrile, butyl rubber, polyvinyl chloride, and polychloroprene.

EPA reviewed safety data sheets (SDSs) for HBCD powder, EPS resin beads containing HBCD, and XPS and EPS foam containing HBCD. EPA did not find any SDSs for XPS masterbatch containing HBCD.

The conditions of use in this risk evaluation in which workers may handle HBCD powder include Processing: Repackaging of Import Containers, Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch, Processing: Manufacturing of XPS Foam using HBCD Powder, and Processing: Formulation of Flux/Solder Pastes. For HBCD powder, an SDS from Great Lakes Chemical Corporation (Great Lakes Chemical, 2003) recommended the use of neoprene gloves and an SDS from Santa Cruz Biotechnology Company, Inc. (Santa Cruz Biotechnology, 2009) recommended the use of gloves made of polychloroprene, nitrile rubber, butyl rubber, Viton, or polyvinyl chloride.

The conditions of use in this risk evaluation in which workers may handle XPS or EPS foam containing HBCD include: Processing: Manufacturing of XPS Foam using XPS Masterbatch, Processing: Manufacturing of XPS Foam using HBCD Powder, Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads, Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam, Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures, Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures, and Recycling of EPS Foam. EPA reviewed seven SDSs for XPS and EPS foam products containing HBCD. All of the reviewed SDSs recommend suitable or appropriate gloves and, in some cases, gloves to protect from mechanical injury. The SDSs do not recommend specific glove materials (Dow Chemical Pacific, 2018; DiversiFoam, 2015; Insulfoam a Division of Carlisle Construction, 2015; Multi-Panels, 2015; O. D. E. , 2013; Airlite Plastics Co dba Fox, 2008; A. C. H. Foam Technologies, 2007).

During Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads, workers may handle EPS resin beads containing HBCD. An SDS from BASF recommends the use of non-static gloves, such as leather gloves, when handling EPS resin beads containing HBCD (Corporation, 2015). Note that, as indicated in Section 1.2.2, BASF has ceased the use of HBCD. EPA did not find additional glove material recommendations.

During Use of Flux/Solder Pastes, workers may handle flux/ solder paste formulations containing HBCD. SDSs from Henkel and Kester recommend the use of nitrile rubber gloves (Henkel, 2016; Kester, 2015). The SDS from Kester also recommends the use of natural rubber gloves.

2.4.1.2 Processing: Repackaging of Import Containers

During repackaging there is potential for worker inhalation exposure to HBCD dust during the unloading of HBCD powder or granules from original import containers and transferring into an intermediate storage vessel or directly into new containers. Because of the larger particle size of the granules, inhalation exposure to dust during unloading of granules is expected to be lower than that from unloading powders (NICNAS, 2012b; ECHA, 2008b). Generated dust may become airborne, resulting in potential inhalation and dermal exposure for nearby workers that do not directly work with the HBCD, also referred to as occupational non-users (ONUs).

Worker inhalation and dermal exposure during the unloading of imported EPS resin beads is not expected due to the larger size of the beads and because HBCD is entrained within the polymeric matrix of the EPS resin beads (NICNAS, 2012b; ECHA, 2008b).

Number of Potentially Exposed Workers and Occupational Non-Users

As discussed in Section 2.2.1, EPA developed release and exposure estimates for repackaging of import containers at a single site. Of the five submitters to 2016 CDR, four submitters estimate that fewer than 10 workers are potentially exposed to HBCD, while the fifth submitter estimated that at least 10 but fewer than 25 workers are potentially exposed to HBCD. However, the companies that previously reported HBCD import volumes to 2016 CDR have stated to EPA that they permanently stopped the activity in 2016 or 2017. Thus, in lieu of using this CDR data from companies that discontinued use of HBCD, EPA estimated the number of workers potentially exposed using Bureau of Labor Statistics (BLS) data.

Based on BLS data for NAICS code 493100, Warehousing and Storage, and related Standard Occupational Classification (SOC) codes, there are on average an estimated three workers and one ONU per site at warehousing and storage facilities. Based on these BLS data and one site for the repackaging of import containers, EPA estimated that a total of three workers and one ONU are potentially exposed during this condition of use.

Inhalation Exposure Assessment

EPA did not find inhalation monitoring data for the repackaging of HBCD in the reviewed literature. EPA reviewed inhalation monitoring data for the manufacturing of HBCD for applicability to this condition of use. HBCD occupational inhalation exposure monitoring data sampled during the manufacture of HBCD at multiple sites in Europe are shown in Table 2-62 (also listed in Appendix E, Table_Apx E-2.) below.

Table 2-62. Inhalation Monitoring Data for Manufacturing of HBCD

Data Source/Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Inhalation Monitoring Data Used to Estimate Worker Exposures									
Searl and Robertson (2005) – 1a	Manufacturing of HBCD	Standard grade HBCD	Personal Breathing Zone	Packaging, compaction, process operations, and working in the warehouse	Mean: 1.23 Median: 0.89 90th percentile: 1.89 Max: 3 mg/m^3	10	8-hr TWA	(ECHA, 2008b) (ECHA, 2009b)	High
Other Inhalation Monitoring Data for the Manufacturing of HBCD									
Searl and Robertson (2005) - 1b	Manufacturing of HBCD	Fine grade HBCD	Personal Breathing Zone	Packaging, compaction, process operations, and working in the warehouse	Mean: 23 90th percentile: 35	4	8-hr TWA	(ECHA, 2008b)	High
Searl and Robertson (2005) – 1c	Manufacturing of HBCD	HBCD of unknown grade	NR	Packaging and compaction of powders	Respirable, mean: 0.18 Inhalable, Mean: 1.23	NR	NR	(ECHA, 2009c)	High
Waindzioch (2000) - 1a	Manufacturing of HBCD	HBCD of unknown grade	Area	Reactor	0.00028 - 0.0285	3	Short-term	(ECHA, 2008b)	Unacceptable
Waindzioch (2000) – 1b	Manufacturing of HBCD	HBCD of unknown grade	Area	Filling Station	0.0094 - 0.097	2	Short-term	(ECHA, 2008b)	High
Biesemeier (1996)	Manufacturing of HBCD	HBCD of unknown grade	NR	Bagging HBCD product	4.0 - 4.5	NR	NR	(ECHA, 2008b)	High
Velsicol (1978)	Manufacturing of HBCD	HBCD of unknown grade	Personal Breathing Zone	Transfer of the HBCD in the hammer-mill to 28 drums	1.9	1	300 minutes	(Velsicol Chem Corp, 1978)	High

Data Source/Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Yi et al. (2016)	Manufacturing of HBCD	HBCD of unknown grade	Personal Breathing Zone	NR	0.0102 - 0.0283	14	NR	(Yi et al., 2016)	High

NR = Not Reported; N/A = Not Applicable
a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.
b - Statistics were calculated by the cited source and are presented here as they were presented in the source.
c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.

EPA did not use the Waindzioch (2000) (noted as 1a in Table 2-62. Inhalation Monitoring Data for Manufacturing of HBCD) data for samples taken near an HBCD reactor because the overall confidence rating is unacceptable.

The remaining data in Table 2-62 have an overall confidence rating of high. EPA selected the data from Searl and Robertson (2005) (1)a to estimate worker inhalation exposures to HBCD during repackaging of HBCD for the following reasons:

- These monitoring data are 8-hr TWA measurements.
- These monitoring data are personal breathing zone monitoring data, which are the preferred type of monitoring data for the assessment of worker exposures as explained in Section 2.4.1.1.
- These monitoring data pertain to standard grade HBCD and this grade of HBCD is associated with the condition of use as discussed in Section 2.2.2
- These monitoring data pertain to workers involved in packaging, compaction, process operations, and working in the warehouse. The condition of use of repackaging of import containers includes the worker activities of packaging of HBCD and working in warehouses.

Based on this rationale, EPA used the median value from Searl and Robertson (2005) (1a in Table 2-62. Inhalation Monitoring Data for Manufacturing of HBCD), 0.89 mg/m^3, as the central tendency and the 90th percentile value, 1.89 mg/m^3, as the high-end exposure for repackaging. The EURAR also estimated potential worker exposures during the manufacturing of HBCD using this data. Specifically, the EURAR estimated a "reasonable worst-case" worker exposure concentration to be equal to the 90th percentile presented in Searl and Robertson (2005) (1a in Table 2-62. Inhalation Monitoring Data for Manufacturing of HBCD) (1.89 mg/m^3) and assumed a "typical" exposure concentration of half of this value (0.95 mg/m^3), stating that workers do not typically spend a full day working with HBCD, so the exposure is expected to be a fraction of the 90th percentile 8-hour TWA value (ECHA, 2008b). The "reasonable worst-case" value calculated by the EURAR and the high-end (90th percentile) value used by EPA for this condition of use are the same. The "typical" value of 0.95 mg/m^3 estimated by the EURAR and the central tendency (median) value of 0.89 mg/m^3 used by EPA for this condition of use are very similar in value. EPA prefers the use of the median value reported for this data over the method used by the EURAR, as the median value is still representative of full-shift worker exposure and consistent with the approach for use of occupational exposure data described in Section 2.4.1.1.

In addition to the monitoring data for the manufacturing of HBCD, EPA also considered monitoring data for the handling of HBCD during other conditions of use. Monitoring data for worker handling of HBCD with an overall confidence rating of high and meeting the criteria above (8-hour TWA, personal breathing zone, and HBCD standard grade power, granules, or containing HBCD) were available in studies by Thomsen (2007) and Searl and Robertson (2005) (noted as 2a-d in Table 2-63. in Section 2.4.1.3). However, EPA did not use these data in the assessment for the following reasons:

- The data from Thomsen (2007) (1a and 1b in Table 2-63.) are reflective of operations that are specific to the manufacturing of XPS foam containing HBCD and are not likely to be applicable to worker activities at importation and repackaging sites.
- The data from Searl and Robertson (2005) (2a-d in Table 2-63.) are for workers that add HBCD into a process, which may be applicable to workers at repackaging sites; however, the data from Searl and Robertson (2005) (1a in Table 2-62. Inhalation Monitoring Data for Manufacturing of HBCD) for the manufacturing of HBCD include a wider variety of worker activities that may occur at repackaging sites (i.e., packaging and working in warehouses).
- EPA notes that the data from Thomsen (2007) (1a and 1b in Table 2-63.) and Searl and Robertson (2005) (2a-d in Table 2-63.) indicate a range of worker inhalation exposure

concentration of 0.0002 to 3.36 mg HBCD/m^3; the values used by EPA from Searl and Robertson (2005) (1a in Table 2-62) of 0.89 mg/m^3 (central tendency – median) and 1.89 mg/m^3 (high-end – 90th percentile) fall within this range.

A major uncertainty of EPA's assessment is that details of the packaging at the European HBCD manufacturing sites, including the packaging method and engineering controls, are not available and cannot be compared to the details of repackaging that would occur in the U.S. and hence, the HBCD exposure concentrations at manufacturing sites in Europe may not be representative of those at U.S. sites. However, due to the lack of reasonably available information and because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

The exposure frequency for this condition of use is a range of 29 to 250 days/year. As discussed in Section 2.2.2, EPA estimated days of release at a repackaging site as a range from 29 to 300 days/year. EPA expects this range of release days is also reflective of the operating days during which HBCD is repackaged at an importation site and workers are potentially exposed to HBCD. However, EPA does not expect that workers will be exposed greater than 250 day/year, accounting for a worker schedule of five days per week and 50 weeks per year. EPA used the midpoint of this range of exposure frequency, rounded up where the midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures are 8-hour time-weighted average (TWA) data.

Dermal Exposure Assessment

Using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model*, which is described in Section 2.4.1.1. and assuming two-hand contact to solids containing 100% HBCD, EPA calculated the potential dose for a worker to be 3,100 mg HBCD/day (U.S. EPA, b).

The EURAR estimated dermal exposure during manufacturing of HBCD (importation and repackaging was not included in the EURAR) using EASE model. The EURAR estimated an exposure to standard grade HBCD powder of 1 mg/cm^2-day. This translates into a dose of 1,070 mg/day, using EPA's two-hand surface area of 1,070 cm^2. The NICNAS report estimated dermal exposure during importation and repackaging to standard grade HBCD powder of 0.1 to 1 mg/cm^2-day using the EASE model. Using EPA's two-hand surface area, this results in a dose of 107 to 1,070 mg/day.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the monitoring data represents occupational inhalation exposure air concentrations pertaining to workers in the U.S. The strength of the assessment is the quality of the data and the limitation of the assessment is the uncertainty in the assessment results. Based on this strength and limitation, EPA has medium confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.3 Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch

Workers are expected to manually unload and transfer HBCD powder or granules into hoppers or other equipment used to feed the HBCD into XPS masterbatch mixing equipment. This manual transfer may result in worker inhalation exposure to HBCD dust and dermal exposure to solid HBCD. Additionally, the generated dust from these transfer activities may result in ONU inhalation and dermal exposure to HBCD.

Workers may also be potentially exposed from occasional cleaning of process equipment and loading of XPS masterbatch into packages, if these activities are manual.

Number of Potentially Exposed Workers and Occupational Non-Users

As discussed in Section 2.2.3, EPA developed exposure estimates for one site for this condition of use. The two submissions in 2016 CDR that identify the industrial sector as "plastic material and resin manufacturing" each estimate that at least 50 but fewer than 100 workers are potentially exposed to HBCD. However, the companies that previously reported HBCD import volumes to CDR have stated to EPA that they permanently stopped the activity in 2016 or 2017. Thus, in lieu of using this CDR data from companies that discontinued use of HBCD, EPA estimated the number of workers potentially exposed using Bureau of Labor Statistics (BLS) data.

Based on data from the Bureau of Labor Statistics (BLS) for NAICS code 325991, Custom Compounding of Purchased Resins, and related Standard Occupational Classification (SOC) codes, there are on average an estimated 20 workers and 7 ONUs per site at custom compounding facilities. Based on these data and one modeled site for the production of XPS masterbatch, EPA estimated that a total of 20 workers and 7 ONUs are potentially exposed during this condition of use.

Occupational Exposure Assessment

Inhalation Exposure Assessment

The data from Searle and Robertson (2005) (noted as 3a-d of Table 2-63) present HBCD occupational inhalation exposure monitoring data pertaining to the compounding of polystyrene resin and production of XPS masterbatch at sites in Europe. The grade of HBCD associated with this exposure monitoring was not reported and the type of sample (personal breathing zone or area) was not reported for half of these data (Searle and Robertson (2005) – 3c-d are unknown sample types). Due to these uncertainties, EPA did not use these data to estimate exposure.

Table 2-63. Summary of Inhalation Monitoring Data for Handling of HBCD

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Inhalation Monitoring Data Used to Estimate Worker Exposures (both in this risk evaluation and the EURAR)									
Searl and Robertson (2005) - 2a	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 2.89-21.5 Mean: 7.2 Median: 5.52 90th percentile: 10.5	12	Short-term (13 to 56 mins)	(NICNAS, 2012b); (ECHA, 2008b)	High
Searl and Robertson (2005) – 2b	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 0.12-3.36 Mean: 1 Median: 0.42 90th percentile: 1.11 (NICNAS, 2012b); 1.3 (ECHA, 2008b)	12	8-hr TWA – note these are 8-hr TWA values of the data in the above row	(NICNAS, 2012b); (ECHA, 2008b)	High
Searl and Robertson (2005) – 2c	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 0.07-14.7 Mean: 1.2 Median: 0.27 90th percentile: 1.10	18	8-hr TWA (ECHA, 2008b); Full-Shift (NICNAS, 2012b)	(NICNAS, 2012b); (ECHA, 2008b)	High
Searl and Robertson (2005) – 2d	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Weighing powder prior to addition to reactor. HBCD bags were weighed and opened concurrently, or weighed in advance, in which case HBCD was transferred from 25-kg sacks using plastic scoop (full-shift measurement).	Range: 4.35-12.1 Mean: 7.2 Median: 6.19 90th percentile: 10.5 (NICNAS, 2012b); 10.6 (ECHA, 2008b);	4	8-hr TWA (ECHA, 2008b); Full Shift (NICNAS, 2012b)	(NICNAS, 2012b); (ECHA, 2008b)	High
Other Inhalation Monitoring Data for Handling of HBCD									
Searl and Robertson (2005) - 3a	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	Area	Weighing and mixing	Max 7.5 (for 2 hours) Mean: 1.89 Median: 0.83 90th percentile: 5.4	10	Short-term	(ECHA, 2008b) (ECHA, 2009b)	High
Searl and Robertson (2005) - 3b	Compounding of Polystyrene resin to produce XPS	HBCD of unknown grade	Area	Weighing and mixing	Mean: 0.88 90th percentile: 1.36	10	8-hr TWA	(ECHA, 2008b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
	Masterbatch containing HBCD								
Searl and Robertson (2005) - 3c	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	NR	Extruder	Mean: 0.12 Median: 0.10 90th percentile: 0.16	4	5 hours	(ECHA, 2008b) (ECHA, 2009b)	High
Searl and Robertson (2005) - 3d	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	NR	Automated handling of HBCD	Negligible	3	NR	(ECHA, 2008b)	High
Abbott (2001) - 1a	Manufacture of XPS from HBCD powder or granules	Standard grade HBCD	Area	At the feed deck near typical operator positions	Range 0.24 – 1.6 Mean: 0.66 90th percentile: 1.45 (excluding 10 ND samples)	16 (10 ND)	8-hr TWA	(ECHA, 2008b)	High
Abbott (2001) - 1b	Manufacture of XPS from HBCD powder or granules	HBCD powder and granules	Personal breathing zone	Activities in the mixer area, including operating a closed automated process excluding potential contact with neat HBCD	Range: 0.0002-0.0009 Mean: 0.0005 Median: 0.0005	6	8-hr TWA	(ECHA, 2008b) (NICNAS, 2012b)	High
Thomsen (2007) - 1a	Manufacture of XPS from HBCD powder or granules	HBCD powder and granules	Personal breathing zone	Weighing and addition of HBCD to the reactor and subsequent washing, centrifugation, sifting, and transfer of product to a silo container	Range: 0.001-0.15 Mean: 0.015 Median: 0.0027	24	8-hr TWA	(ECHA, 2008b) (NICNAS, 2012b)	High
Thomsen (2007) - 1b	Manufacture of XPS from HBCD powder or granules	HBCD granules	Mostly area and some personal breathing zone	Feed deck near typical operator positions	Range 0.005-0.9 Mean: 0.24 90th percentile: 0.47 (excluding 16 ND samples)	43 (16 ND)	60 – 1435 minutes	(ECHA, 2008b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Searl and Robertson (2005) - 4	Manufacture of XPS from HBCD powder or granules	HBCD granules	Area	Logistics, extruding, and laboratory	Mean: 0.00003 90th percentile: 0.00004	12	8-hr TWA	(ECHA, 2008b)	High
Ransbotyn (1999)	Manufacturing of EPS Resin beads	Respirable Dust Inhalable Dust	Personal	Addition of HBCDD to reactor or the supervising of the addition.	Respirable dust: <0.5 Total Inhalable dust: 2.0 Not specific to HBCD	5	Max 8-hr TWA	(ECHA, 2008b)	High
NICNAS (2012) - 1a	All industrial polymer processing sites [d]	Standard grade HBCD	Modelled with EASE	Addition of HBCD into process operation	Typical: 2 to 5 "Worst-case": 5 to 50	N/A - this is a modelled exposure	8-hr TWA	(NICNAS, 2012b)	High
NICNAS (2012) - 1b	HBCD importation / repackaging sites and all industrial polymer processing sites [d]	HBCD granules	Modelled with EASE	Repackaging with the use of LEV (typical) and without LEV (worst-case)	Typical: 0.2 to 0.5 "Worst-case": 0.5 to 5	N/A - this is a modelled exposure	8-hr TWA	(NICNAS, 2012b)	High

NR = Not Reported; N/A = Not Applicable
a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.
b - Statistics were calculated by the cited source and are presented here as they were presented in the source.
c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.
d - Per NICNAS (2012b), this includes EPA's conditions of use for Processing: Compounding of Polystyrene Resin to Product XPS Masterbatch, Processing: Manufacturing of XPS Foam using XPS Masterbatch, Processing: Manufacturing of XPS Foam using HBCD Powder, and Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads.

In addition to Searl and Robertson (2005) (3a-d), EPA evaluated additional monitoring data summarized in Table 2-63 to determine if these data could be used as surrogate data for the assessment of the compounding of polystyrene resin to produce XPS masterbatch. Specifically, EPA reviewed data from Abbott (2001), Thomsen (2007), Rasbotyn (1999), NICNAS (2012), and additional datasets from Searl and Robertson (2005) (specifically 2a-d and 4 of Table 2-63.), as well as the approach taken by the EURAR to estimate worker exposures in the polymer compounding industries. These data, which include the data used by the EURAR (Searl and Robertson [2005] – 2a-d), all have an overall confidence rating of High. EPA selected the approach taken by the EURAR to estimate exposures to HBCD during XPS masterbatch compounding. The EURAR estimated a "reasonable worst-case" exposure concentration of 2.5 mg/m^3 (based on Searl and Robertson [2005] – 2a-d, as described in Appendix E.2), for workers involved in the addition and weighing of HBCD into an EPS compounding process. The EURAR estimated a "typical" value to be half of the reasonable worst-case, or 1.25 mg/m^3. EPA used the EURAR estimate of 2.5 mg/m^3 to estimate high-end worker exposure (this estimate is based on 90^{th} percentile data) and the EURAR estimate of 1.25 mg/m^3 to estimate central tendency worker exposure (based on the EURAR "typical" value, which is half of the high-end).

EPA selected the EURAR approach for the following reasons:

- The monitoring data used by the EURAR were collected from workers who manually weighed and added HBCD powder to a compounding reactor. This activity is similar to the manual addition of HBCD powder into a hopper for mixing in with the polystyrene masterbatch.
- The monitoring data used by the EURAR are of standard grade HBCD, which is used in the conditions of use within the scope of this risk evaluation.
- The monitoring data used by the EURAR are personal breathing zone data.
- EPA used the "reasonable worst-case" and "typical" values estimated by the EURAR because EPA does not have the discrete data points and associated exposure durations for the data from Searl and Robertson (2005) (2a-d), and could only use one 8-hr TWA datapoint from Searl and Robertson (2005) (2a-d) to estimate worker exposures. The EURAR estimates account for multiple datapoints, and therefore multiple worker activities, Searl and Robertson (2005) (2a-d).

The details of the weighing and addition of HBCD at the European EPS compounding sites, including methods and engineering controls, are unknown and cannot be compared to the details of the same activities that would occur in the U.S. Additionally, the extent to which the worker activities at EPS compounding sites are applicable to XPS masterbatch compounding sites is uncertain. However, due to the lack of reasonably available information and because of the similarities in worker activities, EPA believes the EURAR estimates based on surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

Full datasets with discrete data points were not available. EPA could not calculate 50^{th} percentile and 95^{th} percentile values to assess central tendency and high-end exposure, respectively, and uses the "typical" and "reasonable worst-case" values assessed in the EURAR. The EURAR estimates the "reasonable worst-case" value using the 90^{th} percentile values of the exposure monitoring data reported in Searl and Robertson (2005) (2a-d) in Table 2-63. Although EPA's preference is to use 95^{th} percentiles as high-end estimates, 90^{th} percentiles are acceptable for use as high-end estimates as EPA has defined high-end exposures to include the 90^{th} percentile through the 99.9^{th} percentile of the exposure distribution. The EURAR estimates the "typical" value assuming it is one-half of the "reasonable worst-case" value. It is uncertain how one-half of the "reasonable worst-case" value compares with the 50^{th}

percentile of the combined distribution of the monitoring data represented in Searl and Robertson (2005) (2a-d) in Table 2-63. However, EPA believes the EURAR estimates are preferable to using the median and 90th percentile from one dataset in Table 2-64 because the EURAR estimates account for multiple datapoints, and therefore multiple worker activities.

As discussed in Section 2.2.3, EPA estimated a range of release days of 10 to 60 days/year. EPA expects this range of release days is also reflective of the operating days during which HBCD is processed at a compounding site and workers are potentially exposed to HBCD. EPA used the midpoint of this range of exposure frequency, rounded up where the midpoint resulted in fractions of days, to calculate central tendency average daily dose used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposures over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment
EPA estimated dermal exposure to HBCD using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model*, which is described in Section 2.4.1.1. EPA calculated dermal exposure assuming two-hand contact to solids containing 100% HBCD (NICNAS, 2012b; KemI, 2009) because sites that produce HBCD flame-retarded XPS masterbatch receive manufactured or imported HBCD in its pure form to be 3,100 mg HBCD/day.

The EURAR estimated dermal exposure for the use of HBCD standard grade powder as an additive in XPS masterbatch and XPS foam manufacturing. The EASE model estimated this exposure to be 0.1 mg/cm^2-day two-hand surface area of 1,070 cm^2. Using EPA's two-hand surface area of 1,070 cm^2, this results in a dose of 107 to 1,070 mg/day.

Strengths, Limitations, and Confidence in Assessment Results
EPA has medium to high confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the assessed occupational inhalation exposure air concentrations represent the distribution of inhalation exposure air concentrations pertaining to workers in the U.S. The strengths of the assessment are the quality of the data and the applicability of the surrogate monitoring data, while the limitation of the assessment is the uncertainty in the assessment results. Based on these strengths and limitation, EPA has medium to high confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.4 Processing: Manufacturing of XPS Foam using XPS Masterbatch

Workers may be exposed to HBCD while manually unloading and transferring XPS masterbatch directly into the extruder or into equipment used to feed the XPS masterbatch into the extruder. This manual transfer may result in worker inhalation exposure to HBCD dust that was generated from abrasion of the XPS masterbatch pellets or granules during transport (OECD, 2009). Manual transfers may also result in worker dermal exposure to solid HBCD. Additionally, the generated dust from these transfer activities may result in ONU inhalation exposure to HBCD.

Workers may also be potentially exposed from occasional cleaning of process equipment and cutting of the foam (i.e., secondary processing) into slabs or other shapes (ECHA, 2009b).

Number of Potentially Exposed Workers and Occupational Non-Users

The 2016 CDR data identifies multiple submissions that claim industrial use in the "construction" and "plastics product manufacturing" sectors (U. S. EPA, 2016). These industrial sectors are broad and can include a variety of sites, including sites that do not produce or install XPS and EPS foam, thus the reported estimates of number of workers potentially exposed at these sites may not be applicable to this condition of use.

EPA used workers and ONU estimates determined from an analysis of BLS data for the NAICS code 326140, Polystyrene Foam Product Manufacturing. These data indicate that there are, on average, 20 workers and 6 ONUs per site within NAICS code 326140. Based on these data and one modeled site for the manufacturing of XPS foam from XPS masterbatch, EPA estimated that a total of 20 workers and 6 ONUs are potentially exposed during this condition of use.

Inhalation Exposure Assessment

HBCD occupational inhalation exposure monitoring data pertaining to the manufacturing of XPS Foam using XPS masterbatch at multiple sites in Europe are presented in Searl and Robertson (2005) – 5a-d of Table 2-64. As indicated in this table, these data pertain to various worker activities or parts of the process for production of XPS foam from XPS masterbatch containing HBCD. These data were obtained by sampling dust and analyzing the samples for HBCD (ECHA, 2008b).

During this condition of use, HBCD is entrained within XPS masterbatch and the produced XPS foam. The monitoring data presented in Table 2-64 indicate the potential for worker exposure via inhalation of foam particles containing HBCD, assuming that the workers are exposed to the concentration of HBCD within the inhaled foam particles. These concentrations are less than those for the handling of HBCD powder (discussed in Sections 2.4.1.2 and 2.4.1.3). During this condition of use, EPA assessed worker inhalation exposure from inhalation of foam particles containing HBCD, as described below, noting that the exposure to HBCD may be less because HBCD is entrained within the foam particles and may not be fully available for absorption.

Table 2-64. Summary of Inhalation Monitoring Data For Handling of XPS Foam Containing HBCD

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Inhalation Monitoring Data Used to Estimate Worker Exposure									
Searl and Robertson (2005) - 5a	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Secondary processing of XPS foam - including cutting, sawing, and machining to manufacture shaped products	Mean: 0.08 90th percentile: 0.22 [c]	9	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2009b, 2008b)	High
Other Inhalation Monitoring Data for Handling of XPS Foam									
Searl and Robertson (2005) – 5b	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Reclamation of XPS foam - including shredding and reprocessing of process waste	Mean: 0.02 90th percentile: 0.02 [c]	5	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2009b, 2008b)	High
Searl and Robertson (2005) – 5c	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Other process control operators	Mean: 0.03 90th percentile: 0.03 [c]	4	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2009b, 2008b)	High
Searl and Robertson (2005) – 5d	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Process operators handling XPS masterbatch	Mean: 0.03 90th percentile: 0.03 [c]	24	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2009b, 2008b)	High

NR = Not Reported; N/A = Not Applicable
a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.
b - Statistics were calculated by the cited source and are presented here as they were presented in the source.
c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.

All of the data in Table 2-64 have an overall confidence rating of high. The 8-hr TWA values that were reported as mean and 90th percentile values; discrete data points associated with this dataset were not reported in the EURAR, and therefore EPA cannot calculate the mean and 90th percentile of this entire dataset. EPA estimated worker exposure to HBCD during the production of XPS foam from masterbatch using the mean and high-end values; 0.08 mg/m3 as a central tendency estimate of exposure concentration and the 90th percentile value of 0.22 mg/m3 as the high-end estimate of exposure concentration. The monitoring data pertain to secondary processing of XPS foam, which is defined as cutting, sawing, and machining of XPS foam to manufacture shaped products (ECHA, 2009b). EPA selected the data to estimate worker exposure concentrations because these values present both a higher exposure concentration and a wider range of potential exposure concentration than the data in the other rows.

Note that most of the samples associated with the Searl and Robertson (2005) (5a-b) data contained HBCD at levels below the detection limit. Specifically, HBCD was detected in only three of 14 dust samples presented in Searl and Robertson (2005) (5a-b); 9 of these 14 samples were taken during the secondary processing of XPS foam (Searl and Robertson (2005) (5a)) and the other five samples were taken during XPS foam reclamation (Searl and Robertson (2005) (5b)), which is the mechanical grinding of foam pieces that are then reintroduced into the XPS foam manufacturing process. Yet secondary processing of XPS foam still presented the highest HBCD exposure potential as well as the largest range of potential HBCD exposure concentration of the monitored activities (ECHA, 2008b). EPA is uncertain how the mean and 90th percentile values were calculated (i.e., if the non-detect sample results were excluded or if they were included by using the level of detection (LOD) or some variation of the LOD). EPA recognizes these uncertainties, but believes this data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

As discussed in Section 2.2.4, EPA estimated a range of release days of 1 to 16 days/year for air releases. EPA expects this range of release days is reflective of the operating days during which HBCD is processed at a converting site and workers are potentially exposed to HBCD. EPA used the midpoint of the range of exposure frequency, rounded up when the midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

EPA estimated dermal exposure to HBCD during the production of XPS foam from XPS masterbatch using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model*, which is described in Section 2.4.1.1. EPA calculated dermal exposure assuming two-hand contact to solid XPS masterbatch containing 70% HBCD (NICNAS, 2012b; ECHA, 2008b). EPA used this weight fraction because workers at sites that produce XPS foam from XPS masterbatch have the highest potential dermal exposure concentration to HBCD during the unloading of XPS masterbatch. Using this model and 70% HBCD, EPA calculated the potential dose for a worker to be 2,170 mg HBCD/day. The EURAR and NICNAS report do not estimate dermal exposures during this operation.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of directly applicable monitoring data, is

the highest of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the assessed occupational inhalation exposure air concentrations represent the distribution of inhalation exposure air concentrations pertaining to workers in the U.S. Additionally, as HBCD is entrained within foam particles, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption. The strengths of the assessment are the assessment approach and the quality of the data, while the limitation of the assessment is the uncertainty in the assessment results. Based on these strengths and limitation, EPA has medium to high confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.5 Processing: Manufacturing of XPS Foam using HBCD Powder

Workers are expected to manually unload and transfer HBCD powder directly into the extruder or into equipment used to feed the powder into the extruder. This manual transfer may result in worker inhalation exposure to HBCD dust and dermal exposure to solid HBCD. Additionally, the generated dust from these transfer activities may result in ONU inhalation and dermal exposure to HBCD.

Workers may also be potentially exposed from occasional cleaning of process equipment and cutting of the foam into slabs or other shapes, if these activities are manual. However, the unloading of HBCD powder is expected to present the highest potential exposure to HBCD, as HBCD is at the highest concentration during this activity.

Number of Potentially Exposed Workers and Occupational Non-Users

The 2016 CDR data identifies multiple submissions that claim the industrial use in the "construction" and "plastics product manufacturing" sectors (2016 CDR, (U. S. EPA, 2016)). These industrial sectors are broad and can include a variety of sites, including sites that do not product or install XPS and EPS foam, thus the reported estimates of number of workers potentially exposed at these sites may not be applicable to this condition of use.

EPA used workers and ONU estimates determined from an analysis of BLS data for the NAICS code 326140, Polystyrene Foam Product Manufacturing. These data indicate that there are, on average, 20 workers and 6 ONUs per site within NAICS code 326140. Based on this data and one modeled site for the manufacturing of XPS foam from HBCD powder, EPA estimated that a total of 20 workers and 6 ONUs are potentially exposed during this condition of use.

Inhalation Exposure Assessment

The studies from Abbott (2001), Thomsen (2007) and Searl and Robertson (2005) (noted as 4), which are summarized in Table 2-63 in Section 2.4.1.3, contain data for the manufacturing of XPS foam from HBCD powder or granules. These data had an overall confidence rating of High. Of these data, the only 8-hr TWA personal breathing zone samples are from Thomsen (2007). However, the form of HBCD handled was not reported and hence EPA did not use these data in the assessment. These data are lower in magnitude than that used by EPA, as described below. No other data for this condition of use were found in the reviewed literature. EPA reviewed the other data in Table 2-63. and the EURAR approach for surrogate data that is applicable to this condition of use.

Based on this review, EPA used the same methodology to estimate inhalation exposures for this condition of use as that used for Section 2.4.1.3, Compounding of Polystyrene Resin to Produce XPS Masterbatch. Specifically, EPA used the "reasonable worst-case" and "typical" values reported in the

EURAR for use of HBCD as an additive in polymer processing (ECHA, 2008b). As discussed in Section 2.4.1.3, the "reasonable worst-case" reported by the EURAR is based on 90th percentile data and the "typical" value is half this concentration. EPA used the "reasonable worst-case" value of 2.5 mg/m^3 for an estimate of high-end worker exposure and the typical value of 1.25 mg/m^3 for an estimate of central-tendency worker exposure. Refer to Section 2.4.1.3 for additional discussion of this data.

EPA expects the largest source of potential inhalation exposure for both conditions of use is the handling of HBCD standard grade powder. There is also uncertainty whether the worker activities at EPS compounding sites are applicable to XPS masterbatch compounding sites. Additionally, it is uncertain as to the extent to which operations at European sites reflect those at sites in the United States. However, due to the lack of additional data and because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

As discussed in Section 2.2.5, EPA estimated a range of release days of 1 to 16 days/year for air releases. EPA expects this range of release days is also reflective of the operating days during which HBCD is processed at a converting site and workers are potentially exposed to HBCD. EPA used the midpoint of this range of exposure frequency, rounded up where the midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

EPA estimated dermal exposure to HBCD during the production of XPS foam from HBCD powder using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model*, which is described in Section 2.4.1.1. EPA calculated dermal exposure assuming two-hand contact to solid containing 100% HBCD (NICNAS, 2012b; ECHA, 2008b). EPA used this weight fraction because workers at sites that produce XPS foam from HBCD powder have the highest potential dermal exposure concentration to HBCD during the unloading of HBCD powder. Using this model and 100% HBCD, EPA calculated the potential dose for a worker to be 3,100 mg HBCD/day.

The EURAR estimated dermal exposure for the use of HBCD standard grade powder as an additive in XPS masterbatch and XPS foam manufacturing. The EASE model estimated this exposure to be 0.1 mg/cm^2-day. Using EPA's two-hand surface area of 1,070 cm^2, this results in a dose of 107 mg/day. The NICNAS report uses EASE to model dermal exposure during the addition and weighing of HBCD into processes. EASE estimated a dermal dose rate of 0.1 to 1 mg/cm^2-day. Using EPA's two-hand surface area of 1,070 cm^2, this results in a dose of 107 to 1,070 mg/day. The EASE estimates provided in the EURAR and NICNAS are lower than that estimated by EPA (3,100 mg/day) as the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model* predicts a higher quantity of solids on skin per day.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation

exposure air concentration. The major uncertainty of the assessment is the extent to which the assessed occupational inhalation exposure air concentrations represent the distribution of inhalation exposure air concentrations pertaining to workers in the U.S. The strengths of the assessment are the quality of the data and the applicability of the surrogate monitoring data, while the limitation of the assessment is the uncertainty in the assessment results. Based on these strengths and limitations, EPA has medium to high confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.6 Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads

Workers may manually unload the imported EPS resin beads into processing equipment. However, HBCD is entrained in the EPS resin beads and at a low concentration (0.7 wt%), thus the potential for exposure is very low and is not assessed in the EURAR or the Australian risk assessment (NICNAS, 2012b; ECHA, 2008b). Workers are unlikely to be exposed during the automated processing to produce EPS foam from the EPS resin beads but may be exposed if the produced foam is manually cut or trimmed to remove excess foam that was cinched by the molds. During cutting and trimming, particles containing HBCD are formed, which workers and ONUs may inhale.

Number of Potentially Exposed Workers and Occupational Non-Users

The 2016 CDR data identifies multiple submissions that claim the industrial use in the "construction" and "plastics product manufacturing" sectors (U. S. EPA, 2016). These industrial sectors are broad and can include a variety of sites, including sites that do not product or install XPS and EPS foam, thus the reported estimates of number of workers potentially exposed at these sites may not be applicable to this condition of use.

EPA used workers and ONU estimates determined from an analysis of BLS data for the NAICS code 326140, Polystyrene Foam Product Manufacturing. These data indicate that there are, on average, 20 workers and 6 ONUs per site within NAICS code 326140. Based on these data and one modeled site for the manufacturing of EPS foam from imported EPS resin beads, EPA estimated that a total of 20 workers and 6 ONUs are potentially exposed during this condition of use.

Inhalation Exposure Assessment

EPA found data related to the cutting of EPS foam. These data are presented in Table 2-65 below. In addition to these data, EPA considered the XPS foam handling data that was used in Section 2.4.1.4, also presented in Table 2-65 below. The EURAR and NICNAS assessment did not estimate exposures during this condition of use, stating that these exposures are expected to be low in comparison to conditions of use where HBCD is handled in powder, granular, or masterbatch form. However, the monitoring data presented in Table 2-65 indicate the potential for worker exposure via inhalation of foam particles containing HBCD, assuming that the workers are exposed to the concentration of HBCD within the inhaled foam particles. These concentrations are less than those for the handling of HBCD powder (discussed in Sections 2.4.1.2 and 2.4.1.3). During this condition of use, EPA assessed worker inhalation exposure from the inhalation monitoring data for secondary processing of XPS foam, as described below, noting that the exposure to HBCD may overestimate considering that HBCD is entrained within the foam particles and may not be fully available for absorption.

Table 2-65. Summary of Inhalation Monitoring Data for Handling of XPS and EPS Foam Containing HBCD

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Inhalation Monitoring Data Used to Estimate Worker Exposure									
Searl and Robertson (2005) - 5a	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Secondary processing of XPS foam - including cutting, sawing, and machining to manufacture shaped products	Mean: 0.08 90th percentile: 0.22 [c]	9	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Other Inhalation Monitoring Data for the Handling of XPS and EPS Foam									
Searl and Robertson (2005) – 5b	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Reclamation of XPS foam - including shredding and reprocessing of process waste	Mean: 0.02 90th percentile: 0.02 [c]	5	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Searl and Robertson (2005) – 5c	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Other process control operators	Mean: 0.03 90th percentile: 0.03 [c]	4	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Searl and Robertson (2005) – 5d	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Process operators handling XPS masterbatch	Mean: 0.03 90th percentile: 0.03 [c]	24	8-hr TWA	Original source: (Searl and Robertson, 2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Zhang et al. (2012) - 1a	Thermal cutting of XPS boards	XPS foam	NR	Thermal cutting of XPS boards in a closed glovebox	Mean: 0.089	NR	NR	(Zhang et al., 2012)	High
Zhang et al. (2012) – 1b	Thermal cutting of EPS boards	EPS foam	NR	Thermal cutting of EPS boards in a closed glovebox	Mean: 0.057	NR	NR	(Zhang et al., 2012)	High

NR = Not Reported; N/A = Not Applicable

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating

a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.
b - Statistics were calculated by the cited source and are presented here as they were presented in the source.
c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.

In this condition of use, EPS resin beads are used to make EPS foam; handling of HBCD in powder or granule form is not expected. HBCD is entrained in the EPS resin beads and is not readily available for exposure. Based on this information, EPA expects that the processing of the EPS foam containing HBCD is a source of potential worker exposure.

To estimate potential inhalation exposures, EPA used the data from Searl and Robertson (2005) (noted as 5a-b in Table 2-65) for production of XPS Foam from XPS Masterbatch as surrogate for this condition of use. As discussed in Section 2.4.1.4, EPA used the mean value of 0.08 mg/m^3 as a central tendency estimate of exposure concentration and the 90^{th} percentile value of 0.22 mg/m^3 as the high-end estimate of exposure concentration. These values are from Searl and Robertson (2005) (5a of Table 2-65). Refer to Section 2.4.1.4 for additional discussion of these data.

EPA uses the same data as that used in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch because these data are for workers performing secondary processing of XPS foam, which includes cutting, sawing, or machining of XPS foam. EPA recognizes that exposures during cutting of EPS foam will likely differ somewhat from that during the cutting of XPS; however, the results in Zhang et al. (2012) (Zhang et al.) suggest that exposures during the two scenarios are likely similar. The data reported in Zhang et al. (Zhang et al., 2012) is from a laboratory study of thermal (hot wire) cutting of XPS and EPS foam in a laboratory glovebox, which is presented as Zhang et al. (2012) – 1a-b of Table 2-65. EPA did not use data from Zhang et al. (Zhang et al., 2012) because they were taken in a laboratory glovebox, which is not representative of realistic conditions for this use, and because the data are not PBZ data.

As discussed, there is uncertainty as to the extent to which the data on the processing of XPS foam is applicable to the processing of EPS foam. An additional source of uncertainty is that industrial XPS foam manufacturing sites may have different working conditions (i.e., type of cutting equipment used, amount of foam cut in a day, and ventilation) than EPS foam manufacturing sites. Further, uncertainty exists from the potential differences in equipment and controls used at the European sites at which the monitoring was conducted and sites in the United States. However, due to the lack of additional data and because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

As discussed in Section 2.2.6, EPA estimated a range of release days of 16 to 140 days/year. EPA expects this range of release days is also reflective of the operating days during which HBCD is processed at a converting site and workers are potentially exposed to HBCD. EPA used the midpoint of this range of exposure frequency, rounded up where the midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

EPA did not find data on potential levels of dermal exposure for workers engaged in activities related to the production of EPS foam from EPS resin beads. The EURAR and Australian risk assessment did not assess dermal exposures during this condition of use (NICNAS, 2012b; ECHA, 2008b). HBCD is entrained in the imported EPS resin beads and the potential dermal exposure from handling EPS and XPS foams containing HBCD is low due to the small weight fraction of HBCD in the foam and because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). Due to the same considerations, dermal exposures to HBCD during this condition of use are not expected.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the monitoring data represents occupational inhalation exposure air concentrations pertaining to workers in the U.S. Additionally, as HBCD is entrained within foam particles, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption. The strength of the assessment is the quality of the data and the limitation of the assessment is the uncertainty in the assessment results. Based on this strength and limitation, EPA has medium confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.7 Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam

Workers are likely to manually unwrap and further handle the XPS and EPS foam boards during which they will likely have dermal contact with the foam; however, HBCD is expected to be incorporated in the foam matrix and not readily available for exposure (NICNAS, 2012b). Inhalation exposure potential from unwrapping is limited because dust generation from the foam boards is unlikely due to the large size and limited opportunity for rubbing against each other during transport (U.S. EPA, 2014a).

Cutting of the XPS and EPS foam results in particle generation that pose potential for worker and ONU inhalation exposure.

Number of Potentially Exposed Workers and Occupational Non-Users

EPA estimated exposures for workers at two sites based on the methodology described in Section 2.4.1.1. The 2016 CDR data identify multiple submissions that claim the industrial use in the "construction" and "plastics product manufacturing" sectors (U. S. EPA, 2016). These industrial sectors can include a variety of sites, including XPS and EPS foam sites and construction sites, thus the reported estimates of number of workers potentially exposed at these sites may not be applicable to this condition of use.

EPA used workers and ONU estimates determined from an analysis of BLS data for the NAICS code 326140, Polystyrene Foam Product Manufacturing. These data indicate that there are, on average, 20 workers and 6 ONUs per site within NAICS code 326140. Based on these data and one site for each of the SIPs and automotive replacement part production, EPA estimated that a total of 39 workers and 11 ONUs are potentially exposed during this condition of use. Note that EPA used unrounded figures for the number of workers and ONUs per site to calculate these totals, resulting in the slight discrepancy.

Inhalation Exposure Assessment

EPA did not find HBCD inhalation monitoring data for this condition of use. The EURAR and NICNAS assessment did not estimate exposures during this condition of use, stating that these exposures are expected to be low in comparison to conditions of use where HBCD is handled in powder, granular, or masterbatch form. However, the monitoring data presented in Sections 2.4.1.4and 2.4.1.5 indicate the potential for worker exposure via inhalation of foam particles containing HBCD, assuming that the workers are exposed to the concentration of HBCD within the inhaled foam particles. These concentrations are less than those for the handling of HBCD powder (discussed in Sections 2.4.1.2 and 2.4.1.3). During this condition of use, EPA assessed worker inhalation exposure from the inhalation monitoring data for secondary processing of XPS foam, noting that the exposure to HBCD may overestimate considering that HBCD is entrained within the foam particles and may not be fully available for absorption.

To estimate potential inhalation exposures, EPA uses the data discussed in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch as surrogate for this condition of use. This data has an overall confidence rating of High. As discussed in Section 2.4.1.4, EPA used the mean value of 0.08 mg/m^3 as a central tendency estimate of exposure concentration and the 90^{th} percentile value of 0.22 mg/m^3 as the high-end estimate of exposure concentration. These values are from Searl and Robertson (2005) (noted as 5a in Table 2-64 in Section 2.4.1.4). Refer to this section for additional discussion of these data.

For this condition of use, XPS and EPS foam are cut to form SIPs and automobile replacement parts. EPA uses the same data as that used in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch because these data are for workers performing secondary processing of XPS foam, which includes cutting, sawing, or machining of XPS foam. EPA recognizes that exposures during cutting of XPS foam and EPS foam will likely differ somewhat but, due to lack of additional data, uses the values for the secondary processing of XPS foam for this condition of use, which involves the cutting of both XPS and EPS foam, as surrogate. Due to the lack of reasonably available information and because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

There is uncertainty as to the extent to which the monitoring data on the processing of XPS foam is applicable to the processing of EPS foam. An additional source of uncertainty is that industrial XPS foam manufacturing sites may have different working conditions (i.e., type of cutting equipment used, amount of foam cut in a day, and ventilation) than sites that cut XPS and EPS foam to produce SIPs and automobile replacement parts. Further, uncertainty exists from the potential differences in equipment and controls used at the European sites at which the monitoring was conducted and sites in the United States.

As discussed in Section 2.2.7, EPA estimated a range of release days of 16 to 300 days/year. EPA expects this range of release days is also reflective of the operating days during which HBCD is processed at foam cutting sites and workers are potentially exposed to HBCD. However, EPA does not expect that workers will be exposed greater than 250 day/year, accounting for a worker schedule of five days per week and 50 weeks per year. Based on this, EPA estimated worker exposures over a range of 16 to 250 days/year. EPA used the midpoint of this range of exposure frequency, rounded up where the

midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

EPA did not find data on potential levels of dermal exposure for workers engaged in activities related to the manufacturing of SIPs and automotive replacement parts from XPS and EPS foam. The EURAR and Australian risk assessment did not assess dermal exposures during this condition of use, with both reports stating that these exposures are expected to be low because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). The potential dermal exposure from handling EPS and XPS foams containing HBCD is low due to the small weight fraction of HBCD in the foam and because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). Due to the same considerations, dermal exposures to HBCD during this condition of use are not expected.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the monitoring data represents occupational inhalation exposure air concentrations pertaining to workers in the U.S. Additionally, as HBCD is entrained within foam particles, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption. The strength of the assessment is the quality of the data and the limitation of the assessment is the uncertainty in the assessment results. Based on this strength and limitation, EPA has medium confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.8 Use: Installation of Automobile Replacement Parts

EPA does not expect that workers at automotive repair sites further process the replacement parts containing HBCD. Because the automotive replacement parts are received at repair shops as finished articles containing XPS and EPS foam, in which HBCD is incorporated into the foam matrix, inhalation and dermal exposures are not expected(NICNAS, 2012b; ECHA, 2008b).

2.4.1.9 Use: Installation of XPS/EPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

Based on the process description, EPA expects workers will manually install HBCD-containing XPS and EPS foam insulation products into buildings, during which process they may cut the foams. The cutting of XPS and EPS foam produces particulates that may be inhaled by workers and ONUs.

Number of Potentially Exposed Workers and Occupational Non-Users

As discussed in Section 2.2.9, EPA estimated the number of potential construction sites to be as few as 34 large construction sites (assumes HBCD use rate estimated for large-scale use) and as high as 2,696 residential construction sites (assumes HBCD use rate estimated for residential use) may install insulation containing HBCD in a year.

EPA analyzed information from the Bureau of Labor Statistics for the NAICS code 238310, Drywall and Insulation Contractors, to determine an estimate of the number of workers and ONUs that may be present at a construction site. These data indicate that there are, on average, 8 workers and 1 ONU per contractor establishment within NAICS code 238310. Due to the low estimate of workers and ONUs per establishment, EPA assumes that this estimate represents the size of one work crew and that one crew would be present at job sites (i.e., construction sites) at a given time. Thus, EPA estimated 8 workers and 1 ONU per job site. Furthermore, EPA assumes that different crews from separate contractor establishments may install insulation containing HBCD and that these crews may install insulation containing HBCD at more than one job site in a year, although there is the potential for variability.

Using these data for number of workers and ONUs and the lower value estimate of 34 construction sites, a total of approximately 310 workers and 30 ONUs are potentially exposed. Using these data and the upper value estimate of 2,696 residential construction sites, a total of approximately 25,000 workers and 2,400 ONUs are potentially exposed. EPA expects that this range accounts for both the scenario that job crews may install insulation containing HBCD at multiple sites through a year and the scenario that a job crew will only install insulation containing HBCD at one site in a year. These data are summarized in Table 2-66. EPA used unrounded figures for the number of workers and ONUs per site to calculate these totals, resulting in the slight discrepancy. EPA recognizes that smaller residential sites likely have fewer workers than larger sites, thus this is likely an overestimate of the number of potentially exposed people.

Table 2-66. US Number of Establishments and Employees for Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures

2016 NAICS	2016 NAICS Title	Number of Job Sites		Number of Workers per Site [a]	Number of ONUs per Site [a]
		Lower value (large commercial sites)	Upper value (residential sites)		
238310	Drywall and Insulation Contractors	34	2,696	9	1
Lower value of total establishments and number of potentially exposed workers and ONUs = [b]		34		310	30
Upper value of total establishments and number of potentially exposed workers and ONUs = [b]		2,696		25,000	2,400

a – Rounded to the nearest whole number and two significant figures.
b – Unrounded figures were used for total worker and ONU calculations.

Inhalation Exposure Assessment

EPA did not find HBCD inhalation monitoring data for this condition of use. During this condition of use, HBCD is entrained within XPS and EPS foam. The monitoring data presented in Sections 2.4.1.4 and2.4.1.5 indicate the potential for worker exposure via inhalation of foam particles containing HBCD, assuming that the workers are exposed to the concentration of HBCD within the inhaled foam particles. These concentrations are less those for the handling of HBCD powder (discussed in Sections 2.4.1.2 and 2.4.1.3). During this condition of use, EPA assessed worker inhalation exposure from inhalation of foam

particles containing HBCD, as described below, noting that the exposure to HBCD may be less because HBCD is entrained within the foam particles and may not be fully available for absorption.

To estimate potential inhalation exposures, EPA uses the data discussed in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch as surrogate for this condition of use. These data have an overall confidence rating of High. As discussed in Section 2.4.1.4, EPA used the mean value of 0.08 mg/m^3 as a central tendency estimate of exposure concentration and the 90^{th} percentile value of 0.22 mg/m^3 as the high-end estimate of exposure concentration. These values are from Searl and Robertson (2005) (noted as 5a in Table 2-64 in Section 2.4.1.4). Refer to this section for additional discussion of these data.

In this condition of use, XPS and EPS foam are cut so that they can be installed into buildings at construction sites. EPA uses the same data as that used in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch because these data are for workers performing secondary processing of XPS foam, which includes cutting, sawing, or machining of XPS foam. EPA recognizes that exposures during cutting of XPS foam and EPS foam will likely differ somewhat but, due to lack of additional data, EPA uses the values for the secondary processing of XPS foam for this condition of use, which involves the cutting of both XPS and EPS foam, as surrogate. In the absence of relevant EPS data, EPA believes the surrogate data is sufficient. In addition, Zhang et al. (Zhang et al., 2012) reported similar exposure concentrations for the thermal cutting of XPS and EPS foam in a closed glovebox (0.089 mg/m^3 and 0.057mg/m^3, respectively).

There is uncertainty regarding the extent to which the monitoring data pertaining to the secondary processing of foam is applicable to this condition of use. The secondary processing of foam and the condition of use may not be similar in terms of the following determinants of exposure:

1. The method of cutting and sawing of foam:
   The method of cutting or sawing foam at a construction site and the method of cutting foam at the XPS foam manufacturing sites associated with the monitoring data may be different and may generate dust differently in terms of the particle size of the generated dust and the quantity of the generated dust.
2. The rates at which foam is cut or sawed:
   The rate at which foam is typically cut at a construction site (e.g., mass of foam cut or sawed per unit time) is likely not similar to the rate of cutting or sawing at the XPS manufacturing sites associated with the monitoring data. Additionally, rate of cutting and sawing at construction sites may be variable throughout the year given seasonal construction cycles.
3. Ventilation:
   Ventilation at a construction site and ventilation at the XPS foam manufacturing sites associated with the monitoring data are likely different.

EPA did not find data specific to construction sites that install XPS and EPS foam. Due to the lack of additional data and because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data used was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

As discussed in Section 2.2.9, EPA estimated a range of release days of 1 to 3 days/year-site. However, EPA expects that workers may install insulation containing HBCD at multiple sites in a year. EPA does not expect that workers will be exposed greater than 250 day/year, accounting for a worker schedule of

five days per week and 50 weeks per year. Based on this, EPA expects the minimum number of exposure days to be 1 day/per year and the maximum number of exposure days to be 250 days/year. EPA used the midpoint of the range of 1 to 250 days/year of exposure frequency, rounded up to 126 days/year, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

The EURAR and Australian risk assessment did not assess dermal exposures during this condition of use (NICNAS, 2012b; ECHA, 2008b), stating that these exposures are expected to be low. The potential dermal exposure from handling XPS and EPS foams containing HBCD is low due to the small weight fraction of HBCD in the foam and because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). EPA does not expect dermal exposures during this condition of use due to the same considerations.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the monitoring data represents occupational inhalation exposure air concentrations pertaining to workers in the U.S. Additionally, as HBCD is entrained within foam particles, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption. The strength of the assessment is the quality of the data and the limitation of the assessment is the uncertainty in the assessment results. Based on this strength and limitation, EPA has medium confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.10 Demolition and Disposal of EPS/XPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures

During demolition, EPA expects workers may break XPS and EPS foam insulation products and generate dust comprised of foam particles that contain HBCD during demolition work. EPA expects workers may inhale dust that may be generated from the breaking process. Once inhaled, HBCD particulates may deposit in the upper respiratory tract where they may be incidentally ingested.

Number of Potentially Exposed Workers and Occupational Non-Users

EPA did not find information regarding the number of workers typically on a demolition site. To estimate the number of workers potentially exposed per site, EPA assumed that demolition is accomplished by workers who remove the insulation. To estimate the number of these workers, EPA assumed that this number of workers is equivalent to the number of workers who install foam panels and utilized the same methodology for estimating workers potentially exposed during the installation of insulation into buildings, as described below and in Section 2.4.1.9.

As described in Section 2.4.1.9, EPA analyzed information from the Bureau of Labor Statistics for the NAICS code 238310, Drywall and Insulation Contractors, to determine an estimate of the number of workers and ONUs that may be present at a construction site. These data indicate that there are, on average, 8 workers and 1 ONU per contractor establishment within NAICS code 238310. Using these

data for number of workers and ONUs and the lower value estimate of 578 construction sites, a total of approximately 5,300 workers and 510 ONUs are potentially exposed. Using these data and the upper value estimate of 45,832 residential construction sites, a total of approximately 420,000 workers and 40,000 ONUs are potentially exposed. Note that EPA expects that this range accounts for both the scenario that job crews may install insulation containing HBCD at multiple sites through a year and the scenario that a job crew will only install insulation containing HBCD at one site in a year.

EPA expects that demolition materials are not further cut or manually broken at landfill and incineration sites.

Inhalation Exposure Assessment

EPA did not find HBCD inhalation monitoring data for this condition of use. During this condition of use, HBCD is entrained within XPS and EPS foam. Based on the process description, there is potential for worker exposure via inhalation of HBCD particles. During this condition of use, EPA assessed worker inhalation exposure from inhalation of foam particles containing HBCD, as described below, noting that the exposure to HBCD may be less because HBCD is entrained within the foam particles and may not be fully available for absorption.

To estimate potential inhalation exposures, in the absence of monitoring data, EPA uses an estimation method based on the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for particulates not otherwise regulated (PNOR), which is 15 mg/m^3 for total dust (U.S. EPA, 2013a). In accordance with this method, EPA estimated the potential exposure concentration of HBCD, by multiplying the OSHA PEL for PNOR by the HBCD concentration in XPS and EPS foam, 2 wt% and 0.7 wt%, respectively (ECHA, 2008b). EPA calculates potential HBCD exposure concentrations ranging from 0.105 to 0.30 mg/m3. The OSHA PEL for PNOR and EPA's estimate are 8-hour TWA values. The specific value of exposure concentration using this method is dependent on the proportion of each type of foam, XPS and/or EPS, being demolished.

EPA used the OSHA PEL for PNOR because EPA did not find directly applicable inhalation monitoring data or surrogate monitoring data for this condition of use, which is preferable to regulatory limits, as discussed in Section 2.4.1.1. EPA considered the use of the data discussed in Section2.4.1.4, which is data for workers performing secondary processing of XPS foam, which includes cutting, sawing, or machining of XPS foam. EPA did not use these data as surrogate for this condition of use because, based on the process description, EPA does not expect the use of the same tools for breaking down of foam in this condition of use as those used for the secondary processing of XPS foam at an XPS foam manufacturing site, resulting in different dust generation potential. Specifically, as discussed in the process description, this condition of use involves manually breaking foam insulation or demolishing with equipment such as a wrecking ball.

EPA's estimate for occupational inhalation exposure to HBCD using the OSHA PEL for PNOR assumes that the dust to which workers are exposed at demolition sites is generated entirely from EPS and XPS foam. There is uncertainty about this assumption. There is also uncertainty as to the extent that the OSHA PEL for PNOR is reflective of the dust exposures that workers experience at demolition sites.

As discussed in Section 2.2.10, EPA estimated a range of release days of 1 to 3 days/year-job site. However, EPA expects that workers may demolish insulation containing HBCD at multiple sites in a year. EPA does not expect that workers will be exposed greater than 250 day/year, accounting for a worker schedule of five days per week and 50 weeks per year. Based on this, EPA expects the minimum

number of exposure days to be 1 day/per year and the maximum number of exposure days to be 250 days/year. Workers may only perform demolition activities intermittently throughout a year. EPA believes the upper estimate of 250 days/year is likely an overestimate but does not have any data to estimate the exact number of working days. EPA used the midpoint of the range of 1 to 250 days/year of exposure frequency, rounded up to 126 days/year, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

The EURAR and Australian risk assessment did not assess dermal exposures during this condition of use (NICNAS, 2012b; ECHA, 2008b). The potential dermal exposure from handling XPS and EPS foams containing HBCD is low due to the small weight fraction of HBCD in the foam and because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). EPA does not expect dermal exposures to HBCD during this condition of use due to the same considerations.

Strengths, Limitations, and Confidence in Assessment Results

EPA has low to medium confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of the OSHA PEL for PNOR, is the second to lowest approach of the inhalation exposure approach hierarchy. The major uncertainty of the assessment is the extent to which the OSHA PEL for PNOR represents occupational inhalation exposure air concentrations. The limitation of the assessment is the uncertainty in the representativeness of the OSHA PEL for PNOR. Additionally, as HBCD is entrained within foam particles, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption. Based on the strengths and limitations, EPA has a low to medium confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.11 Processing: Recycling of EPS Foam and Reuse of XPS Foam

Workers at EPS foam recycling sites will likely unload EPS foam boards into grinding equipment where the boards are ground and transported to the EPS foam molding equipment. Workers may cut the EPS foam prior to grinding to allow the EPS boards to fit into the grinder. The grinding of recycled EPS boards may produce dust that becomes airborne, which can be inhaled by workers and ONUs. In addition, once new EPS foam is produced, it may be cut or reshaped. XPS reuse may involve the cutting or reshaping of the XPS insulation, which may produce particulates to which workers may be exposed via inhalation.

Number of Potentially Exposed Workers and Occupational Non-Users

EPA estimated exposures for workers at two recycling and reuse sites based on the information in Section 2.2.11. To recycle EPS foam, the EPS boards are grinded and introduced into the EPS molding process with virgin EPS (ECHA, 2008b). Therefore, EPS recycling is likely to be performed at sites with similar operations to those described for EPS foam manufacturing in Section 2.2.6. Thus, EPA assumed the same number of workers and ONUs as described in Section 2.4.1.6 (Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads). For this estimate, EPA utilized worker and ONU estimates determined from an analysis of BLS data for the NAICS code 326140, Polystyrene Foam Product Manufacturing. These data indicate that there are, on average, 20 workers and 6 ONUs per site within NAICS code 326140. Based on these data and two sites for the recycling of EPS foam and reuse of XPS, EPA estimated that a total of 39 workers and 11 ONUs are

potentially exposed during this life cycle stage. EPA used unrounded figures for the number of workers and ONUs per site to calculate these totals, resulting in the slight discrepancy.

EPA notes that the number of workers potentially exposed during reuse of XPS may differ from the estimate above, if XPS is reused directly at construction sites and is not first processed (i.e., cut or otherwise re-shaped) at industrial processing sites.

Inhalation Exposure Assessment

EPA did not identify HBCD inhalation monitoring data for this condition of use. The EURAR and NICNAS assessment did not estimate exposures, stating that these exposures are expected to be low in comparison to conditions of use where HBCD is handled in powder, granular, or masterbatch form, due to the lower concentration of HBCD and because it is within the XPS or EPS matrix ((NICNAS, 2012b; ECHA, 2008b). However, the monitoring data presented in Section 2.4.1.4 and 2.4.1.5 indicate the potential for worker exposure via inhalation of foam particles containing HBCD, assuming that the workers are exposed to the concentration of HBCD within the inhaled foam particles. These concentrations are less those for the handling of HBCD powder (discussed in Sections 2.4.1.2 and 2.4.1.3). During this condition of use, EPA assessed worker inhalation exposure from inhalation of foam particles containing HBCD, as described below, noting that the exposure to HBCD may be less because HBCD is entrained within the foam particles and may not be fully available for absorption.

To estimate potential inhalation exposures, EPA uses the data discussed in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch as surrogate for this condition of use. This data had an overall confidence rating of High. As discussed in Section 2.4.1.4, EPA used the mean value of 0.08 mg/m^3 as a central tendency estimate of exposure concentration and the 90^{th} percentile value of 0.22 mg/m^3 as the high-end estimate of exposure concentration. These values are from Searl and Robertson (2005) (noted as 5a in Table 2-64 in Section 2.4.1.4). Refer to this section for additional discussion of these data.

For this condition of use, EPS foam is broken down and grinded so that it can be introduced into the EPS converting process and reprocessed into EPS foam. XPS reuse may involve the cutting or reshaping of the XPS insulation. EPA uses the same data as that used in Section 2.4.1.4 for the production of XPS Foam from XPS Masterbatch because these data are for workers performing secondary processing of XPS foam, which includes cutting, sawing, or machining of XPS foam. EPA recognizes that exposures during processing of EPS foam will likely differ somewhat from that during cutting of XPS; however, the results in Zhang et al. (Zhang et al., 2012) (noted as Zhang et al. (2012) – 1a-b in Table 2-64) suggest that exposures during the two scenarios are likely similar. The data reported in Zhang et al. (2012) is from a laboratory study of thermal (hot wire) cutting of XPS and EPS foam in a laboratory glovebox (Zhang et al., 2012),which is presented in Zhang et al. (2012) – 1a-b of Table 2-64, as well as Table_Apx E-3. in Appendix 0. EPA did not use data from Zhang et al. (Zhang et al., 2012) because they were taken in a laboratory glovebox, which is not representative of realistic conditions for this use and because the data are not PBZ data.

As discussed, there is uncertainty as to the extent to which the data on the processing of XPS foam is applicable to the processing of EPS foam. An additional source of uncertainty is that industrial XPS foam manufacturing sites may have different working conditions (i.e., type of cutting equipment used, amount of foam cut in a day, and ventilation) than EPS foam manufacturing sites. Further, uncertainty exists from the potential differences in equipment and controls used at the European sites at which the monitoring was conducted and sites in the United States. However, due to the lack of additional data and

because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

As discussed in Section 2.2.11, EPA estimated a range of release days of 1 to 140 days/year. EPA expects this range of release days is also reflective of the operating days during which foam containing HBCD is recycled at a converting site and workers are potentially exposed to HBCD. EPA used the midpoint of this range of exposure frequency, rounded up where the midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

EPA did not find data on potential levels of dermal exposure for workers engaged in activities related to the recycling of EPS foam. The EURAR and Australian risk assessment did not assess dermal exposures during this condition of use, with both reports stating that these exposures are expected to be low because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). The potential dermal exposure from handling EPS and XPS foams containing HBCD is low due to the small weight fraction of HBCD in the foam and because HBCD is incorporated into the foam matrix, thus is not readily available for exposure (NICNAS, 2012b; ECHA, 2008b). EPA does not expect dermal exposures to HBCD during this condition of use due to the same considerations.

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the monitoring data represents occupational inhalation exposure air concentrations pertaining to workers in the U.S. Additionally, as HBCD is entrained within foam particles, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption. The strength of the assessment is the quality of the data and the limitation of the assessment is the uncertainty in the assessment results. Based on this strength and limitation, EPA has medium confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.12 Processing: Formulation of Flux/Solder Pastes

The flux/solder paste formulation site purchases HBCD of unknown physical form and HBCD concentration. EPA estimated exposures for workers that handle HBCD as a solid that may generate dust during transfer activities. The concentration of HBCD received at this site is unknown. EPA estimated worker exposures assuming that this site receives pure HBCD or formulations containing nearly 100% HCBD.

Workers at formulation sites will likely unload HCBD into mixing equipment, where the HBCD is mixed with other ingredients and becomes suspended in the solder flux component formulation. This HBCD transfer may result in worker inhalation exposure to HBCD dust and dermal exposure to solid

HBCD. Additionally, the generated dust from these transfer activities may result in ONU inhalation and dermal exposure to HBCD.

Workers may also be potentially exposed from occasional cleaning of process equipment and loading of formulations into containers to be shipped to China for final formulation of the flux/solder paste. However, the unloading of HBCD powder is expected to present the highest potential exposure to HBCD, as HBCD is at the highest concentration during this activity.

Number of Potentially Exposed Workers and Occupational Non-Users

As discussed in Section 2.2.13, EPA estimated exposures for workers at one solder flux component formulation site.

The number of workers and ONUs potentially exposed during this condition of use was estimated using BLS data for the NAICS code 325998, All Other Miscellaneous Chemical Product and Preparation Manufacturing. These data are summarized in Table 2-67 below. Based on these data, EPA estimated that a total of 14 workers and 5 ONUs are potentially exposed during this condition of use.

Table 2-67. US Number of Establishments and Employees for Formulation of Solder Flux

Scenario	2016 NAICS	2016 NAICS Title	Number of Establishments	Number of Workers per Site [a]	Number of ONUs per Site [a]
Formulation of flux and solder	325998	All Other Miscellaneous Chemical Product and Preparation Manufacturing	1	14	5

[a] Rounded to the nearest whole number.

Inhalation Exposure Assessment

EPA did not identify personal monitoring data for the formulation of flux/solder pastes using HBCD powder. EPA used the same methodology to estimate inhalation exposures for this condition of use as that used for Section 2.4.1.3, Compounding of Polystyrene Resin to Produce XPS Masterbatch. Specifically, EPA used the "reasonable worst-case" and "typical" values reported in the EURAR for use of HBCD as an additive in polymer processing (ECHA, 2008b). These data had an overall confidence rating of High. As discussed in Section 2.4.1.3, the "reasonable worst-case" reported by the EURAR is based on 90th percentile data and the "typical" value is half this concentration. EPA used the "reasonable worst-case" value of 2.5 mg/m^3 for an estimate of high-end worker exposure and the typical value of 1.25 mg/m^3 for an estimate of central-tendency worker exposure. Refer to Section 2.4.1.3 for additional discussion of this data.

EPA expects the largest source of potential inhalation exposure for both conditions of use is the handling of HBCD standard grade powder. However, there is uncertainty in the extent to which the worker activities at compounding sites are applicable to solder formulation sites. An uncertainty of this assessment is also the extent to which operations at European sites reflect those at sites in the United States. However, due to the lack of additional data and because of the similarities in worker activities, EPA believes this surrogate data is sufficient. The quality of the data was assessed through EPA's systematic review process and evaluated on the credibility of the source, transparency of the data, and applicability of the data. The monitoring data was rated an overall confidence rating of high.

As discussed in Section 2.2.12, EPA estimated days of release at a formulation site as a range from 5 to 300 days/year. EPA expects this range of release days is also reflective of the operating days during which HBCD is processed at a formulation site and workers are potentially exposed to HBCD. However, EPA does not expect that workers will be exposed greater than 250 day/year, accounting for a worker schedule of five days per week and 50 weeks per year. Based on this information, EPA estimated worker exposures over the exposure frequency of 5 to 250 days/year. EPA used the midpoint of this range of exposure frequency, rounded up where the midpoint resulted in fractions of days, to calculate central tendency average daily dose. EPA used the high-end of this range of exposure frequency to calculate high-end average daily dose. Additionally, EPA estimated worker exposure over the full working day, or eight hours/day, as the data used to estimate inhalation exposures is 8-hour TWA data.

Dermal Exposure Assessment

EPA estimated dermal exposure to HBCD from unloading HBCD powder using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model*, which is described in Section 2.4.1.1. EPA calculated dermal exposure assuming two-hand contact to solids containing 100% HBCD . EPA used this weight fraction because workers have the highest potential dermal exposure concentration to HBCD during the unloading of HBCD powder, prior to formulation. EPA calculated the potential dose for a worker to be 3,100 mg HBCD/day. The EURAR did not estimate dermal exposures during this condition of use. The NICNAS report did use EASE to model dermal exposure during the addition and weighing of HBCD into processes, which is covered in this condition of use. The NICNAS report estimated a dermal dose rate of 0.1 to 1 mg/cm^2-day. This results in a dose of 107 to 1,070 mg/day, using EPA's two-hand surface area of 1,070 cm^2 (NICNAS, 2012b; ECHA, 2008b).

Strengths, Limitations, and Confidence in Assessment Results

EPA has medium to high confidence in the assessed air concentrations presented above. EPA considered the assessment approach, the quality of the data, and uncertainties in assessment results to determine the level of confidence. The assessment approach, which is the use of surrogate monitoring data, is in the middle of the inhalation exposure approach hierarchy. Using systematic review, EPA assigned an overall confidence rating of high to the surrogate monitoring data that was used to assess the inhalation exposure air concentration. The major uncertainty of the assessment is the extent to which the assessed occupational inhalation exposure air concentrations represent the distribution of inhalation exposure air concentrations pertaining to workers in the U.S. The strengths of the assessment are the quality of the data and the applicability of the surrogate monitoring data, while the limitation of the assessment is the uncertainty in the assessment results. Based on these strengths and limitation, EPA has medium to high confidence in the assessed occupational inhalation exposure air concentrations.

2.4.1.13 Use of Flux/Solder Paste

The website of the flux and solder formulator identified in 2017 TRI indicates that these formulations are frequently supplied in small containers, such as syringes and 100-gram jugs. Workers may be potentially exposed during unloading into application equipment.

Number of Potentially Exposed Workers and Occupational Non-Users

EPA estimated exposures for workers at 227 sites based on the information in Section 2.2.13. For this estimate, EPA utilized workers and ONU estimates determined from an analysis of BLS data for the NAICS code 334400, Semiconductor and Other Electronic Component Manufacturing. These data indicate that there are, on average, 30 workers and 37 ONUs per site within NAICS code 334400. Based on these data and 227 sites, EPA estimated that a total of 6,800 workers and 6,100 ONUs are potentially exposed during this life cycle stage. EPA used unrounded figures for the number of workers and ONUs per site to calculate these totals, resulting in the slight discrepancy.

Inhalation

During this condition of use HBCD is in paste form within the flux/solder paste and is not available for particulate generation and exposure. Additionally, based on the process description, EPA does not expect the use of flux/solder pastes to generate mists or other particulates, nor vapors, due to the low volatility of HBCD. The EURAR and NICNAS RAR indicate that HBCD begins to thermally degrade at temperatures around 190 degrees Celsius (NICNAS, 2012b; ECHA, 2008b). Typical soldering formulations start to melt between 183-188 degrees Celsius, and the soldering temperatures are expected to be set higher up to 300 degrees Celsius (Indium Corporation, 2019a, b). EPA expects that the soldering process will destroy (via thermal degradation) the HBCD, making it unavailable for exposure. Based on this description, EPA does not expect worker inhalation exposure to HBCD during this condition of use.

Dermal

EPA estimated dermal exposure to HBCD from unloading HBCD powder using the *EPA/OPPT Direct 2-Hand Dermal Contact with Container Surfaces (Solids) Model*, which is described in Section 2.4.1.1. EPA used this model because the amount of dermal contact that workers are potentially exposed to is likely smaller than that estimated in the other conditions of use. This model uses a smaller quantity of solids on hands to estimate potential dose, based on worker contact with container surfaces. EPA calculated dermal exposure assuming two-hand contact to solids containing 1% HBCD. Using this model and 1% HBCD, EPA calculated the potential dose for a worker to be 11.0 mg HBCD/day. The EURAR and NICNAS did not estimate dermal exposures during this condition of use (NICNAS, 2012b; ECHA, 2008b).

Strengths, Limitations, and Confidence in Assessment Results

EPA did not assess occupational inhalation exposures during this condition of use based on literature and industry information indicating that the temperatures at which soldering occurs are likely to result in the degradation of HBCD, as discussed above.

2.4.1.14 Assumptions and Key Sources of Uncertainties for Occupational Exposures

Uncertainty is "the lack of knowledge about specific variables, parameters, models, or other factors" and can be described qualitatively or quantitatively. The following sections discuss uncertainties throughout the assessed HBCD condition of use scenarios.

2.4.1.14.1 Number of Workers

There are a number of uncertainties surrounding the estimated number of workers potentially exposed to HBCD, as outlined below.

First, BLS' OES employment data for each industry/occupation combination are only available at the 3-, 4-, or 5-digit NAICS level, rather than the full 6-digit NAICS level. This lack of granularity could result in an overestimate of the number of exposed workers if some 6-digit NAICS are included in the less granular BLS estimates but are not, in reality, likely to use HBCD for the assessed applications. EPA addressed this issue by refining the OES estimates using total employment data from the U.S. Census' SUSB. However, this approach assumes that the distribution of occupation types (SOC codes) in each 6-digit NAICS is equal to the distribution of occupation types at the parent 5-digit NAICS level. If the distribution of workers in occupations with HBCD exposure differs from the overall distribution of

workers in each NAICS, then this approach may result in inaccuracy, resulting in either an overestimation or underestimation of the number of potentially exposed workers.

Second, EPA's judgments about which industries (represented by NAICS codes) and occupations (represented by SOC codes) are associated with the uses assessed in this assessment are based on EPA's understanding of how HBCD is used in each industry. Designations of which industries and occupations have potential exposures is nevertheless subjective, and some industries/occupations with few exposures might erroneously be included, or some industries/occupations with exposures might erroneously be excluded. This would result in inaccuracy and could either overestimate or underestimate the estimate of exposed workers.

2.4.1.14.2 Analysis of Exposure Monitoring Data

EPA used worker potential inhalation exposure monitoring data from the EURAR to develop exposure estimates for most of the conditions of use. The conclusion of EPA's systematic review of this data source is a rating of high confidence in this data source. Whether the data source is a trusted source is one of the factors of the confidence rating. EPA's assessment is that the EU RAR is a trusted data source and therefore EPA used this data source even though there is uncertainty about whether there is inherent bias in the worker potential inhalation exposure monitoring data that the EU RAR contains and uncertainty about the statistical attributes of this data. Worker monitoring data may be inherently biased, depending on the circumstances of the monitoring. For example, bias may be present if exposure monitoring was conducted to address concerns regarding adverse human health effects reported following exposures during use. The scope and purpose of the monitoring may result in overestimation or underestimation of exposures. Also, the discrete data from the original source was not available, so EPA used reported statistics in the EURAR (e.g., median, mean, 90th percentile). This results in some uncertainty because EPA could not verify these statistics.

Another factor of the confidence rating of the EURAR is the geographic attribute (i.e., the location at which monitoring occurred) of the worker inhalation exposure monitoring data that are reported in the EURAR. The data reported in the EURAR pertains to worker exposure at sites in Europe and the extent to which this data is applicable to exposure of workers in the U.S. is uncertain.

EPA did not find worker potential inhalation exposure monitoring data for some of the occupational exposure scenarios. EPA assessed these scenarios by using surrogate worker inhalation exposure monitoring data for scenarios that EPA considers to be similar to the assessed scenario. There is uncertainty about the extent to which the scenarios are similar and the extent to which the monitoring data is applicable to the assessed exposure scenarios. However, EPA selected the surrogate data that EPA considers to be the most applicable, based on expected worker activities and operating conditions.

During some conditions of use, HBCD is entrained within XPS and EPS foam. For these conditions of use, EPA assessed worker inhalation exposure from monitoring data on the inhalation of particles from foam containing HBCD, assuming that the workers are exposed to the concentration of HBCD within the inhaled particles reported in the study. As HBCD is entrained within the foam during these conditions of use, this assessment could overestimate worker exposure to HBCD because it may not be fully available for absorption.

EPA expects potential inhalation exposures of ONUs to HBCD dust or foam particles containing HBCD. EPA expects these ONU exposures to be lower than the potential exposures of the corresponding workers, as discussed in this document. EPA did not assess these ONU exposures quantitatively due to lack of data. The lower HBCD air concentration to which ONUs are potentially

exposed would result in lower risk for ONUs as compared to workers, with regards to inhalation exposure.

EPA calculated average daily dose (ADD) for use in risk characterization assuming an exposure frequency equal to the midpoint and high-end of the range of operating days per year, as discussed for each condition of use. Use of the high-end exposure days assumes the workers are exposed every working day, which may be an overestimate if workers do not handle HBCD during each day of operation.

2.4.1.14.3 Modeling Dermal Exposures

To model dermal exposures, EPA used the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model* and the *EPA/OPPT Direct 2-Hand Dermal Contact with Container Surfaces (Solids) Model*. The dermal models are screening-level models that uses a high-end quantity of solids on the skin (U.S. EPA, 2013a). These models do not account for the potential exposure reduction due to glove use. The use of these models may result in overestimation of exposures if workers wear glove protection. EPA modeled dermal exposures using an upper-end estimate of 6.5% steady-state absorption (see Section 3.2.2). Absorption in occupational settings may be lower than this value based on frequent hand washing or uneven distribution across skin.

2.4.1.15 Summary of Occupational Exposures

For the risk characterization of occupational exposures, EPA used the 8-hour TWA exposure concentrations (both central tendency and high-end values) that EPA selected for each condition of use (refer to Sections 2.4.1.2 through 2.4.1.13 for rationale for these selections). Specifically, EPA used these exposure concentration values to calculate acute exposure dose (AED) and acute daily dose (ADD), which were then multiplied by the inhalation absorption factor of 100% (discussed in Section 3.2.2) to estimate the acute absorbed dose (AAD) and chronic absorbed dose (CAD), respectively. Similarly, for dermal exposures, EPA used the potential dermal dose rates (refer to Sections 2.4.1.2 through 0 for rationale for EPA's determination of these values) to calculate AED and ADD, them multiplied these values by a dermal absorption factor of 6.5% (discussed later in Section 3.2.2) to estimate the AAD and CAD.-Additional explanation of these equations and example calculations are located in Appendix E.4 and Appendix E.5, respectively.

A summary of the 8-hour TWA or dermal dose rate, AAD, and CAD values used in this risk evaluation is presented in Table 2-68 and below. The ADD and CAD are used to characterize chronic, non-cancer risks in Section 4.2.

Table 2-68. Acute and Chronic Inhalation Exposure Estimates, Worker Occupational Scenarios[a]

Occupational Scenario – Inhalation Exposure	Eight-Hour TWA Exposures C_{HBCD}, 8-hr TWA (mg/m^3)		Acute Absorbed Dose AAD_{HBCD} (mg/kg-day)		Chronic Absorbed Dose CAD_{HBCD} (mg/kg-day)		Characterization
	High-End	Central Tendency	High-End	Central Tendency	High-End	Central Tendency	
Processing: Repackaging of import containers	1.9E+00	8.9E-01	2.4E-01	1.1E-01	1.6E-01	4.27E-02	High-end: 90th percentile Central Tendency: Median
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	2.5E+00	1.3E+00	3.1E-01	1.6E-01	5.1E-02	1.50E-02	High-end: Reasonable 'worst-case' from EURAR Central Tendency: Typical from EURAR
Processing: Manufacturing of XPS Foam Using XPS Masterbatch	2.2E-01	8.0E-02	2.8E-02	1.0E-02	1.2E-03	2.47E-04	High-end: 90th percentile Central Tendency: Mean
Processing: Manufacturing of XPS Foam Using HBCD Powder	2.5E+00	1.3E+00	3.1E-01	1.6E-01	1.4E-02	3.85E-03	High-end: Reasonable 'worst-case' from EURAR Central Tendency: Typical from EURAR
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads	2.2E-01	8.0E-02	2.8E-02	1.0E-02	1.1E-02	2.14E-03	High-end: 90th percentile Central Tendency: Mean
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam	2.2E-01	8.0E-02	2.8E-02	1.0E-02	1.9E-02	3.64E-03	High-end: 90th percentile Central Tendency: Mean
Use: Installation of Automobile Replacement Parts[b]	--	--	--	--	--	--	
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	2.2E-01	8.0E-02	2.8E-02	1.0E-02	1.9E-02	3.45E-03	High-end: 90th percentile Central Tendency: Mean
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	3.0E-01	1.1E-01	3.8E-02	1.3E-02	2.6E-02	4.53E-03	This is a range using the OSHA PNOR PEL of 15 mg/m3 and HBCD concentration of 0.7% in EPS and 2% in XPS.
Processing: Recycling of EPS Foam	2.2E-01	8.0E-02	2.8E-02	1.0E-02	1.1E-02	1.95E-03	High-end: 90th percentile Central Tendency: Mean

Processing: Formulation of Flux / Solder Paste	2.5E+00	1.3E+00	3.1E-01	1.6E-01	2.1E-01	5.48E-02	High-end: Reasonable 'worst-case' from EURAR Central Tendency: Typical from EURAR
Use of Flux / Solder Paste[b]	--	--	--	--	--	--	
Note: [a]As discussed in Section 2.4.1.1 EPA expects potential inhalation exposure of an Occupational Non-User (ONU) in the case of some of the conditions of use but EPA did not assess this exposure due to lack of data. EPA expects these exposures to be lower than the exposures of the corresponding workers. [b]EPA did not estimate inhalation exposures for these conditions of use as EPA does not expect the generation of dust for these conditions of use.							

Table 2-69. Acute and Chronic Dermal Exposure Estimates, Worker Occupational Scenarios

Occupational Scenario – Dermal Exposure	Potential Dose Rate D_{exp} (mg/day)	Acute Absorbed Dose AAD_{HBCD} (mg/kg-day)	Chronic Absorbed Dose CAD_{HBCD} (mg/kg-day)[a]		Characterization
			High-End	Central Tendency	
Processing: Repackaging of import containers	3.1E+03	2.5E+00	1.7E+00	9.7E-01	Chronic absorbed dose – High-end: Maximum number of exposure days Central tendency: midpoint of exposure days
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	3.1E+03	2.5E+00	4.1E-01	2.4E-01	Chronic absorbed dose – High-end: Maximum number of exposure days Central tendency: midpoint of exposure days
Processing: Manufacturing of XPS Foam Using XPS Masterbatch	2.2E+03	1.8E+00	7.7E-02	4.4E-02	Chronic absorbed dose – High-end: Maximum number of exposure days Central tendency: midpoint of exposure days
Processing: Manufacturing of XPS Foam Using HBCD Powder	3.1E+03	2.5E+00	1.1E-01	6.2E-02	Chronic absorbed dose – High-end: Maximum number of exposure days Central tendency: midpoint of exposure days
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads	--	--	--		
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam	--	--	--		
Use: Installation of Automobile Replacement Parts	--	--	--		
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and	--	--	--		

Occupational Scenario – Dermal Exposure	Potential Dose Rate D_{exp} (mg/day)	Acute Absorbed Dose AAD_{HBCD} (mg/kg-day)	Chronic Absorbed Dose CAD_{HBCD} (mg/kg-day)[a]		Characterization
			High-End	Central Tendency	
Commercial Buildings, and Other Structures					
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	--	--	--		
Processing: Recycling of EPS Foam	--	--	--		
Processing: Formulation of Flux / Solder Paste	3.1E+03	2.5E+00	1.7E+00	8.8E-01	Chronic absorbed dose – High-end: Maximum number of exposure days Central tendency: midpoint of exposure days
Use of Flux / Solder Paste	1.1E+01	8.9E-03	6.1E-03	3.1E-03	Chronic absorbed dose – High-end: Maximum number of exposure days Central tendency: midpoint of exposure days

2.4.2 Exposure to General Population and Highly Exposed Groups

2.4.2.1 Approach and Methodology

HBCD is used primarily as an additive flame retardant in a variety of materials. HBCD has been detected in the indoor and outdoor environment and in human biomonitoring indicating that some amount of exposure is occurring in some individuals, although exposures likely vary across the general population. See *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment. (U.S. EPA, 2019d)* for a summary of environmental and biomonitoring studies where HBCD has been detected.

The migration of additive flame retardants from indoor sources such as building materials, plastics, and other articles appears a likely source of flame retardants found in indoor dust, suspended particles, and indoor air (Guo, 2013; Dodson et al., 2012b; Weschler and Nazaroff, 2010). However, the relative contribution of different sources of HBCD in these matrices is not well characterized. For example, HBCD present in building insulation, textiles, and recycled XPS and EPS materials are likely to have differing magnitudes of emissions.

Emission of HBCD is likely to occur through the following mechanisms: diffusion from sources and gas-phase mass-transfer, abrasion of materials to form small particulates through routine use, and direct transfer from articles to dust adhered to the article surface. Releases of flame retardants to the outdoor environment may occur through direct releases to water and air as well as indirect releases from the indoor environment.

The general population may be exposed to HBCD through oral, inhalation, or dermal exposure although oral exposure is the greatest contributor to overall exposure. EPA considered available monitoring data to characterize exposures to the general population. EPA considered both available monitoring data and scenario-specific modeled estimates to characterize exposure for highly-exposed groups (e.g., workers or people with high fish ingestion rates). Estimates of exposure for highly-exposed groups likely apply to relatively fewer individuals, while the general population exposure estimates are expected to be relevant for more people in the general population.

Exposure to the general population is more homogenous as this group is exposed to primarily background-levels of HBCD in media. Highly-exposed group(s) are more heterogenous in that they are also exposed to scenario-specific exposures, which can also vary depending on the subpopulation, from releases to water, air, and consumer articles. For all exposure groups, EPA estimated exposures using EPA exposure factors, some of which were recently updated (U.S. EPA, 2011b). EPA also considered estimated intakes and doses reported by others but acknowledges that these estimates were generally derived using different exposure factors. EPA acknowledges that some exposure factors for highly-exposed groups could be higher than the general population. Further discussion of highly exposed groups is provided in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment. (U.S. EPA, 2019d)*.

In this evaluation, general population is considered to be individuals who are not expected to live close to point sources (far-field) and are not expected to have HBCD-containing articles in their home, although data on the prevalence of articles containing HBCD in homes throughout the United States is

not well characterized. Exposure to these individuals was characterized using monitoring data. No modeling data was used for this population. The following exposure pathways were evaluated for the general population:

- Dietary (all foods- breast milk, fish/shellfish, meat/eggs/dairy, grain/vegetables/fruit)
- Dust and Soil Ingestion
- Inhalation of particles
- Dermal absorption of dust

In this evaluation, highly-exposed groups include individuals who are expected to live close by point sources and/or have HBCD insulation products in their homes and/or automotive components in their vehicles. Exposure to these individuals is supplemented by modeling and compared with monitoring data. All exposure scenarios identified in Section 2.2 are part of the highly exposed group. EPA also identified additional scenarios for highly exposed groups, some of which have quantitative exposure estimates and some of which have a qualitative discussion. Modeled dust and indoor air concentrations, modeled outdoor air concentrations, modeled water concentrations, and estimated soil, fish, and dietary concentrations will be considered alongside available monitoring data. The following exposure pathways/scenarios are considered for highly exposed groups in this assessment.

Table 2-70. Exposure Scenario Description for Highly Exposed Groups

	Source	Media/Pathway	Receptor	Approach
A1	HBCD emitted from any point source during its lifecycle from Scenarios described in Section 2.2	**Fish Tissue:** Emission into water and uptake into fish tissue	Children, adults	Quantitative, PSC and Lipid Normalized Upper Trophic Level BAF, Monitoring
A2	HBCD emitted from any point source during its lifecycle from Scenarios described in Section 2.2	**Air:** Emission to air and subsequent inhalation of particles	Children, Adults	Quantitative, IIOAC
A3	EPS/XPS insulation in residences	**Dust**: Emission from insulation into indoor air settled dust	Children and Adults	Quantitative-IECCU
A4	HBCD contained in automobile components	**Dust**: Emission into automobile cabin air and settled dust	Children and Adults	Quantitative-IECCU
A5	EPS and XPS insulation in buildings during use	**Air:** Emission from building interior to ambient air surrounding buildings	Children and Adults living near buildings containing HBCD	Qualitative
A6	Recycled consumer articles that contain HBCD	**Articles:** Mouthing, direct contact	Young children	Quantitative

	Source	Media/Pathway	Receptor	Approach
A7	HBCD sent to landfill across the lifecycle	**Air, Soil, Water:** Comingled HBCD containing materials leach into soil, disposed food, and water	Populations living near landfills Nesting birds living near landfills	Qualitative

Central tendency and high-end exposure descriptors are provided for general population and highly exposed groups as shown in Table 2-71. EPA reports age-specific doses for each overall exposure group and acknowledges that there could be further refinement of highly exposed (high-end) and potentially exposed or susceptible subpopulations (PESS) within this overall schema as receptor categories overlap and individuals may belong to multiple receptor groups. Further characterization of heterogeneity of who is included in the highly-exposed group and associated variability of exposure factors within the highly-exposed group is discussed in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d).* Further discussion of qualitative and semi-quantitative examples of highly exposed and susceptible subpopulations is also provided in Section 4.4.1.

Table 2-71. Exposure Descriptors Corresponding to Exposure Groups

Exposure Group	Exposure Descriptor	
	Central Tendency	**High-End**
General Population by Age Group	- Individuals not living near facilities - Uncertainty associated with source apportionment of indoor sources - Fewer exposure pathways - Central tendency exposure factors and concentrations - Assumed to represent the general population, i.e., applies to the most people	- Individuals not living near facilities - Uncertainty associated with source apportionment of indoor sources - Fewer exposure pathways - High-end exposure factors and concentrations - Assumed to represent the high-end of the general population (i.e., applies to fewer people in the general population)
Highly Exposed by Age Group	- Individuals who are living near facilities - Modeled HBCD insulation as source of indoor dust and air - Includes more exposure pathways - Central tendency exposure factors and concentrations - Overlaps more with PESS, these exposure estimates will be the high but will apply to fewer people	- Individuals who are living near facilities - Modeled HBCD insulation as source of indoor dust and air - Includes more exposure pathways - High-end Exposure Factors and Concentrations (e.g., subsistence fishers) - Overlaps with PESS, these exposure estimates will be the highest but will apply to the fewest number of people

EPA notes that should sources emitted from industrial facilities continue to decline, over time exposures near these facilities could likely trend towards general population exposures. Recently, manufacturers of HBCD indicated that production of HBCD in the United States has ceased as discussed in Section 1.2.2. Since the initiation of this risk evaluation period in December 2016, HBCD may still be imported into the United States and handled by processing facilities. However, the amount of HBCD and the uses of HBCD in the United States may be lower when compared to past amounts and uses. Therefore, exposure potential in the future may be lower than the past. EPA has included a discussion of observed trends in monitoring data and has noted observed trends with estimated releases to the environment. While both trends suggest reduced sources of HBCD in the environment, HBCD's persistence and the potential for long-range transport, coupled with extended shelf-life of HBCD-containing articles in buildings and recycling of these same articles throughout the United States suggests that there may be a continuing sources for emission of HBCD extending into the future.

EPA also considered age-specific differences in exposure. EPA used the CHAD database (U.S. EPA, 2009a) to inform how much time individuals spend in various microenvironments. EPA used the Exposure Factors Handbook (U.S. EPA, 2011b) to inform body weights and intake rates for children and adults. This approach is described in *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d).* Table 2-72 and Table 2-73 provide an overview of exposure pathways considered for age groups.

Table 2-72. Summary of Exposure Pathway and Receptor Age Groups used in the Analysis of HBCD

Exposure Pathway	Highly Exposed	General Population	Age Groups
Dietary: **Meats** **Dairy** **Fish and Shellfish** **Fruits** **Vegetables** **Grains** **Breast Milk** **Drinking Water**	Monitoring values and modeled estimates.	Monitoring values	All age groups for all food types. Note, infants only for breast milk ingestion (no formula-fed) and individuals older than 1 for fish/shellfish ingestion.
Dust Ingestion	Monitoring values and modeled estimates from indoor sources.	Monitoring values	All age groups.
Soil Ingestion	Monitoring values and modeled estimates from outdoor sources.	Monitoring values	All age groups.
Dermal contact with Dust and Soil	Monitoring values and modeled estimates from indoor and outdoor sources.	Monitoring values	All age groups.

Exposure Pathway	Highly Exposed	General Population	Age Groups
Inhalation of Suspended Particles	Monitoring values and modeled estimates from indoor and outdoor sources.	Monitoring values	All age groups.
Biomonitoring			All age groups

Table 2-73. Summary of Exposure Pathway and Approach used in the Analysis of HBCD

Exposure Pathway	Direct Use of Reported Monitoring Data	Interpretation, Scaling of Reported Monitoring Data, Previously Completed Assessments	IECCU	IIOAC	Interpretation, Scaling of Modeled Water or Soil Concentrations with Lipid Normalized Upper Trophic Level Fish BAF Values
Dietary: **Meats** **Dairy** **Fish and Shellfish** **Fruits** **Vegetables** **Grains** **Breast Milk** **Drinking Water**	Yes	Yes			Yes
Dust Ingestion	Yes	Yes	Yes		
Soil Ingestion	Yes	Yes			
Dermal Contact with Dust and Soil	Yes	Yes			
Inhalation of Suspended Particles		Yes	Yes	Yes	
All Pathways from Human Biomonitoring Data		Yes			

IECCU - EPA's Indoor Environmental Concentrations in Buildings with Conditioned and Unconditioned Zones
IIOAC - EPA's Integrated Indoor-Outdoor Air Calculator

2.4.2.2 General Population Exposures from Environmental Monitoring and Exposure Factors and from Human Biomonitoring and Reverse Dosimetry

EPA estimated exposures to the general population in two ways and found general concordance between the approaches. First, EPA estimated exposure doses by combining environmental monitoring data (i.e., HBCD concentration in dietary sources, dust, soil, ambient air, indoor air, and dermal loading) with age specific exposure factors and activity patterns. EPA also estimated exposure doses by combining human biomonitoring data from various environmental matrices with assumptions about lipid content and generalized one-compartment half-life in the body.

Both approaches consider multiple pathways of exposure. HBCD exposures to the general population are highly variable and are influenced by both sources into the environment and degradation and removal from the environment.

EPA describes the equations and environmental monitoring data used to estimate exposures to the general population in Sections 2.4.2.2 through 2.4.2.5. In short, EPA used central tendency monitoring data rounded to one significant figure based on the range of acceptable studies for a pathway and combined that with central tendency exposure factors to derive age specific central tendency doses. EPA also assumed a lognormal distribution for monitoring data by selecting a high-end monitoring data point rounded to one significant figure. This value was assigned to the 95th percentile and the central tendency value was assigned as the geometric mean. This distribution as combined with a range of exposure factors to estimate a high-end age specific dose.

EPA describes the approach used to estimate doses based on biomonitoring below. HBCD has been quantified in human samples in blood serum in adults, cord serum, breast milk, and adipose tissue in generally small, primarily European cohorts in a range of studies. An approach to estimate external doses of HBCD based on biomonitoring data is reported in Aylward and Hays (Aylward and Hays, 2011b). A simple one-compartment model estimates a 64 day half-life of HBCD in the body. This coupled with an assumed percent lipid in the body, allows ng/g lipid weight (lw) biomonitoring values reported in various matrices to be converted to external exposure doses (mg/kg/day).

HBCD human biomonitoring data were previously extracted from peer-reviewed studies and cleaned to produce one set of summary statistics per study. A total of 53 peer-reviewed studies, resulting in 62 data sets with sampling years from 1973 to 2015, reported HBCD data in human adipose tissue, blood, breast milk, feces, fetal tissue, hair, and placental tissue across the general population, occupational workers and highly exposed populations. Table 2-74 provides the number of data sets for each population and media type. Prior to any calculations of dose, the biomonitoring data were standardized to have the same concentration units of ng/g lipid as follows:

- For data reported as ng/g whole blood or ng/g serum, it was assumed that the lipid content in whole blood and serum was 25%.
- For data reported as ng/g hair, it was assumed that the lipid content in hair was 6%
- For data reported as ng/L serum, the density of serum (1.024 g/mL as reported in Sniegoski and Moody, 1979) was used to convert volume to mass.

Table 2-74. Human HBCD Biomonitoring Data Sets by Population, Type and Number

Population	Media Type	No. of Data Sets
General	Adipose Tissue	5
General	Blood / Serum	15
General	Breast Milk	32
General	Feces	1
General	Hair	1
General	Placental / Fetal Tissue	2
Highly Exposed	Blood	2
Highly Exposed	Breast Milk	3
Occupational	Breast Milk	1

For each set of human biomonitoring data, the estimated external dose of HBCD was estimated using the approach in Aylward and Hays (Aylward and Hays, 2011a). Aylward and Hays used a basic one-compartment, first-order pharmacokinetic (PK) model to estimate chronic daily dose. The mass balance equation for change in chemical mass in one compartment is:

$$\Delta \boldsymbol{M_c} = (\boldsymbol{D} \cdot \boldsymbol{BW} \cdot \Delta \boldsymbol{t}) - (\boldsymbol{k} \cdot \boldsymbol{M_c} \cdot \Delta \boldsymbol{t})$$

where M_c is the mass of HBCD in the body [mg]
D is the chronic daily dose [mg/kg body weight/day]
BW is the body weight [kg body weight]
Δt is the change in time [days]
k is the first-order elimination rate constant [1/day]

The following equations can be substituted into the mass balance equation:

$$\boldsymbol{C} = \frac{\boldsymbol{M_c}}{\boldsymbol{M_{lipid}}}$$

$$\boldsymbol{M_{lipid}} = \boldsymbol{BW} \cdot \boldsymbol{F_l}$$

$$\boldsymbol{k} = \frac{\ln(2)}{\boldsymbol{t_{1/2}}}$$

where C is the mass of HBCD per mass of lipid in the body [mg/kg lipid]
M_{lipid} is the mass of lipid in the body [kg lipid]
F_l is the fraction of body weight that is lipid [kg lipid/kg body weight]
$t_{1/2}$ is the half-life of HBCD [days]

At steady state, this gives:

$$D = k \cdot C \cdot F_l$$

$$D = \frac{\ln(2)}{t_{1/2}} \cdot C \cdot F_l$$

In this model, the assumptions are:

- Steady state conditions
- Elimination of HBCD from the body is due to a first-order degradation progress
- HBCD distributes equally in lipid throughout the body
- No difference in toxicokinetic parameters between different HBCD isomers

The parameter values used in Aylward and Hays, and subsequently used in the EPA calculations were:

- Fraction of body weight that is lipid was assumed to be 25%
- Half-life of HBCD was previously estimated by (Geyer et al., 2004) to be 64 days with a range of 23 to 219 days. Geyer et al. calculated the half-life using HBCD concentrations in human breast milk from the literature (250-2400 ng/kg fat, mean of 700), a daily intake rate of 142 ng/day from two studies of Darnerud and Lind et al., and assuming that the fraction of dose absorbed from food was 100%.

Changes to either of the two parameters, fraction of body weight that is lipid (F_l) and HBCD half-life ($t_{1/2}$), would change the estimated dose.

The figure below shows how these two approaches compare. The overall distribution based on the biomonitoring data appears to be lognormal and the EPA estimated doses fall within the range of doses derived from. This comparison provides confidence that EPA is within the correct order of magnitude to estimate doses to the general population.

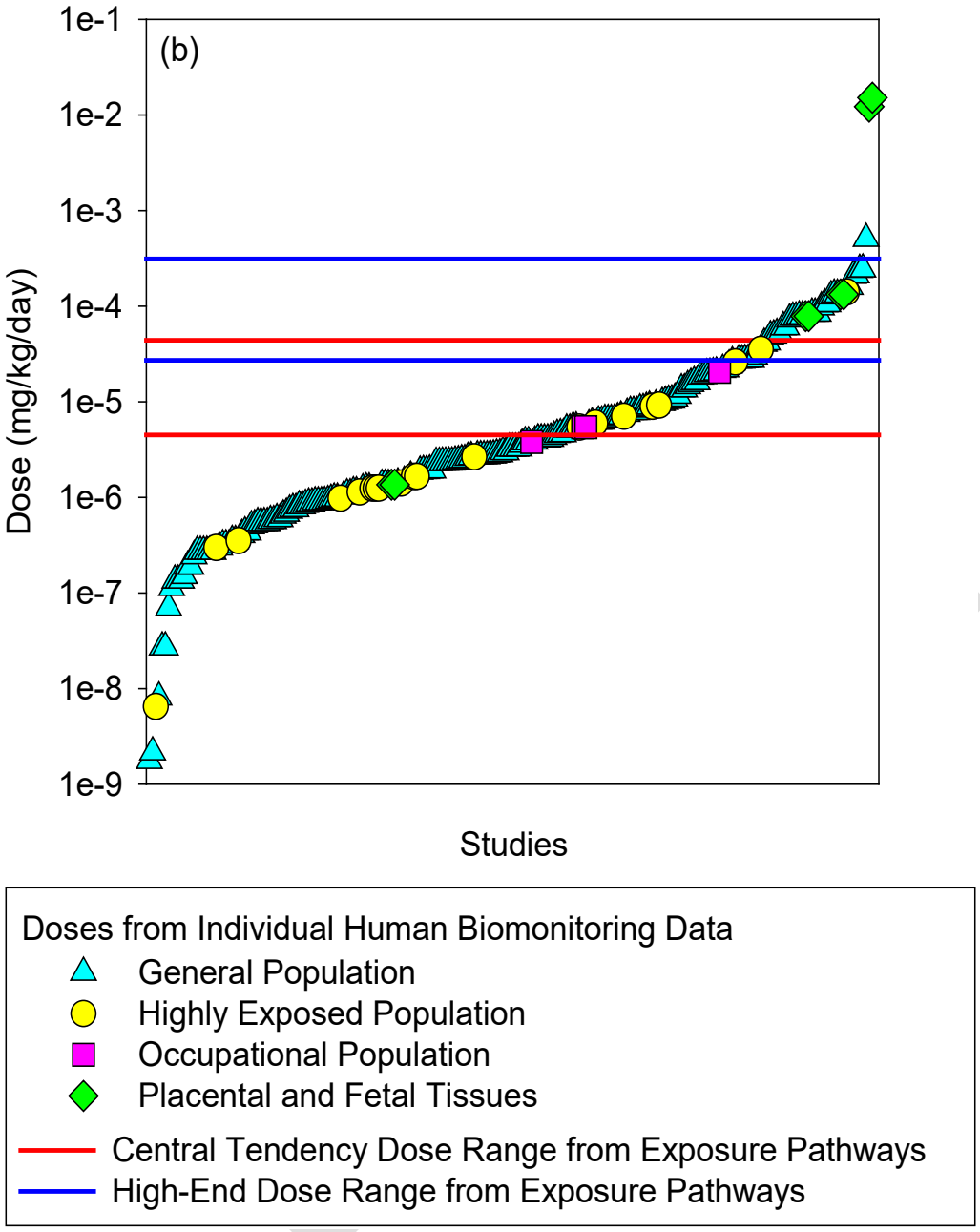

Figure 2-2. Comparison of HBCD Exposure via Environmental Monitoring/Exposure Factor and Human Biomonitoring/Reverse Dosimetry Approaches

As described earlier in the section, it is unknown how scenario-specific estimates of exposure for highly exposed populations compare to the doses estimated for the general population. It is also unknown how temporal trends will ultimately impact biomonitoring studies. One recent study from Australia has looked at biomonitoring of HBCD over time after their phase out. The authors note that while HBCD levels are starting to decline, it may be some time before levels decline significantly due to the persistence of HBCD in the body and ongoing sources of HBCD in the environment (Drage et al., 2015). This approach is for total HBCD, not specific to the isomeric forms. While not specifically addressed in

this assessment, HBCD exists in three isomeric forms (alpha, beta, gamma). The different isomeric forms have $K_{Octanol:Water}$ values that differ by more than one log unit, whose biological half-lives vary significantly (Szabo et al., 2011a; Szabo et al., 2011b, 2010). It is not known if the isomers have species specific differences in toxicokinetics or toxicodynamics between animals and humans. Given these uncertainties in the isomeric forms as well as in the pharmacokinetic data used in developing the equivalent doses, there are uncertainties in the estimated external exposure doses based on biomonitoring data. Biomonitoring studies in the literature are summarized in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d)*.. There is not a pharmacokinetic model to fully describe the relationship between HBCD dose and lipid-adjusted HBCD concentrations in humans, so therefore there is uncertainty associated with using a simpler approach to describe toxicokinetics and toxicodynamics of HBCD.

2.4.2.3 Dietary Exposure

For general population exposure, EPA estimated dietary exposure from all food groups based on monitoring data. For highly exposed groups, EPA focused on estimates from fish-ingestion. The exposure dose associated with ingesting food is generally derived by multiplying the concentration of chemical in food by the ingestion rate for that food and dividing by body weight (U.S. EPA, 1992). Within this overall framework, exposures could be estimated by grouping all foods and liquids together and using a generic overall exposure factor, disaggregating discrete food groups and using food group specific exposure factors, or estimating exposures for unique food items. For general population exposure, available monitoring data was used to estimate central tendency and high-end concentrations of HBCD in food groups. Note, that for general population estimates monitoring data based on breast milk, and purchased seafood, meat, dairy, fruits, and vegetables was used. For highly exposed groups, monitoring data based on fish-tissue concentrations as well as modeled estimates of fish tissue based on modeled concentrations of HBCD in dissolved surface water and lip normalized BAFs were used (U.S. EPA, 2007). The upper trophic level lipid normalized BAF calculated from the data of Wu et al. (Wu et al., 2010) and converted to a wet weight BAF of 46,488 was used in the exposure estimates. See Section 2.1.3.

Table 2-75 shows how these general approaches were used to estimate dietary exposures for general population and highly exposed groups.

Table 2-75: Summary of Food and Fish Concentrations used in the Analysis of HBCD

Approach	Highly Exposed	General Population
Monitored central tendency (CT) and high-end (HE) food group concentration		Yes
Full range of monitored surface water concentrations (SWC) and low-end lipid normalized upper trophic level fish BAF value to estimate fish tissue concentration	Yes	
Scenario specific modeled mean 21-day average dissolved surface water concentrations (SWC) and lipid normalized upper trophic level fish BAF value	Yes	

Equations used to estimate exposure due to dietary exposures are presented below.

For fish ingestion, when monitored or modeled surface water concentrations are available:

$$\boldsymbol{ADD = \frac{SWC \times BAF \times IR \times CF1 \times CF2 \times ED}{BW \times AT}} \qquad \textbf{Equation 2-5}$$

Where

ADD = Average daily dose due to fish ingestion (mg/kg-day)
SWC = Surface water (dissolved) concentration (µg/L)
BAF = Bioaccumulation factor (L/kg)
IR = Fish ingestion rate (g/day)
CF_1 = Conversion factor for mg/µg
CF_2 = Conversion factor for kg/g
ED = Exposure duration (year)
BW = Body weight (kg)
AT = Averaging time (year)

For all food groups, when food concentrations from monitoring data are available:

$$\boldsymbol{ADD = \frac{FC \times IR \times CF1 \times CF2 \times ED}{BW \times AT}} \qquad \textbf{Equation 2-6}$$

Where

ADD = Average daily dose due to fish ingestion (mg/kg-day)
FC = Food concentration (µg/kg)
IR = Food ingestion rate (g/day)
CF_1 = Conversion factor for mg/µg
CF_2 = Conversion factor for kg/g
ED = Exposure duration (year)
BW = Body weight (kg)
AT = Averaging time (year)

Meat, Dairy, Vegetables, Fruit, Grains, and Seafood

EPA used market basket monitoring studies to identify concentrations of HBCD present in different food groups. Note, that seafood used in this context is different from wild-fish caught in a river. Also note, that breast milk ingestion is another exposure pathway specific to infants. Both fish ingestion and breast milk ingestion are discussed later in this section.

Market-basket monitoring studies typically collect many samples and may pool similar types of foods together for chemical or statistical analysis. The levels of HBCD present in these food groups are typically lower than levels detected in wild animals and in plants. As described in section 2.4.2.1, EPA selected central tendency and high-end monitoring values, rounded to one significant figure after review and integration of all dietary monitoring data that passed data evaluation. Central tendency values were derived by taking the median of all extracted central tendency values. High-end values were derived by taking the 90th percentile of all extracted data, excluding zero values. These food concentrations are similar to previous estimates based on a study by Barghi et al. (Barghi et al., 2016).

The following data was used in EPA's assessment of dietary exposure for the general population.

Table 2-76. Dietary Ingestion Rates

Parameter	Central Tendency	High-End
Fruits, Vegetables, and Grains Concentration (mg/g wet weight)	1.0E-7	7.2E-7
Ingestion Rate of Fruits, Vegetables, and Grains[a] (g/kg day)		
Infants (< 1 year)	20.5	54.6
Young Toddlers (1 - < 2 years)	22.9	53
Toddlers (2 - < 3 years)	20.1	46.2
Small Children (3 - < 6 years)	17.1	40.2
Children (6 - < 11 years)	11.6	28.6
Teenagers (11 - < 16 years)	6.7	17.2
Adults (16 - < 70 years)	5.9	15
Meat, Dairy, Fat - mg/g wet weight	1.3E-7	1.0E-6
Ingestion Rate of Meat, Dairy, Fat[a] (g/kg day)		
Infants (< 1 year)	16.1	73.1
Young Toddlers (1 - < 2 years)	52.9	110.1
Toddlers (2 - < 3 years)	40.4	88.3
Small Children (3 - < 6 years)	26.6	60.1
Children (6 - < 11 years)	16.8	38.5
Teenagers (11 - < 16 years)	9	23.1
Adults (16 - < 70 years)	5	13.8
Fish/Shellfish (from store-not wild) - mg/g wet weight	2.6E-7	2.1E-6
Ingestion Rate of Fish/Shellfish[b] (g/kg day)		
Young Toddlers (1 - < 2 years)	0.052	0.41
Toddlers (2 - < 3 years)	0.043	0.34
Small Children (3 - < 6 years)	0.037	0.31
Children (6 - < 11 years)	0.034	0.24
Teenagers (11 - < 16 years)	0.019	0.14
Adults (16 - < 70 years)	0.063	0.27

[a] (U.S. EPA, 2011b)
[b] (U.S. EPA, 2014b)

Table 2-77 presents the values that were used in the equations to estimate exposure from fish ingestion.

Table 2-77. Summary of Values for Estimating HBCD Fish Ingestion Dose

	Fish Concentration (mg/kg) wet weight	Reference
Range (median) of All Values from Monitoring Data	2.5E-8 to 1.0E+1 (1.1E-3)	See(U.S. EPA, 2019d)
Range (median) of Central Tendency Values from Monitoring Data	2.0E-6 to 3.2E+0 (1.6E-3)	See (U.S. EPA, 2019d)
Range (median) of Modeled Fish Tissue Concentration	5.4E-2 to 1.6E+3 (2.6E+0)	PSC with lipid normalized upper trophic level fish BAF
Range (median) of Modeled Fish Tissue Concentration (Central)	5.4E-2 to 7.1E+1 (5.6E-1)	PSC with lipid normalized upper trophic level fish BAF

EPA assumed that children in the highly exposed group live near a facility with elevated concentrations of HBCD for the entire duration of that life stage. EPA assumed that adults in the highly exposed group live near a facility for a portion of their adult life, depending on whether it was high-end or a central tendency estimate. The upper-end estimate for residential mobility is 33 years and was selected for a high-end exposure duration (U.S. EPA, 2011b). For a central tendency estimate for residential mobility, a value of 13 years was selected (U.S. EPA, 2011b). For the other portion of their adult life, it was assumed that they were exposed to central tendency fish-tissue concentration values based on monitoring data.

Fish concentrations were reported in the literature on a lipid weight and wet weight basis. Species-specific lipid content as reported by the individual studies, was not collected. Lipid content in fish ranges from <1% to 15% (U.S. EPA, 2011b). To convert from lipid concentration to wet weight concentration, the following equation is used.

$$\boldsymbol{Conc, ww = Conc, lw \times \frac{\%\ lipid}{100\%}} \qquad \textbf{Equation 2-7}$$

Where

Conc, ww = Concentration on a wet weight basis, µg/kg ww
Conc, lw = Concentration on a lipid weight basis, µg/kg lw
% lipid = Percentage of fish that is comprised of lipids

EPA used reported lipid weight values in deriving a BAF number. EPA used a generic default of 5% lipid content for any monitoring study that only reported fish-tissue data in wet weight and did not provide enough detail on lipid-weight to estimate a lipid weight concentration.

Fish-tissue concentrations can be derived by multiplying dissolved surface water concentration values BCF or BAF values. A wide range of BCF and BAF values are available in the literature. EPA chose a BAF value at the low-end of the reported range. This was done because the modeled dissolved surface water estimates are generally larger than values reported in the literature. Pairing a higher lipid

normalized upper trophic level fish BAF value with higher surface water values could result in unreasonably high estimated fish-tissue concentrations. EPA compared the range of reported fish-tissue concentrations from monitoring data and found the modeled fish tissue concentrations (range of modeled dissolved surface water and low-end lipid normalized upper trophic level fish BAF) to be of a similar order of magnitude. Note, for human exposure estimation estimates of wet-weight fish tissue concentration need to be matched with exposure factors (intake rates) that are also in wet weight. Use of lipid weight or lipid normalized concentrations is considered in the ecological exposure and risk assessment sections. See Section 2.4.4 regarding a qualitative sensitivity analysis for BCF and BAF values.

In addition to reviewing the studies, the following key studies provide additional information on HBCD levels in fish. (Chen et al., 2011) noted temporal and spatial trends for HBCD concentrations in fish. In Hyco River samples collected in Virginia, the authors note an increase in HBCD concentrations in carp, catfish, redhorse sucker, gizzard shad, and flathead catfish. Across all samples, mean HBCD concentrations ranged from ND to 22 µg/kg lw in 1999-2002 samples and increased to 13 to 4,640 µg/kg lw. Assuming 10% lipid, this converts to 1.3e-6 µg/mg ww to 4.64e-4 µg/mg ww.

In addition, (Chen et al., 2011) conducted a meta-analysis of their present study and seventeen other studies to see if near-facility concentrations in fish differed from fish samples collected further away from facilities. The authors report that concentrations in fish sampled near point sources were generally 1 to 2 orders of magnitude higher than fish located further away from sources. (Chen et al., 2011) reported fish concentrations near point sources ranging from 38 to 6,660 µg/kg lw (3.8E-6 to 6.6E-4 µg/mg ww) and concentrations in fish from more remote areas ranging from 0.1 to 51.5 µg/kg lw (1.0E-8 to 5.2E-6 µg/mg lw).

(Allchin and Morris, 2003) reported HBCD concentrations in eel and trout from eight sampling locations along industrialized rivers in the UK. HBCD concentrations in eel ranged from 3.9e-5 to 1.0e-2 µg/mg ww, with average values ranging from 3.4E-4 to 4.7E-4 µg/mg ww. HBCD concentrations in trout ranged from <1.2E-6 µg/mg ww to 6.8E-3 µg/mg ww, with average values ranging from 2.0E-5 to 2.3E-3 µg/mg ww.

Dietary Exposure from HBCD Emitted from Point Sources

Scenario from Table 2-70	Source	Pathway	Receptor	Approach
A1	HBCD emitted from any point source during its lifecycle from Scenarios described in Section 2.2	Emission into water and uptake into fish tissue	Children, adults (including highly exposed subsistence fishers and tribes)	Quantitative, PSC and lipid normalized upper trophic level fish BAF, Monitoring

EPA estimated wet weight fish tissue concentrations using 21-day average mean flow modeled dissolved water concentrations from PSC modeling and a low-end lipid normalized upper trophic level fish BAF value. All scenarios from Section 2.2 were modeled. Description of sub-scenarios are provided in Section 2.3.1.

Table 2-78. Estimated HBCD Dissolved Water Concentrations and Fish Tissue Concentrations

Scenario Label	Water Column (µg/L) 21 day average Mean Flow (50th percentile)	Water Column (µg/L) 21 day average Mean Flow (10th percentile)	Fish Tissue Concentration (mg/kg) Mean Flow (50th percentile)	Fish Tissue Concentration (mg/kg) Mean Flow (10th percentile)
1.1	1.1E-02	2.5E-01	5.2E-01	1.2E+01
1.2	9.2E-03	2.1E-01	4.3E-01	9.5E+00
1.3	5.6E-02	1.2E+00	2.6E+00	5.8E+01
1.4	4.6E-02	1.0E+00	2.2E+00	4.6E+01
1.5	5.2E-02	2.8E-01	2.4E+00	1.3E+01
1.6	4.2E-02	2.3E-01	2.0E+00	1.1E+01
1.7	2.6E-01	1.4E+00	1.2E+01	6.5E+01
1.8	2.1E-01	1.2E+00	9.9E+00	5.4E+01
2.1	5.4E-03	1.2E-01	2.5E-01	5.5E+00
2.2	3.5E-03	7.8E-02	1.6E-01	3.6E+00
2.3	1.2E-02	2.7E-01	5.6E-01	1.2E+01
2.4	8.1E-03	1.8E-01	3.8E-01	8.3E+00
2.7	1.2E-03	2.7E-02	5.6E-02	1.2E+00
2.11	5.6E-03	3.0E-02	2.6E-01	1.4E+00
3.1	1.8E-02	3.8E-01	8.1E-01	1.8E+01
3.2	1.2E-03	2.6E-02	5.4E-02	1.2E+00
3.3	4.3E-02	9.2E-01	2.0E+00	4.3E+01
3.4	2.9E-03	6.4E-02	1.3E-01	3.0E+00
3.5	1.8E-03	3.8E-02	8.1E-02	1.8E+00
3.7	4.3E-03	9.2E-02	2.0E-01	4.3E+00
3.9	8.0E-03	4.2E-02	3.7E-01	2.0E+00
3.11	2.0E-02	1.0E-01	9.1E-01	4.8E+00
4.1	1.7E-02	3.6E-01	7.8E-01	1.7E+01
4.2	1.4E-03	3.1E-02	6.5E-02	1.4E+00
4.3	1.7E-03	3.6E-02	7.8E-02	1.7E+00
4.5	7.6E-03	4.0E-02	3.5E-01	1.9E+00
5.1	1.1E+00	2.5E+01	5.2E+01	1.2E+03
5.2	1.1E-01	2.5E+00	5.2E+00	1.2E+02
5.3	5.1E-01	2.8E+00	2.4E+01	1.3E+02
5.4	9.0E-01	2.0E+01	4.2E+01	9.3E+02
5.5	9.0E-02	2.0E+00	4.2E+00	9.3E+01
5.6	4.1E-01	2.2E+00	1.9E+01	1.0E+02
5.7	1.5E+00	3.4E+01	7.1E+01	1.6E+03
5.8	1.5E-01	3.4E+00	7.1E+00	1.6E+02
5.9	7.0E-01	3.8E+00	3.3E+01	1.8E+02
5.1	1.2E+00	2.7E+01	5.7E+01	1.3E+03

Scenario Label	Water Column (µg/L) 21 day average Mean Flow (50th percentile)	Water Column (µg/L) 21 day average Mean Flow (10th percentile)	Fish Tissue Concentration (mg/kg) Mean Flow (50th percentile)	Fish Tissue Concentration (mg/kg) Mean Flow (10th percentile)
5.11	1.2E-01	2.7E+00	5.7E+00	1.3E+02
5.12	5.6E-01	3.1E+00	2.6E+01	1.4E+02
6.1	5.2E-03	1.1E-01	2.4E-01	5.3E+00
6.4	5.0E-03	1.1E-01	2.3E-01	5.1E+00
6.7	2.3E-02	5.1E-01	1.1E+00	2.4E+01
6.8	2.3E-03	5.1E-02	1.1E-01	2.4E+00
6.9	1.1E-02	5.7E-02	4.9E-01	2.7E+00
6.1	2.2E-02	4.9E-01	1.0E+00	2.3E+01
6.11	2.2E-03	4.9E-02	1.0E-01	2.3E+00
6.12	1.0E-02	5.5E-02	4.7E-01	2.6E+00
8.3	3.7E-03	2.8E-02	1.7E-01	1.3E+00
10.1	2.4E-02	5.2E-01	1.1E+00	2.4E+01
10.2	2.4E-03	5.2E-02	1.1E-01	2.4E+00
10.3	1.1E-02	5.8E-02	5.1E-01	2.7E+00
10.4	1.2E-03	2.7E-02	5.6E-02	1.3E+00
10.7	2.9E-02	6.2E-01	1.3E+00	2.9E+01
10.8	2.9E-03	6.2E-02	1.3E-01	2.9E+00
10.9	1.3E-02	6.9E-02	6.0E-01	3.2E+00
10.10	1.4E-03	3.2E-02	6.7E-02	1.5E+00

The following three figures show the range of potential fish ingestion doses using three approaches. EPA used modeled surface water estimates plus lipid normalized upper trophic level fish BAF as described above. EPA also used all available fish-tissue monitoring data to estimate possible dose ranges. EPA also used all reported surface water monitoring data plus lipid normalized upper trophic level fish BAF to estimate possible dose range. While the modeled estimates apply to a smaller population who live near a facility and may ingest fish caught within proximity to the river, the fish ingestion estimates based on monitoring data apply to whatever conditions were present when those samples were taken.

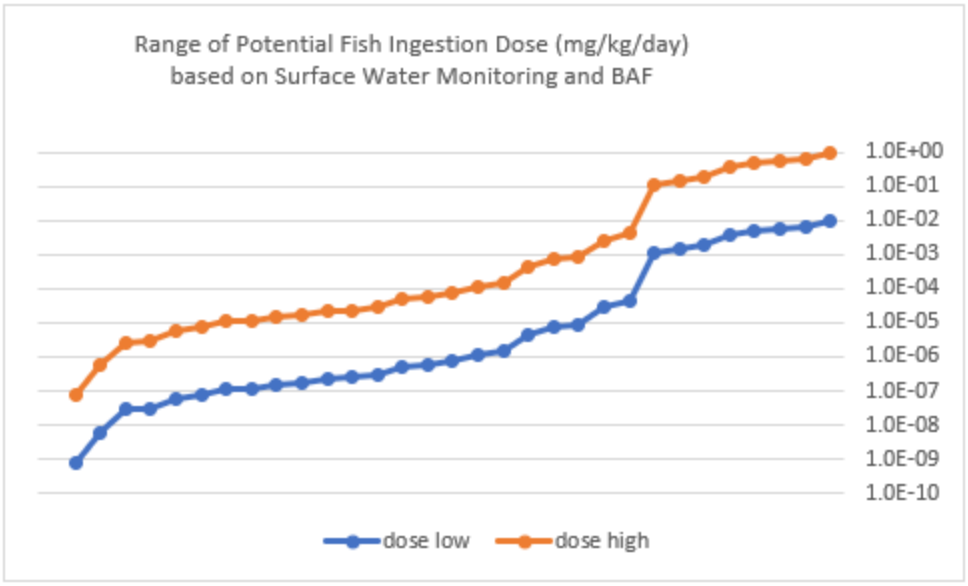

Figure 2-3. Range of Potential HBCD Fish Ingestion Dose based on Surface Water Monitoring and Lipid Normalized Upper Trophic Level Fish BAF (mg/kg/day)

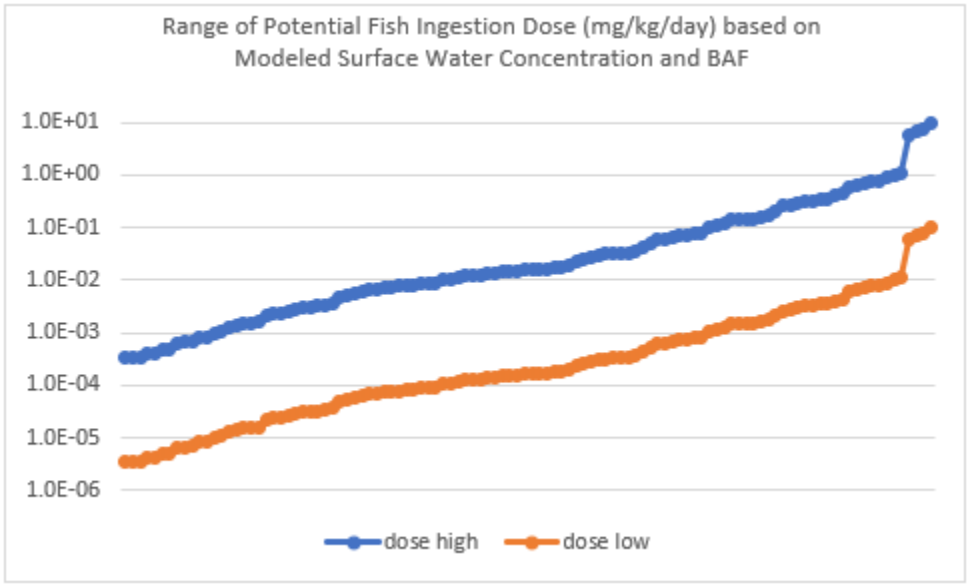

Figure 2-4. Range of Potential HBCD Fish Ingestion Dose based on Modeled Surface Water Concentrations and Lipid Normalized Upper Trophic Level Fish BAF (mg/kg/day)

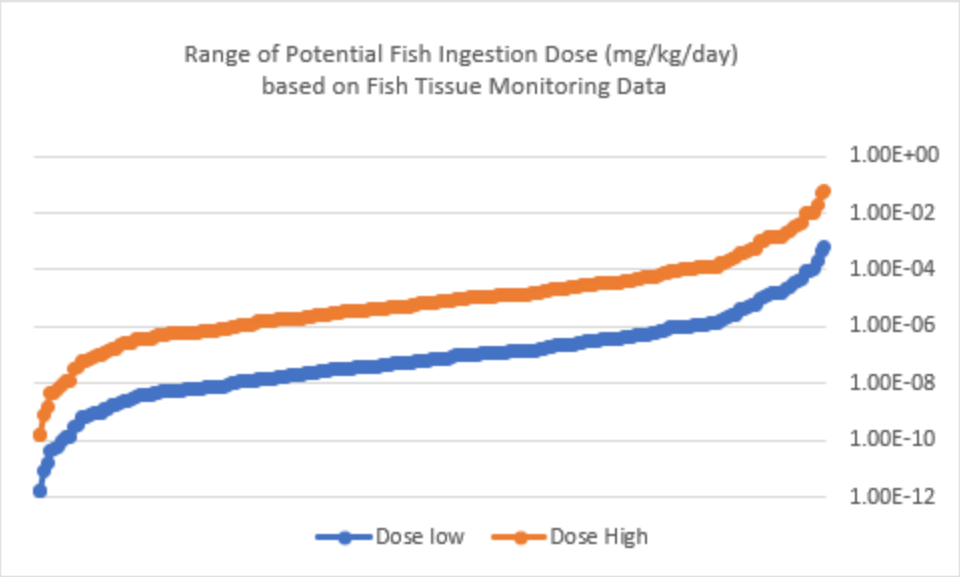

Figure 2-5. Range of Potential HBCD Fish Ingestion Dose based on Fish Tissue Monitoring Data

EPA selected high-end fish ingestion rates for calculation of ADR values in order to represent acute exposures. ADD values representing chronic exposure utilized central-tendency fish ingestion rates, which are expected to be more representative of the most populations over a sustained period. Estimated fish ingestion doses for all lifestages are presented in Table 2-79.

Table 2-79. HBCD: Acute Dose Rate and Average Daily Doses (mg/kg/day) for Fish Ingestion for All Lifestages

Scenario Label	Young Toddler (1 - < 2 years)		Toddler (2 - < 3 years)		Small Child (3 - < 6 years)		Child (6 - < 11 years)		Teen (11 - < 16 years)		Adult (16 - < 70 years)		
	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD (HE)	ADD (CT)
1.1	4.8E-03	2.7E-05	3.9E-03	2.3E-05	3.6E-03	2.0E-05	2.8E-03	1.8E-05	1.7E-03	1.0E-05	3.2E-03	1.4E-05	5.5E-06
1.2	3.9E-03	2.3E-05	3.3E-03	1.9E-05	3.0E-03	1.6E-05	2.3E-03	1.5E-05	1.4E-03	8.3E-06	2.7E-03	1.1E-05	4.5E-06
1.3	2.4E-02	1.4E-04	2.0E-02	1.1E-04	1.8E-02	9.9E-05	1.4E-02	9.1E-05	8.5E-03	5.1E-05	1.6E-02	7.0E-05	2.8E-05
1.4	1.9E-02	1.1E-04	1.6E-02	9.4E-05	1.5E-02	8.1E-05	1.1E-02	7.5E-05	6.8E-03	4.2E-05	1.3E-02	5.8E-05	2.3E-05
1.5	5.4E-03	1.3E-04	4.4E-03	1.0E-04	4.1E-03	9.0E-05	3.1E-03	8.3E-05	1.9E-03	4.6E-05	3.6E-03	6.4E-05	2.5E-05
1.6	4.4E-03	1.0E-04	3.6E-03	8.5E-05	3.3E-03	7.4E-05	2.6E-03	6.8E-05	1.6E-03	3.8E-05	3.0E-03	5.2E-05	2.1E-05
1.7	2.7E-02	6.3E-04	2.2E-02	5.2E-04	2.0E-02	4.5E-04	1.6E-02	4.2E-04	9.5E-03	2.3E-04	1.8E-02	3.2E-04	1.3E-04
1.8	2.2E-02	5.2E-04	1.8E-02	4.3E-04	1.7E-02	3.7E-04	1.3E-02	3.4E-04	7.9E-03	1.9E-04	1.5E-02	2.6E-04	1.0E-04
2.1	2.3E-03	1.3E-05	1.9E-03	1.1E-05	1.7E-03	9.5E-06	1.3E-03	8.7E-06	8.0E-04	4.9E-06	1.5E-03	6.7E-06	2.6E-06
2.2	1.5E-03	8.6E-06	1.2E-03	7.1E-06	1.1E-03	6.1E-06	8.8E-04	5.6E-06	5.3E-04	3.2E-06	1.0E-03	4.4E-06	1.7E-06
2.3	5.1E-03	3.0E-05	4.2E-03	2.5E-05	3.9E-03	2.1E-05	3.0E-03	2.0E-05	1.8E-03	1.1E-05	3.4E-03	1.5E-05	5.9E-06
2.4	3.4E-03	2.0E-05	2.8E-03	1.6E-05	2.6E-03	1.4E-05	2.0E-03	1.3E-05	1.2E-03	7.3E-06	2.3E-03	1.0E-05	4.0E-06
2.7	5.1E-04	3.0E-06	4.2E-04	2.5E-06	3.9E-04	2.1E-06	3.0E-04	2.0E-06	1.8E-04	1.1E-06	3.4E-04	1.5E-06	5.9E-07
2.11	5.7E-04	1.4E-05	4.7E-04	1.1E-05	4.3E-04	9.7E-06	3.4E-04	8.9E-06	2.0E-04	5.0E-06	3.9E-04	6.9E-06	2.7E-06
3.1	7.2E-03	4.3E-05	6.0E-03	3.5E-05	5.5E-03	3.1E-05	4.2E-03	2.8E-05	2.6E-03	1.6E-05	4.9E-03	2.2E-05	8.6E-06
3.2	5.0E-04	2.9E-06	4.1E-04	2.4E-06	3.8E-04	2.1E-06	2.9E-04	1.9E-06	1.8E-04	1.1E-06	3.4E-04	1.5E-06	5.7E-07
3.3	1.8E-02	1.1E-04	1.5E-02	8.7E-05	1.3E-02	7.5E-05	1.0E-02	6.9E-05	6.3E-03	3.9E-05	1.2E-02	5.3E-05	2.1E-05
3.4	1.2E-03	7.1E-06	1.0E-03	5.8E-06	9.3E-04	5.0E-06	7.2E-04	4.6E-06	4.4E-04	2.6E-06	8.3E-04	3.6E-06	1.4E-06
3.5	7.2E-04	4.3E-06	6.0E-04	3.5E-06	5.5E-04	3.1E-06	4.2E-04	2.8E-06	2.6E-04	1.6E-06	4.9E-04	2.2E-06	8.6E-07
3.7	1.8E-03	1.1E-05	1.5E-03	8.7E-06	1.3E-03	7.5E-06	1.0E-03	6.9E-06	6.3E-04	3.9E-06	1.2E-03	5.3E-06	2.1E-06
3.9	8.1E-04	2.0E-05	6.7E-04	1.6E-05	6.1E-04	1.4E-05	4.7E-04	1.3E-05	2.9E-04	7.2E-06	5.4E-04	9.9E-06	3.9E-06
3.11	2.0E-03	4.8E-05	1.6E-03	3.9E-05	1.5E-03	3.4E-05	1.2E-03	3.1E-05	7.0E-04	1.8E-05	1.3E-03	2.4E-05	9.6E-06
4.1	6.9E-03	4.1E-05	5.7E-03	3.4E-05	5.2E-03	2.9E-05	4.0E-03	2.7E-05	2.4E-03	1.5E-05	4.6E-03	2.1E-05	8.2E-06
4.2	5.9E-04	3.4E-06	4.9E-04	2.8E-06	4.5E-04	2.5E-06	3.5E-04	2.3E-06	2.1E-04	1.3E-06	4.0E-04	1.7E-06	6.9E-07
4.3	6.9E-04	4.1E-06	5.7E-04	3.4E-06	5.2E-04	2.9E-06	4.0E-04	2.7E-06	2.4E-04	1.5E-06	4.6E-04	2.1E-06	8.2E-07
4.5	7.7E-04	1.9E-05	6.4E-04	1.5E-05	5.8E-04	1.3E-05	4.5E-04	1.2E-05	2.7E-04	6.8E-06	5.2E-04	9.5E-06	3.7E-06

Scenario Label	Young Toddler (1 - < 2 years)		Toddler (2 - < 3 years)		Small Child (3 - < 6 years)		Child (6 - < 11 years)		Teen (11 - < 16 years)		Adult (16 - < 70 years)		
	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD (HE)	ADD (CT)
5.1	4.8E-01	2.7E-03	3.9E-01	2.3E-03	3.6E-01	2.0E-03	2.8E-01	1.8E-03	1.7E-01	1.0E-03	3.2E-01	1.4E-03	5.5E-04
5.2	4.8E-02	2.7E-04	3.9E-02	2.3E-04	3.6E-02	2.0E-04	2.79E-02	1.80E-04	1.69E-02	1.01E-04	3.21E-02	1.39E-04	5.49E-05
5.3	5.3E-02	1.3E-03	4.4E-02	1.0E-03	4.0E-02	9.0E-04	3.14E-02	8.25E-04	1.89E-02	4.62E-04	3.60E-02	6.38E-04	2.51E-04
5.4	3.8E-01	2.2E-03	3.2E-01	1.8E-03	2.9E-01	1.6E-03	2.25E-01	1.44E-03	1.36E-01	8.08E-04	2.58E-01	1.12E-03	4.39E-04
5.5	3.8E-02	2.2E-04	3.2E-02	1.8E-04	2.9E-02	1.6E-04	2.25E-02	1.44E-04	1.36E-02	8.08E-05	2.58E-02	1.12E-04	4.39E-05
5.6	4.3E-02	1.0E-03	3.6E-02	8.3E-04	3.3E-02	7.2E-04	2.52E-02	6.61E-04	1.52E-02	3.70E-04	2.90E-02	5.11E-04	2.01E-04
5.7	6.5E-01	3.7E-03	5.4E-01	3.1E-03	4.9E-01	2.7E-03	3.82E-01	2.46E-03	2.30E-01	1.38E-03	4.38E-01	1.90E-03	7.49E-04
5.8	6.5E-02	3.7E-04	5.4E-02	3.1E-04	4.9E-02	2.7E-04	3.82E-02	2.46E-04	2.30E-02	1.38E-04	4.38E-02	1.90E-04	7.49E-05
5.9	7.3E-02	1.7E-03	6.0E-02	1.4E-03	5.5E-02	1.2E-03	4.29E-02	1.13E-03	2.59E-02	6.31E-04	4.92E-02	8.72E-04	3.43E-04
5.10	5.2E-01	3.0E-03	4.3E-01	2.5E-03	4.0E-01	2.2E-03	3.07E-01	1.98E-03	1.85E-01	1.11E-03	3.52E-01	1.53E-03	6.02E-04
5.11	5.2E-02	3.0E-04	4.3E-02	2.5E-04	4.0E-02	2.2E-04	3.07E-02	1.98E-04	1.85E-02	1.11E-04	3.52E-02	1.53E-04	6.02E-05
5.12	5.9E-02	1.4E-03	4.9E-02	1.1E-03	4.4E-02	9.8E-04	3.45E-02	9.04E-04	2.08E-02	5.06E-04	3.96E-02	6.99E-04	2.75E-04
6.1	2.2E-03	1.3E-05	1.8E-03	1.0E-05	1.7E-03	9.0E-06	1.29E-03	8.28E-06	7.76E-04	4.64E-06	1.48E-03	6.40E-06	2.52E-06
6.4	2.1E-03	1.2E-05	1.7E-03	1.0E-05	1.6E-03	8.7E-06	1.24E-03	7.96E-06	7.46E-04	4.46E-06	1.42E-03	6.15E-06	2.42E-06
6.7	9.8E-03	5.6E-05	8.1E-03	4.7E-05	7.4E-03	4.0E-05	5.73E-03	3.70E-05	3.46E-03	2.07E-05	6.58E-03	2.86E-05	1.13E-05
6.8	9.8E-04	5.6E-06	8.1E-04	4.7E-06	7.4E-04	4.0E-06	5.73E-04	3.70E-06	3.46E-04	2.07E-06	6.58E-04	2.86E-06	1.13E-06
6.9	1.1E-03	2.6E-05	9.1E-04	2.1E-05	8.3E-04	1.8E-05	6.44E-04	1.69E-05	3.89E-04	9.45E-06	7.39E-04	1.31E-05	5.14E-06
6.10	9.4E-03	5.4E-05	7.8E-03	4.5E-05	7.1E-03	3.9E-05	5.51E-03	3.54E-05	3.33E-03	1.98E-05	6.33E-03	2.74E-05	1.08E-05
6.11	9.4E-04	5.4E-06	7.8E-04	4.5E-06	7.1E-04	3.9E-06	5.51E-04	3.54E-06	3.33E-04	1.98E-06	6.33E-04	2.74E-06	1.08E-06
6.12	1.1E-03	2.5E-05	8.7E-04	2.0E-05	8.0E-04	1.8E-05	6.19E-04	1.62E-05	3.74E-04	9.09E-06	7.11E-04	1.26E-05	4.95E-06
8.3	5.3E-04	9.2E-06	4.4E-04	7.6E-06	4.0E-04	6.5E-06	3.13E-04	6.01E-06	1.89E-04	3.37E-06	3.59E-04	4.65E-06	1.83E-06
10.1	9.9E-03	5.9E-05	8.2E-03	4.9E-05	7.5E-03	4.2E-05	5.82E-03	3.86E-05	3.51E-03	2.16E-05	6.68E-03	2.98E-05	1.18E-05
10.2	9.9E-04	5.9E-06	8.2E-04	4.9E-06	7.5E-04	4.2E-06	5.82E-04	3.86E-06	3.51E-04	2.16E-06	6.68E-04	2.98E-06	1.18E-06
10.3	1.1E-03	2.7E-05	9.2E-04	2.2E-05	8.4E-04	1.9E-05	6.51E-04	1.75E-05	3.93E-04	9.81E-06	7.47E-04	1.36E-05	5.34E-06
10.4	5.1E-04	2.9E-06	4.2E-04	2.4E-06	3.9E-04	2.1E-06	3.02E-04	1.93E-06	1.82E-04	1.08E-06	3.46E-04	1.49E-06	5.88E-07
10.7	1.2E-02	7.0E-05	9.7E-03	5.8E-05	8.9E-03	5.0E-05	6.93E-03	4.60E-05	4.18E-03	2.57E-05	7.95E-03	3.56E-05	1.40E-05
10.8	1.2E-03	7.0E-06	9.7E-04	5.8E-06	8.9E-04	5.0E-06	6.93E-04	4.60E-06	4.18E-04	2.57E-06	7.95E-04	3.56E-06	1.40E-06

Scenario Label	Young Toddler (1 - < 2 years)		Toddler (2 - < 3 years)		Small Child (3 - < 6 years)		Child (6 - < 11 years)		Teen (11 - < 16 years)		Adult (16 - < 70 years)		
	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD	ADR	ADD (HE)	ADD (CT)
10.9	1.3E-03	3.2E-05	1.1E-03	2.6E-05	1.0E-03	2.3E-05	7.74E-04	2.09E-05	4.67E-04	1.17E-05	8.89E-04	1.62E-05	6.37E-06
10.10	6.1E-04	3.5E-06	5.0E-04	2.9E-06	4.6E-04	2.5E-06	3.58E-04	2.30E-06	2.16E-04	1.29E-06	4.11E-04	1.78E-06	7.00E-07
Notes: ADR = acute dose rate; ADD = average daily dose; HE = high end residency, CT = central tendency residency													

Table 2-80. Summary of HBCD Fish Concentration Data for Estimating Fish Ingestion Dose

	Fish Tissue Concentration	Reference	Systematic Review Score
Range of Fish Concentrations Away from Point Sources	ND – 30317 (ng/g lipid) ND – 10275 (ng/g wet weight)	(Köppen et al., 2010); (Allchin and Morris, 2003)	Medium; Medium
Range of Central Tendency Values of Fish Concentrations Away from Point Sources	1.57E-2 – 3216 (ng/g lipid) 0.24 – 6846 (ng/g wet weight)	(Meng et al., 2012); (Allchin and Morris, 2003); (Sudaryanto et al., 2007); (Köppen et al., 2010)	High; Medium; Medium; Medium
Range of Fish Concentrations Near Point Sources	10 – 13 (ng/g lipid weight)	(Chokwe et al., 2015)	High
Range of Central Tendency Values of Fish Concentrations Near Point Sources	89.5 – 554.4 (ng/g wet weight)	(Eljarrat et al., 2004)	Medium
Range of Modeled Fish Tissue Concentrations	54 – 1.6E6 (ng/g wet weight)	PSC with lipid normalized upper trophic level fish BAF	

Breast Milk Exposure

There are approximately 30 studies reporting HBCD concentrations in breast milk. Within those studies there is a wide range of concentrations, although there is general concordance across studies at central tendency. There were three key studies that provide a reasonable cross-section of available data sources.

The highest concentrations were observed by Eljarrat et al. (2009b), in which HBCD was measured in milk samples collected from women in Spain, ranging from ND to 188 µg/kg lw, with an average of 47 µg/kg lw and a median of 27 µg/kg lw. Another study by Eggesbo et al. (2011), collected milk samples from 193 mothers as part of the Norwegian Human Milk Study. HBCD levels in breast milk ranged from 0.1 to 31 µg/kg lw, with an average of 1.1 µg/kg lw. In the United States, Carignan et al. (2012a) measured HBCD in the breast milk of 43 mothers. HBCD was detected in all samples with concentrations ranging from 0.36 to 8.1 µg/kg lw, with a geometric mean of 1.02 µg/kg lw.

Table 2-81. Summary of HBCD Breast Milk Concentration Data for Estimating Breast Milk Ingestion Dose

	Breast Milk Concentration (ng/g)	Reference	Systematic Review Score
Range of All Values from Monitoring Data	ND - 188	(Eljarrat et al., 2009a)	High
Range of Central Tendency Values from Monitoring Data	2.5E-2- 47	(Devanathan et al., 2012); (Eljarrat et al., 2009a)	Medium; Medium
Range of Breast Milk Concentrations from Key Studies (Central Tendency Values)	0.1 - 31 (1.1, 0.54)	(Eggesbø et al., 2011)	Medium
	0.36 - 8.1 (1.02)	(Carignan et al., 2012b)	High
	ND - 188 (47, 27)	(Eljarrat et al., 2009a)	High

The equation used to estimate exposure from ingestion of breastmilk is below.

$$ADD = \frac{BMC \times BMR}{BW}$$ **Equation 2-8**

Where

ADD = Average daily dose due to ingestion of breastmilk (mg/kg-day)
BMC = Chemical concentration in breastmilk lipids (mg/g)
BMR = Breastmilk lipid ingestion rate (g/day)
BW = Body weight (kg)

Parameters and data sources used as inputs into this equation are provided in Table 2-82. Additional detail is provided in *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d).*

Table 2-82. Concentrations Used to Estimate HBCD Breast Milk Ingestion

Parameter	Central Tendency	High-End
Breast Milk Concentration µg/g (µg/kg) lipid	1.0E-03 (1)	5.0E-02 (50)
Ingestion Rate of Breast Milk Lipid (mg/L)	26	41.5

EPA considered ingestion of drinking water but did not quantify those concentrations in this risk evaluation. The concentration of HBCD in surface water is generally low and monitored levels of HBCD in drinking water are unavailable. Other assessments have included drinking water as a pathway and noted that expected exposures are quite low. The following exposure pathways are possible:

1. Ingestion of finished water at the tap, expected HBCD levels are low
2. Ingestion of surface water, including suspended sediment, during recreation in lakes and rivers. HBCD levels are likely slightly more elevated than drinking water but intake rates and frequency of exposure are lower.

A qualitative discussion of this is included in Section 2.4.2.7.

2.4.2.4 Dust and Soil Ingestion

The exposure dose associated with incidentally ingested dust and soil is generally derived by multiplying the chemical concentration in dust or soil by the empirically derived ingestion rate of dust or soil and dividing by body weight (U.S. EPA, 1992). The ingestion rate can be derived through tracer methods which measure tracer chemicals present both in soil and dust and in the urine and feces of humans and through biokinetic methods that use biomonitoring data and physiologically based pharmacokinetic (PBPK) models to back-calculate ingestion rates. An activity-pattern based method models hand-to-mouth and object-to-mouth contact to derive transfer rates of soil and dust to the mouth to estimate ingestion rate (Moya and Phillips, 2014). Estimated ingestion rates based on the activity-pattern method are informed by empirically and estimated variables (Ozkaynak et al., 2011) including:

- Hand and object to mouth frequency indoors and outdoors
- Dust loading
- Object: floor dust loading ratio
- Soil skin adherence rate
- Skin/soil surface contact rate
- Maximum dermal loading of soil loading on hands
- Surface to hand dust transfer efficiency
- Hand to mouth and object to mouth transfer efficiency
- Area of object mouthed and fraction of hand mouthed/event
- Bath and hand wash removal efficiency and frequency

Chemical concentrations in dust or soil are required for the tracer and biokinetic methods. Loadings of a chemical in dust or soil are required for the activity-pattern method. The chemical concentration in dust or soil is defined as the mass of chemical present per mass of dust or soil. The chemical loading in dust is defined as the mass of chemical per surface area.

These terms are all related, but often only one of the three is reported in monitoring studies. If the surface area units are the same for loadings, the chemical dust loading divided by the total dust loading is equal to the chemical concentration. However, dust loadings of overall dustiness can also vary substantially by building or within a building. If paired chemical dust loading and chemical concentration data are available, an empirical relationship can be used to derive a relationship and conversion equation.

When an activity pattern method is used an overall dust or soil factor (units surface area/time) that incorporates variability from the bulleted list above can be used to estimate intake.

Equations used to estimate soil and dust ingestion are reported below. Note, this HBCD assessment uses Equation 2-9, while future assessments may use Equations 2-9 and/or 2-10 depending on data availability.

$$\boldsymbol{ADD = \frac{DC \times IR \times FD \times CF1 \times ED}{BW \times AT}} \qquad \textbf{Equation 2-9}$$

Where

ADD = Average daily dose due to soil or dust ingestion (mg/kg-day)
DC = Dust or soil concentration (µg/g)
IR = Dust or soil ingestion rate (g/day)
CF_1 = Conversion factor for mg/µg
FD = Fraction of day spent (dust Ingestion only) in indoor microenvironment (unitless)

ED = Exposure duration (Soil only-considers near facility time 13 and 33 years) (years)
BW = Body weight (kg)
AT = Averaging time (years)

$$ADD = \frac{DL \times DF \times TA \times ED}{BW \times AT}$$ **Equation 2-10**

Where

ADD = Average daily dose due to soil or dust ingestion (mg/kg-day)
DL = Dust or soil loading (µg/cm^2)
DF = Dust or soil factor (cm^2/ µg * mg/hr)
TS = Time spent in different microenvironments, total should equal time awake (hr/day)
ED = Exposure duration (Soil only-considers near facility time 13 and 33 years) (years)
BW = Body weight (kg)
AT = Averaging time (years)

A wide range of studies have reported HBCD concentrations in dust in a variety of indoor environments. No studies were identified that identified HBCD loadings in dust. Therefore, empirically-derived ingestion rates based on the tracer and biokinetic approaches were used for this assessment.

The dust sampling locations were identified for each monitoring study and grouped into a microenvironment classification: residential, public and commercial building, automobile, and outdoors. The time spent by children and adults in each of these microenvironments was estimated for three generic activity-pattern profiles informed by EPA's Consolidated Human Activity Patterns Database (U.S. EPA, 2009a). The hours spent in each microenvironment were used to derive a fraction of the day that an individual was exposed to the selected HBCD concentrations in each microenvironment.

Table 2-83 presents all values that were used in Equation 2-9 to estimate exposures from dust and soil ingestion. Additional details on how these values were derived is available in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d).*

Table 2-83. Dust and Soil Monitoring and Ingestion Values used in Estimating Dust and Soil Ingestion Dose for HBCD

Parameter	Central Tendency	High-End
Monitored Dust Concentration-Residence µg/mg (µg/kg)	5.0E-04 (500)	5.0E-03 (5,000)
Monitored Dust Concentration-P&CB µg/mg (µg/kg)	5.0E-03	5.0E-02 (50,000)
Monitored Dust Concentration-Automobile µg/mg (µg/kg)	5.0E-02 (50,000)	5.0E-01 (500,000)
Monitored Soil Concentration near facility µg/mg (µg/kg)	5.0E-05	5.0E-04 (500)
Monitored Soil Concentration general population µg/mg (µg/kg)	5.0E-06 (5)	3.0E-05 (30)
Dust Ingestion Rate, varies by age mg/day	20-50	60-100
Soil Ingestion Rate, varies by age mg/day **See Supplemental Document for other ages** (U.S. EPA, 2019d)	10-40	50-90

Dodson measured flame retardants in house dust samples collected in 16 California homes in 2006 and 2011 Dodson et al. (2012a). Total HBCD was detected in 100% of the dust samples and ranged from 82 to 6,800 µg/kg (median = 190 µg/kg) in 2006 and from 39 to 1,800 µg/kg (median = 160 µg/kg) in 2011.

Shoeib measured flame retardants in house dust samples collected from homes located in Vancouver, Canada, between 2007 and 2008 (Shoeib et al., 2012). Total HBCD was detected in all samples (n = 116) with concentrations that ranged from 20 to 4,700 µg/kg (mean = 450 µg/kg; median = 270 µg/kg).

Abdallah reported dust concentration across home, office, car, and public microenvironments Abdallah et al. (2008b). HBCD was detected in all 97 samples. Levels in homes ranged from 140 to 140,000 µg/kg, offices from 90 to 6,600 µg/kg, cars from 190 to 69,000 µg/kg, and public microenvironments from 2,300 to 3,200 ug/kg.

Harrad et al measured dust in daycares and schools in the UK. HBCD was detected in all 43 samples and ranged from 72 to 89,000 µg/kg (Harrad et al., 2010). 95th percentile levels were reported at 37,000 µg/kg and average levels were 8,900 µg/kg.

Allen et al (Allen et al., 2013) collected dust samples within airplanes. 40 dust samples were collected between November and December of 2010 from carpeted floors and low-lying air return vents on the walls of 19 commercial airplanes. Total HBCD was detected in 100% of the dust samples and ranged from 180 to 1,100,000 µg/kg. Central tendency estimates were 7,600 µg/kg in floor samples and 10,000 µg/kg in vent samples.

Studies measuring the concentration of HBCD in soil are limited, with most studies measuring samples located near industrial facilities Li et al. (2012b). Li et al (Li et al., 2016c) reported a statistically significant negative correlation between HBCD soil concentrations and distance from facility, noting a distance of 4 kilometers. The majority of soil sampling has been performed in Asia, most notably China. Li et al (2016c) reported soil concentrations ranging from 0.88 to 6,901, which are likely more applicable to near-facility locations. Note that the 0.88 µg/kg sample was taken at a control site not located near facilities. The next highest concentration reported was 2,295 and the geometric mean across all samples was 83 µg/kg, and Tang et al. (2014b) collected in waste dumping sites, industrial areas, and traffic areas ranged from 6 to 106 µg/kg. The sample depth and proximity to source influence soil concentrations.

Tang collected 90 samples across the Ningbo Region of China that are more likely applicable to the general population Tang et al. (2014b). Samples collected in residential and agricultural areas ranged from ND to 46 µg/kg.

Table 2-84. Summary of HBCD Dust and Soil Monitoring Values (ng/g)

	Dust Concentration (ng/g)	Soil Concentration (µg/kg)	Reference	Systematic Review Score
Range of All Values from Monitoring Data	ND – 1.1E+6	ND – 1300	(Allen et al., 2013); (Remberger et al., 2004)	Medium; Medium
Range of Central Tendency Values from Monitoring Data	6 – 1.9E+4	2.33E-2 – 67.4	(Hassan and Shoeib, 2014) (Abdallah et al., 2008);Abdallah et al. (2008b) (Meng et al., 2011);	Medium; High; High; High

	Dust Concentration (ng/g)	Soil Concentration (µg/kg)	Reference	Systematic Review Score
			(Tang et al., 2014a)	
Range (Central Tendency) of Values from Key Studies	39 – 6800 (160, 190)	NA	(Dodson et al., 2012b)	High
	20 – 4700 (270, 450)	NA	(Shoeib et al., 2012)	Medium
	90 – 1.4E+5 (760, 1.9E+04)	NA	(Abdallah et al., 2008)	Medium
	72 – 8.9E+4 (4100, 8900)	NA	(Harrad et al., 2010)	Medium
	180 – 1.1E+6 (7600, 1.0E+04)	NA	(Allen et al., 2013)	Medium
	NA	ND – 103 (7.75, 67.4)	(Tang et al., 2014a)	High
	NA	ND – 3.4	(Li et al., 2012a)	Medium

Dermal Exposures to Dust, Soil, and from Materials

EPA estimated the loading expected to present on skin through contact with dust, soil, and materials containing HBCD throughout the day. Two approaches were used to estimate this loading. The first approach was based on empirical data where HBCD present in dust on people's hands was sampled using hand-wipes. The second approach was based on measured dust and soil concentrations and age-specific adherence factors. After estimating the dermal loading, an absorbed fraction of 6.5% was applied as discussed in Section 3.2.2.

2.4.2.5 Exposures from Suspended Particulates in Air

Inhalation of Suspended Particles

EPA considered available air monitoring data to derive near-facility and general population (including highly exposed groups) air concentrations of HBCD. EPA also estimated air releases using its Integrated Indoor and Outdoor Air Calculator (IIOAC) tool, based on AERMOD results from a suite of dispersion scenarios. While site specific meteorological conditions are not available, representative central tendency and high-end meteorological stations, release estimates, and assumptions were used to derive a range of estimated air concentrations for a given exposure scenario and release type (fugitive, stack, incineration).

Estimated dose from ingestion of suspended particles was calculated for both general population and highly exposed groups living near facilities. When a choice was available for central tendency or high-end input, high-end choices were made to estimate the acute dose rate (ADR) and central tendency choices were made to estimate average daily dose (ADD). Fenceline estimates are defined as air concentrations at 100-meter ring while community average air concentrations are defined as average air concentrations within 1 km of the facility. Note, rather than averaging outdoor and indoor air concentrations by time spent, EPA assumed that the indoor-outdoor ratio for HBCD was 1 (high-end) for ADR estimates and was 0.65 (central-tendency) for ADD estimates. Refer to the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d)* for additional

details on air modeling.

Table 2-85. Summary of HBCD Air Concentrations

Approach	Highly Exposed	General Population
Monitored Ambient Air Concentrations	No	Yes
Modeled Ambient Air Concentrations	Yes	No
Monitored Indoor Air Concentrations	No	Yes
Modeled Indoor Air Concentrations	Yes	No

Studies of HBCD in ambient air are limited. Hoh and Hites (2005b) was chosen as a key study for general population air concentrations. HBCD was measured in five sites across five states and detected in 120 of 156 samples. The Michigan site had HBCD concentrations that ranged from 0.2 to 8.0 pg/m^3, the Illinois site from 0.9 to 9.6 pg/m^3, the Indiana site from 0.2 to 3.6 pg/m^3, the Arkansas site from 0.2 to 11 pg/m^3, and the Louisiana site from 0.16 to 6.2 pg/m^3. Across all sites central tendency concentrations ranged from approximately 1 to 5 pg/m^3.

Elevated HBCD concentrations for near-facility locations were measured by Hu et al. (2011) from 1 site over 4 seasons, collecting 28 samples. Particle-phase was separated from gas-phase, with particle-phase comprising over 95% of total HBCD. The sampling location was Menzu University in Beijing, China. HBCD concentrations in air ranged from 0.000020-0.00180 µg/m^3 (mean = 0.00039 µg/m^3 and median = 0.00028 µg/m^3). The six samples taken near construction waste facilities, textile industries and urban locations summarized here ranged from 0.00013 to 0.00074 µg/m^3.

There are twelve studies measuring HBCD in indoor air. All studies characterized particle-phase HBCD and two of three conducted sampling in different microenvironments. The Ni and Zeng calculated concentrations of HBCD in air conditioning dust (Ni and Zeng, 2013). They estimated small particles ($PM_{2.5}$) differently from bigger particles (PM_{10}). The PM_{10} estimates are considered more appropriate in the exposure assessment and range from 1.84E-5 to 2.27E-3 µg/m^3. Abdallah et al. (2008b) estimated HBCD concentrations in homes, offices and public microenvironments with concentrations ranging from 6.7E-5 to 1.3E-3 µg/m^3. Hong et al. reported particulate-phase HBCD concentrations in homes, offices and other workplaces ranging from 8.9E-7 to 2.46E-4 µg/m^3 (Hong et al., 2016). While there are only three studies available, they are generally consistent with each other and modeled indoor air estimates based on dust concentrations are within the same order of magnitude.

A range of studies have reported ambient and indoor air concentrations in a variety of indoor and outdoor environments. The air sampling locations were identified for each monitoring study and grouped into microenvironments: residential, public and commercial building, automobile and outdoors. The time spent by children and adults in each microenvironment was estimated for three generic activity-pattern profiles informed by EPA's Consolidated Human Activity Patterns Database (U.S. EPA, 2009a). The hours spent in each microenvironment were used to derive a fraction of the day where an individual was exposed to the selected HBCD concentrations in each microenvironment.

The distribution of HBCD between gas-phase and particle phase in indoor air and the resulting particle size distribution is an important consideration. Smaller particles are expected to be respirable while larger particles are expected to be inhalable. The particle size distribution was not available for many monitoring studies, although most studies did report whether the sample was particulate or vapor. Only

particulate values were considered for this pathway. Equation 2-11 was used to estimate dose from ingestion of suspended particles in air is below.

$$\boldsymbol{ADD = \frac{AC \times IR \times IF \times FD \times ED}{BW \times AT}} \qquad \textbf{Equation 2-11}$$

Where

ADD = Average daily dose due to suspended particle ingestion (mg/kg- day)
AC = Concentration of particulates in air (mg/m^3)
IF = Fraction of inhaled particles that are ingested (unitless)
IR = Inhalation rate (m^3/day)
FD = Fraction of day spent (dust Ingestion only) in microenvironment (unitless)
ED = Exposure duration (years)
BW = Body weight (kg)
AT = Averaging time (years)

The concentration of HBCD particulate in indoor air can be derived directly from air monitoring data or estimated from measured indoor dust monitoring or total indoor air (vapor and particulate) concentrations. Estimated particulate air concentrations align well with reported monitoring values and are summarized in Table 2-86.

Table 2-86. HBCD Concentrations in Indoor and Ambient Air (ng/m^3)

	Indoor Air Concentration (ng/m3)	Ambient Air Concentration (ng/m3)	Reference	Systematic Review Score
Range of all Monitoring Data	ND – 24 residential ND – 29.5 commercial	ND – 6.7 background	(Saito et al., 2007); (Qi et al., 2014)	Medium; Medium
Range of Central Tendency Values from Monitoring Data	6.5E-4 – 0.28 residential 6.4E-3 – 0.9 commercial	1.0E-5 – 0.36 background 1.3E-2 – 1070 near facility	(Newton et al., 2015); (Takigami et al., 2009); (Hong et al., 2016); (Abdallah et al., 2008); (Zhu et al., 2014); (Li et al., 2016c); (Remberger et al., 2004)	Medium; Medium; High; High; High; Medium; Medium
Range (Central Tendency) of Key Studies	1.35E-2 – 1.099 (0.505, 0.516) modeled	NA	(Ni and Zeng, 2013)	High
	6.7E-2 - 1.3 (0.18, 0.25) residential	NA	(Abdallah et al., 2008)	High
	4.0E-3 – 1.6E-2 (0.0064, 0.0082) commercial 8.9E-4 – 8.5E-3 (0.0054, 0.0067) residential	NA	(Hong et al., 2016)	High
	NA	2.0E-2 to 1.8 (0.39) background	{Hu et al. (2011)	Medium
	NA	ND – 1.1E-2 (0.0004, 0.0045) background	(Hoh and Hites, 2005a)	Medium

Parameters and data sources used as inputs into this equation are provided in Table 2-87. Additional detail is provided in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d).*

Table 2-87. Data Sources and Inputs for Estimation of HBCD Inhalation Dose

Parameter	Central Tendency	High-End
Air Concentration Particulate Outdoors (near facility) µg/m^3	5.0E-4	1.0E-3
Air Concentration Particulate Outdoors (general population) µg/m3	5.0e-6	5.0E-5
Air Concentration Particulate Residence µg/m^3	5.0E-6	5.0E-5
Air Concentration Particulate P&CB µg/m^3	5.0E-4	1.0E-3
Air Concentration Particulate Auto µg/m^3	5.0E-6	5.0E-5
Inhalation Rate m^3/day for adults, varies with age	15.7	21.3
Exposure Duration for near facility concentration- years	13 and 33 years	

Emission to Air and Subsequent Inhalation of Particles from Point Sources

Scenario from Table 2-70	**Source**	**Pathway**	**Receptor**	**Approach**
A2	HBCD emitted from any point source during its lifecycle from Scenarios described in Section 2.2	Emission to Air and subsequent inhalation of particles	Children, Adults	Quantitative, IIOAC

Twelve scenarios from Section 2.2 were considered, ranging from import/repackaging to use of solder. For scenarios with site-specific information, this information was used in the IIOAC model runs. When site-specific information was not unknown, default parameters were used (see *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d)*).

Modeled results are presented in Table 2-88 for daily-averaged and annual-averaged ambient air concentration, respectively, and in Table 2-97 and Table 2-98 for ADR and ADD by toddler and adult. Under each scenario, multiple model runs were performed to include different source types, high end and central tendency climate regions, and high end and central tendency release estimates. These results are further summarized in Table 2-88 where the high-end daily-averaged ambient air concentration and the central tendency annual-averaged ambient air concentration are presented.

Table 2-88. Overall Summary of HBCD Ambient Air Concentrations for 12 Emission Scenarios
(Gray cells indicate no release data for this source.)

Scenario Name	Fugitive Air Concentration Range (µg/m^3) 24-Hour Average / Yearly Average	Average Incineration Air Concentration Range (µg/m^3) 24-Hour Average / Yearly Average	Incineration Air Concentration Range (µg/m^3) 24-Hour Average / Yearly Average
1. Import, Repackaging, Dust Release during Unloading of HBCD	6.72E-02 - 5.85E+00 / 8.74E-04 - 4.41E-03	1.17E-02 - 8.54E-01 / 6.72E-04 - 3.36E-03	3.28E-04 - 3.16E-02 / 2.56E-04 - 1.28E-03
2. Compounding of Polystyrene Resin to Produce XPS Masterbatch	3.43E-03 - 2.64E-02 / 5.35E-06 - 6.39E-06	4.90E-04 - 3.80E-03 / 4.08E-06 - 5.70E-06	NA
3. Manufacturing of XPS Foam using XPS Masterbatch	1.30E-01 - 2.77E+00 / 5.05E-05 - 5.06E-05	1.85E-02 - 3.50E-01 / 3.86E-05 - 3.86E-05	NA
4. Manufacturing of XPS Foam using HBCD Powder	1.64E-02 - 3.49E-01 / 6.36E-06 - 6.37E-06	2.33E-03 - 2.90E+00 / 4.86E-06 - 3.46E-04	6.84E-03 - 2.30E-01 / 1.78E-04 - 1.89E-04
5. Manufacturing of EPS Foam from Imported EPS Resin Beads, Dust Release during Converting Process	1.97E-01 - 1.13E+01 / 8.74E-04 - 4.38E-03	3.16E-02 - 1.60E+00 / 6.67E-04 - 3.91E-03	2.09E-02 - 4.96E-01 / 5.36E-03 - 1.02E-02
6. Manufacturing of SIPs and Automotive Replacement Parts, Dust Release During Sawing / Cutting of Foam	3.40E-03 - 5.07E-01 / 4.42E-05 - 1.98E-04	5.93E-04 - 7.20E-02 / 3.37E-05 - 1.51E-04	3.29E-03 - 3.13E-01 / 2.57E-03 - 6.45E-03
8. Installation of Insulation in Buildings, Dust release during sawing / cutting of foam	8.97E-05 - 8.93E-03 / 1.64E-09 - 5.78E-07	NA	1.25E-04 - 6.60E-03 / 9.47E-08 - 1.88E-05
10. Recycling of EPS Foam, Dust release from Grinding ofFoam	1.38E-04 - 1.67E-01 / 6.11E-07 - 3.07E-06	2.21E-05 - 2.12E-02 / 4.67E-07 - 2.34E-06	1.47E-05 - 5.90E-03 / 3.75E-06 - 4.47E-06
11. Formulation of Solder, TRI Data	2.93E-04 - 3.10E-02 / 6.60E-06 - 6.71E-06	1.92E-03 - 1.63E-01 / 7.54E-05 - 7.62E-05	NA
12. Use of Solder, Disposal of Transport Containers and Overapplied/Unused Solder	NA	NA	5.77E-06 - 1.22E-03 / 4.50E-06 - 5.07E-06

2.4.2.6 Consumer Exposures

2.4.2.6.1 Consumer Exposures to EPS/XPS Insulation In Residences – Emission from Insulation into Indoor Air and Settled Dust

Scenario from Table 2-70	Source	Pathway	Receptor	Approach
A3	EPS/XPS Insulation in residences	Emission from insulation into indoor air settled dust	Children and Adults	Quantitative-IECCU

In order to estimate the presence and fate of HBCD in vapor phase, settled dust, airborne particulate matter, and interior surfaces, a series of simulations were conducted for a "typical" residential building and a "typical" passenger vehicle by using existing mass transfer models and simulation tools. Most parameters were either obtained from data in the literature or estimated with empirical and QSAR models. All the simulations were conducted with IECCU version 1.1 (U.S. EPA, 2019o).

The modeling results were compared with limited experimental data. The predicted HBCD concentrations in settled dust in the living space were in line with the field measurements. Additionally, the predicted temperature dependence of the HBCD emission rate is in good agreement with the laboratory testing results reported by the Japanese researchers.

EPA used a general mass balance approach as defined in the user guide of the IECCU model to estimate the indoor concentrations of HBCD in indoor air and dust of a multi-zone indoor environment (U.S. EPA, 2019o). Additional details are provided in Appendix F.

EPA used modeled indoor air and dust estimates over time to quantify doses. The highest 24-hour average indoor air and dust concentration was combined with a high-end intake to quantify age specific ADR values. The long-term average indoor air and dust concentration was combined with a central tendency intake to quantify age specific ADD values. EPA assumed that 90% of time was spent in the residence with the modeled concentration and 10% of time was spent in another microenvironment where the dust and indoor air concentrations were set at central tendency for ADD estimates and high-end for ADR estimates. These dose estimates are of a similar order of magnitude to those estimates for general population. The ADR estimates are generally slightly lower than general population high-end estimates and the ADD estimates are generally slightly higher than general population central tendency estimates. However, all modeled doses are within a factor of five, when compared to general population estimates.

Table 2-89. Age Specific ADR and ADD Associated with Residential Insulation Scenario A3

	TOTAL ADR (mg/kg/day)	TOTAL ADD (mg/kg/day)
Infant (<1 year)	1.0E-04	2.4E-05
Young Toddler (1-<2 years)	9.7E-05	2.5E-05
Toddler (2-<3 years)	8.5E-05	2.2E-05
Small Child (3-<6 years)	6.4E-05	1.8E-05
Child (6-<11 years)	4.4E-05	1.3E-05
Teen (11-<16 years)	3.1E-05	8.7E-06
Adult (16-<78 years)	2.2E-05	6.5E-06

2.4.2.6.2 Consumer Exposure to HBCD Contained in Automobile Components

Scenario from Table 2-70	Source	Pathway	Receptor	Approach
A4	HBCD contained in automobile components	Emission into automobile cabin air and settled dust	Children and Adults	Quantitative-IECCU

EPA followed a similar process to use modeled indoor air and dust estimates over time to quantify doses. The highest 24-hour average indoor air and dust concentration was combined with a high-end intake to quantify age specific ADR values. The long-term average indoor air and dust concentration was combined with a central tendency intake to quantify age specific ADD values. EPA assumed that 10% of time was spent in the automobile with the modeled concentration and 90% of time was spent in another microenvironment where the dust and indoor air concentrations were set at central tendency for ADD estimates and high-end for ADR estimates. These dose estimates are of a similar order of magnitude to those estimates for general population. The ADR estimates are generally slightly lower than general population high-end estimates and the ADD estimates are generally slightly higher than general population central tendency estimates. However, all modeled doses are within a factor of five, when compared to general population estimates.

Table 2-90. Age Specific ADR and ADD associated with Auto Component - Scenario A4

	TOTAL ADR (mg/kg/day)	TOTAL ADD (mg/kg/day)
Infant (<1 year)	9.7E-05	3.2E-05
Young Toddler (1-<2 years)	9.2E-05	3.5E-05
Toddler (2-<3 years)	8.1E-05	2.3E-05
Small Child (3-<6 years)	6.0E-05	1.8E-05
Child (6-<11 years)	4.2E-05	1.2E-05
Teen (11-<16 years)	2.9E-05	6.8E-06
Adult (16-<78 years)	2.1E-05	5.0E-06

2.4.2.6.3 Exposure to Recycled Consumer Articles that Contain HBCD

Scenario from Table 2-70	Source	Pathway	Receptor	Approach
A6	Recycled consumer articles that contain HBCD	Mouthing, direct contact	Young children	Quantitative

EPA identified information in the open literature that describes articles which contain HBCD, and recognizes this as an important pathway for young children who may mouth articles. EPA considered mouthing of recycled plastic products using experimental product-testing information on HBCD content in consumer articles. EPA identified two data sources that measured HBCD content and provided additional contextual information on the type of consumer article and whether it was new or recycled (Abdallah et al., 2018; Vojta et al., 2017). EPA determined which of these consumer articles were not likely to be mouthed (i.e., insulation products, building materials) and which products could be mouthed (i.e., food packaging materials, toys). The concentration of HBCD in consumer articles that were not likely to be mouthed was higher than the concentration present in consumer articles that could be mouthed.

The concentration of HBCD present in all products was higher (<1 ppm to 6,000 ppm) than the concentration of HBCD present in the products likely to be mouthed (<1 ppm to 250 ppm). While HBCD can be present in many consumer articles, presence at levels such as <1 ppm to 250 ppm are not likely to impart flame retardancy and are likely due to mixing of recycled feedstocks from many sources. Generally, as the concentration of HBCD increases the potential for imparting flame retardancy and the potential for exposure increases. Presence of HBCD at higher levels (>250 ppm) may also be due to mixing of recycled feedstocks from many sources. However, EPA used any data above the detection limit for products likely to be mouthed rather than identify a lower or upper cut-off based on the potential for exposure and/or the potential for imparting flame retardancy. Additional details are provided in Appendix F.

Table 2-91. Estimated Exposure from Mouthing of Articles Containing HBCD

Summary Statistic	HBCD Concentration in Consumer Articles Likely to be Mouthed (ppm)	Migration Rate into Saliva (µg/cm²/hr)	ADR 1-2 yrs (Central Tendency)	ADR 1-2 yrs (High End)	ADD 1-2 yrs (Central Tendency)	ADD 1-2 years (High End)
min	0.0015	3.8E-08	5.39E-11	5.39E-10	3.69E-11	3.69E-10
10th	0.003643	9.3E-08	1.33E-10	1.33E-09	9.09E-11	9.09E-10
50th	0.0915	2.2E-06	3.18E-09	3.18E-08	2.18E-09	2.18E-08
geomean	0.137864	3.3E-06	4.76E-09	4.76E-08	3.26E-09	3.26E-08
75th	0.56575	1.3E-05	1.91E-08	1.91E-07	1.31E-08	1.31E-07
90th	19.3096	4.3E-04	6.19E-07	6.19E-06	4.24E-07	4.24E-06
95th	32.66395	7.3E-04	1.04E-06	1.04E-05	7.11E-07	7.11E-06
98th	75.1788	1.7E-03	2.36E-06	2.36E-05	1.62E-06	1.62E-05
99th	90.41996	2.0E-03	2.83E-06	2.83E-05	1.94E-06	1.94E-05
max	249.7	5.4E-03	7.70E-06	7.70E-05	5.28E-06	5.28E-05

2.4.2.7 Qualitative Exposure Scenarios

This section describes qualitative or semi-quantitative scenarios used to provide context for exposure scenarios that were identified in EPA's conceptual model but that were not ultimately quantified and carried through for risk characterization. Note while some of these scenarios do provide quantitative estimates, these values are provided with the sole purpose to provide context for EPA's best estimate of potential exposure. These estimates are highly uncertain and are based on limited data. While these scenarios have exposure potential, exposures are likely to be highly variable for reasons described below.

Emissions to Ambient Air from EPS and XPS Insulation in Residences

Scenario from Table 2-70	Source	Pathway	Receptor	Approach
A5	EPS and XPS insulation in residences	Emission from building interior to ambient air surrounding buildings	Children and adults living near buildings containing HBCD	Qualitative

Ventilation is the most important means by which HBCD is removed from the indoor environment. However, the effect of HBCD release from buildings to surrounding ambient air is expected to be low. The HBCD release rate is estimated to be 0.02 g/day over the first 100 days after the application of insulation. The mass balance table from the consumer articles section shows that the total HBCD vented out over a 100-day period is 2.06×10^6 µg (i.e., 2.06 g). This gives a source strength for a single home, strength of point source = 2.06×10^6 µg ÷ 100 days = 2.06×10^4 µg/day (or 0.02 g/day).

To estimate the effect of indoor emissions on ambient air, consider a 100-square mile, densely populated urban area with a housing density of 1000 units per square mile. In this example, the total source strength is:

$$\text{Total source strength} = 100\ \text{mile}^2 \times 1000\ \text{units/mile}^2 \times 2.06\times10^4\ \mu\text{g/day} = 2.06\times10^9\ \mu\text{g/day}.$$

Next, calculate the size of the air box that moves through the city over a 24-h period.

Mixing height: The mixing height in urban area is usually between 300 and 1000 m. Consider the worse-case scenario with a mixing height of only 150 m due to temperature inversion, which was the case during the London fog episode in 1952. Wind speed and travel distance: The worst-case scenario occurs when there is little wind. In this calculation, a wind speed of 1 m/s was used (i.e., the Beaufort number = 1 on a 0-to-12 scale). Thus, the distance of the air will travel over a 24-h period is 1 m/s × 3600 s/h × 24 h = 86400 m. Furthermore, the diameter of the city area (100 mile^2) is 18200 m. From these values, the size of the air box moving through the city over a 24-h period can be calculated,

$$\text{Air box volume} = 150\ \text{m} \times 86400\ \text{m} \times 18200\ \text{m} = 2.35\times10^{11}\ \text{m}^3$$

Dividing the total source strength by the air volume yields the HBCD concentration in the urban air below the mixing height:

$$\text{Possible Concentration} = 2.06\times10^9\ \mu\text{g} \div 2.35\times10^{11}\ \text{m}^3 = 8.75\times10^{-3}\ \mu\text{g/m}^3$$

If other factors are considered such as other types of buildings which may have insulation and the fraction of total buildings that have HBCD EPS or XPS insulation as opposed to other kinds of insulation, there is additional variability that should be considered in the quantified air concentration. It is noteworthy that this estimated air concentration is near the top-end of the range for extracted ambient air monitoring data. Other refinements based on data could be used to modify this estimate closer to central tendency monitoring values, but this was not undertaken at this time. In summary, emissions from HBCD insulation to ambient air represent a potential ongoing source of exposure to the environment.

HBCD Sent to Landfill Across the Lifecycle

Scenario from Table 2-70	Source	Pathway	Receptor	Approach
A7	HBCD sent to landfill across the lifecycle	Comingled HBCD containing materials leach into soil, disposed food, and water	Populations living near landfills Nesting birds living near landfills	Qualitative

Over 99% of landfill releases are expected from the insulation use: 408,687 out of 411,948 kg/year. There is potential for HBCD released to landfill to migrate to the nearby environment. However, typical management controls such as coverings, liners, and treatment may partially or fully mitigate this. ECHA acknowledges that there are no commonly accepted models available to predict releases and exposures from landfills. Further, they encourage a qualitative discussion of landfill exposure, as is provided here. HBCD is expected to strongly sorb to soil particle, is not volatile and would likely only escape to air through windblown soil particles. Due its high KoC, HBCD any potential migration through the landfill to effluent would be slow. Very few effluent monitoring studies are available. One recent experimental study noted that HBCD migration from materials into effluent can occur and is influenced by experimental conditions mimicking real-world conditions (Stubbings and Harrad, 2014). However, even though the total annual releases appear large, EPA provides the following context. If the annual releases were divided by the number of active landfills in the US and the average size of a landfill in the US, and divided this mass into the top of layer of soil in a landfill this concentration would approximate central tendency estimates from extracted soil monitoring data. However, there is a high degree of variability associated with any estimated exposure from landfill releases. In summary, under some conditions it is possible that landfills represent a potential source of exposure to the nearby environment.

2.4.2.8 Values Used in the Assessment of General Population, Highly Exposed, and Consumer Exposure

EPA summarized inputs used to estimate general population and highly exposed groups. For each exposure pathway, all central tendency and high-end doses were estimated by combining monitored and/or modeled environmental concentrations with age specific activity patterns and exposure factors.

EPA's Human Exposure Guidelines defined central tendency exposures as "an estimate of individuals in the middle of the distribution." It is anticipated that these estimates apply to most individuals in the U.S.

High-end exposure estimates are defined as "plausible estimate of individual exposure for those individuals at the upper end of an exposure distribution, the intent of which is to convey an estimate of exposure in the upper range of the distribution while avoiding estimates that are beyond the true distribution." It is anticipated that these estimates apply to some individuals, particularly those who may live near facilities with elevated concentrations.

To better under the distribution of exposures and to assess the impact of variability in environmental concentrations and exposure factor variables that influence exposure, an analysis was conducted using Python. In this analysis, the full distribution of input variables was sampled in a Monte Carlo analysis that allowed for the construction of a full distribution of estimated exposures. For environmental monitoring data, the distribution was conducted assuming a lognormal distribution where the central tendency input was representative of the median and the high-end input was representative of the 95th percentile. A lognormal distribution was selected to reflect the skewness commonly found in environmental data. For exposure factors and all other inputs that had both a central tendency and high-end estimate, normal distributions were assumed thus avoiding extreme values for physiological variables such as body weight. These distributions are summarized below and presented in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d).*

The final pathway and aggregate exposure distributions were generated as follows:

- Computer code in Python software was used to implement the simulation.
- A total of 10,000 realizations were used after testing to ensure that this was adequate to achieve distributional convergence.
- Each variable's distribution was truncated to not allow a value equal or less than zero or greater than three standard deviations, or in the case of lognormal distributions, geometric standard deviations, to be selected.
- The median was selected to represent central tendency estimates, and the 95th percentile was selected to represent high end estimates.

Table 2-92 below provides additional information on which distributions were assumed.

All variables and distributions used to estimate highly exposed and general population exposure estimates are listed in Table 2-92. There are variations between general population and highly exposed groups.

Table 2-92. Variables and Distribution Type used to Estimate Central Tendency, High-End Estimates of General Population Exposures to HBCD

Exposure Pathway	Variable	Distribution
Fish Ingestion	Concentration in Fish Tissue	Lognormal
Fish Ingestion	Fish Ingestion Rate	Normal
Dust Ingestion	Concentration in Dust	Lognormal
Dust Ingestion	Dust Ingestion Rate	Normal
Soil Ingestion	Concentration in Soil	Lognormal
Soil Ingestion	Soil Ingestion Rate	Normal
Ambient Air	Concentration in Air	Lognormal

Exposure Pathway	Variable	Distribution
Indoor Air	Concentration in Air	Lognormal
Ambient and Indoor Air	Inhalation Rate	Normal
Fish, Ambient, and Indoor Air	Time living near facility	Uniform
Dermal Loading	Loading present on hands	Lognormal
Dermal	Surface Area of Hands to Body Weight Ratio	Normal
Dietary (other)	Fruit, Vegetable, Meat, Dairy Concentration	Lognormal
Dietary (intake)	Fruit, Vegetable, Meat, Dairy Ingestion Rate	Normal
Breast Milk ingestion	Breast Milk Concentration	Lognormal
Breast Milk ingestion	Ingestion rate	Normal
All pathways	Body Weight	Normal

For estimating fish ingestion doses to highly exposed populations, as described in Section 2.3.2, EPA used the Point Source Calculator model to estimate surface water concentrations resulting from emissions to surface water associated with the scenario specific conditions of use. The results of all modeling runs are presented in Table 2-93 (mean flow for 50th percentile facility) and in Table 2-94 (mean flow for 10th percentile facility). Dissolved water concentrations were used to estimate fish ingestion doses as described in Section 2.4.2.3 with the 50th percentile, 21 day average dissolved water concentrations were used to estimate the ADD and the 10th percentile, 21 day average dissolved water concentrations were used to estimate the ADR. The resulting fish ingestion doses, arrayed by scenario and age group are shown in Table 2-95 and Table 2-96.

Table 2-93. Estimated Surface Water Concentrations of HBCD Modeled using PSC (Mean Flow 50th Percentile)

Scenario Label	Water Column Total 1 Day µg/L	Water Column 1 Day Dissolved µg/L	Water Column 1 Day Suspended µg/L	Water Column Total 21 day avg. µg/L	Water Column 21 day avg. Dissolved µg/L	Water Column 21 day avg. Suspended µg/L	Sediment 28 day average (128)[a] µg/kg	Sediment 28 day average (11)[a] µg/kg
1.1	1.2E-01	8.9E-02	1.8E-02	1.1E-02	8.5E-03	1.7E-03	2.4E+01	1.1E+01
1.2	1.1E-02	8.6E-03	1.7E-03	9.2E-03	6.9E-03	1.4E-03	2.3E+01	1.0E+01
1.3	5.9E-01	4.5E-01	8.9E-02	5.6E-02	4.3E-02	8.5E-03	1.2E+02	5.3E+01
1.4	5.7E-02	4.3E-02	8.7E-03	4.6E-02	3.5E-02	7.0E-03	1.2E+02	5.2E+01
1.5	5.4E-01	4.1E-01	8.1E-02	5.2E-02	3.9E-02	7.8E-03	1.1E+02	4.8E+01
1.6	5.2E-02	3.9E-02	7.9E-03	4.2E-02	3.2E-02	6.4E-03	1.1E+02	4.7E+01
1.7	2.7E+00	2.0E+00	4.1E-01	2.6E-01	2.0E-01	3.9E-02	5.4E+02	2.4E+02
1.8	2.6E-01	2.0E-01	4.0E-02	2.1E-01	1.6E-01	3.2E-02	5.4E+02	2.4E+02
2.1	1.1E-01	8.6E-02	1.7E-02	5.4E-03	4.1E-03	8.2E-04	8.5E+00	4.1E+00
2.2	1.8E-02	1.4E-02	2.8E-03	3.5E-03	2.7E-03	5.3E-04	7.9E+00	3.5E+00
2.3	2.5E-01	1.9E-01	3.8E-02	1.2E-02	9.2E-03	1.8E-03	1.9E+01	9.1E+00

Scenario Label	Water Column Total 1 Day µg/L	Water Column 1 Day Dissolved µg/L	Water Column 1 Day Suspended µg/L	Water Column Total 21 day avg. µg/L	Water Column 21 day avg. Dissolved µg/L	Water Column 21 day avg. Suspended µg/L	Sediment 28 day average (128)[a] µg/kg	Sediment 28 day average (11)[a] µg/kg
2.4	4.2E-02	3.2E-02	6.4E-03	8.1E-03	6.1E-03	1.2E-03	1.8E+01	8.1E+00
2.5	1.1E-02	8.6E-03	1.7E-03	5.4E-04	4.1E-04	8.2E-05	8.5E-01	4.1E-01
2.7	2.5E-02	1.9E-02	3.8E-03	1.2E-03	9.2E-04	1.8E-04	1.9E+00	9.1E-01
2.9	5.2E-02	3.9E-02	7.8E-03	2.5E-03	1.9E-03	3.7E-04	3.9E+00	1.9E+00
2.11	1.2E-01	8.8E-02	1.8E-02	5.6E-03	4.2E-03	8.4E-04	8.8E+00	4.2E+00
3.1	3.7E-01	2.8E-01	5.6E-02	1.8E-02	1.3E-02	2.6E-03	1.5E+01	1.1E+01
3.2	2.5E-02	1.9E-02	3.7E-03	1.2E-03	8.9E-04	1.8E-04	2.7E+00	1.2E+00
3.3	9.0E-01	6.8E-01	1.4E-01	4.3E-02	3.2E-02	6.5E-03	3.6E+01	2.7E+01
3.4	6.0E-02	4.6E-02	9.1E-03	2.9E-03	2.2E-03	4.4E-04	6.7E+00	3.0E+00
3.5	3.7E-02	2.8E-02	5.6E-03	1.8E-03	1.3E-03	2.6E-04	1.5E+00	1.1E+00
3.6	2.5E-03	1.9E-03	3.7E-04	1.2E-04	8.9E-05	1.8E-05	2.7E-01	1.2E-01
3.7	9.0E-02	6.8E-02	1.4E-02	4.3E-03	3.2E-03	6.5E-04	3.6E+00	2.7E+00
3.8	6.0E-03	4.6E-03	9.1E-04	2.9E-04	2.2E-04	4.4E-05	6.7E-01	3.0E-01
3.9	1.7E-01	1.3E-01	2.5E-02	8.0E-03	6.0E-03	1.2E-03	6.8E+00	5.1E+00
3.10	1.1E-02	8.4E-03	1.7E-03	5.4E-04	4.0E-04	8.1E-05	1.2E+00	5.6E-01
3.11	4.1E-01	3.1E-01	6.2E-02	2.0E-02	1.5E-02	3.0E-03	1.7E+01	1.3E+01
3.12	2.8E-02	2.1E-02	4.2E-03	1.3E-03	1.0E-03	2.0E-04	3.1E+00	1.4E+00
4.1	3.5E-01	2.6E-01	5.3E-02	1.7E-02	1.3E-02	2.5E-03	1.4E+01	1.1E+01
4.2	2.9E-02	2.2E-02	4.5E-03	1.4E-03	1.1E-03	2.1E-04	2.5E+00	1.1E+00
4.3	3.5E-02	2.6E-02	5.3E-03	1.7E-03	1.3E-03	2.5E-04	1.4E+00	1.1E+00
4.4	2.9E-03	2.2E-03	4.5E-04	1.4E-04	1.1E-04	2.1E-05	2.5E-01	1.1E-01
4.5	1.6E-01	1.2E-01	2.4E-02	7.6E-03	5.8E-03	1.2E-03	6.4E+00	4.9E+00
4.6	1.3E-02	1.0E-02	2.0E-03	6.4E-04	4.9E-04	9.7E-05	1.2E+00	5.2E-01
5.1	2.4E+01	1.8E+01	3.6E+00	1.1E+00	8.5E-01	1.7E-01	2.7E+03	1.2E+03
5.2	2.4E+00	1.8E+00	3.6E-01	1.1E-01	8.5E-02	1.7E-02	2.7E+02	1.2E+02
5.3	1.1E+01	8.1E+00	1.6E+00	5.1E-01	3.9E-01	7.8E-02	1.3E+03	5.7E+02
5.4	2.7E+00	2.0E+00	4.1E-01	9.0E-01	6.8E-01	1.4E-01	2.3E+03	1.0E+03
5.5	2.7E-01	2.0E-01	4.1E-02	9.0E-02	6.8E-02	1.4E-02	2.3E+02	1.0E+02
5.6	1.2E+00	9.3E-01	1.9E-01	4.1E-01	3.1E-01	6.2E-02	1.1E+03	4.7E+02
5.7	3.2E+01	2.4E+01	4.9E+00	1.5E+00	1.2E+00	2.3E-01	3.7E+03	1.7E+03
5.8	3.2E+00	2.4E+00	4.9E-01	1.5E-01	1.2E-01	2.3E-02	3.7E+02	1.7E+02
5.9	1.5E+01	1.1E+01	2.2E+00	7.0E-01	5.3E-01	1.1E-01	1.7E+03	7.7E+02
5.10	3.7E+00	2.8E+00	5.6E-01	1.2E+00	9.3E-01	1.9E-01	3.2E+03	1.4E+03
5.11	3.7E-01	2.8E-01	5.6E-02	1.2E-01	9.3E-02	1.9E-02	3.2E+02	1.4E+02
5.12	1.7E+00	1.3E+00	2.5E-01	5.6E-01	4.3E-01	2.5E-01	1.5E+03	6.4E+02
6.1	1.1E-01	8.2E-02	1.6E-02	5.2E-03	3.9E-03	7.8E-04	1.3E+01	5.7E+00
6.2	1.1E-02	8.2E-03	1.6E-03	5.2E-04	3.9E-04	7.8E-05	1.3E+00	5.7E-01
6.3	4.9E-02	3.7E-02	7.4E-03	2.4E-03	1.8E-03	3.6E-04	5.7E+00	2.6E+00
6.4	5.8E-03	4.4E-03	8.7E-04	5.0E-03	3.7E-03	7.5E-04	1.2E+01	5.5E+00

Scenario Label	Water Column Total 1 Day µg/L	Water Column 1 Day Dissolved µg/L	Water Column 1 Day Suspended µg/L	Water Column Total 21 day avg. µg/L	Water Column 21 day avg. Dissolved µg/L	Water Column 21 day avg. Suspended µg/L	Sediment 28 day average (128)[a] µg/kg	Sediment 28 day average (11)[a] µg/kg
6.7	4.8E-01	3.6E-01	7.3E-02	2.3E-02	1.7E-02	3.5E-03	5.6E+01	2.5E+01
6.8	4.8E-02	3.6E-02	7.3E-03	2.3E-03	1.7E-03	3.5E-04	5.6E+00	2.5E+00
6.9	2.2E-01	1.7E-01	3.3E-02	1.1E-02	7.9E-03	1.6E-03	2.6E+01	1.2E+01
6.10	2.6E-02	1.9E-02	3.9E-03	2.2E-02	1.7E-02	3.3E-03	5.5E+01	2.4E+01
6.11	2.6E-03	1.9E-03	3.9E-04	2.2E-03	1.7E-03	3.3E-04	5.5E+00	2.4E+00
6.12	1.2E-02	8.9E-03	1.8E-03	1.0E-02	7.6E-03	1.5E-03	2.5E+01	1.1E+01
8.1	6.6E-04	5.0E-04	1.0E-04	3.2E-05	2.4E-05	4.8E-06	2.7E-02	2.0E-02
8.3	7.8E-02	5.9E-02	1.2E-02	3.7E-03	2.8E-03	5.7E-04	3.6E+00	2.4E+00
10.1	5.0E-01	3.8E-01	7.6E-02	2.4E-02	1.8E-02	3.6E-03	2.0E+01	1.5E+01
10.2	5.0E-02	3.8E-02	7.6E-03	2.4E-03	1.8E-03	3.6E-04	2.0E+00	1.5E+00
10.3	2.3E-01	1.7E-01	3.5E-02	1.1E-02	8.3E-03	1.7E-03	9.3E+00	7.0E+00
10.4	3.6E-03	2.7E-03	5.4E-04	1.2E-03	9.1E-04	1.8E-04	3.1E+00	1.4E+00
10.7	6.0E-01	4.5E-01	9.1E-02	2.9E-02	2.2E-02	4.3E-03	2.4E+01	1.8E+01
10.8	6.0E-02	4.5E-02	9.1E-03	2.9E-03	2.2E-03	4.3E-04	2.4E+00	1.8E+00
10.9	2.7E-01	2.1E-01	4.1E-02	1.3E-02	9.8E-03	2.0E-03	1.1E+01	8.3E+00
10.10	4.3E-03	3.2E-03	6.5E-04	1.4E-03	1.1E-03	2.2E-04	3.7E+00	1.6E+00
12.1	1.9E-03	1.4E-03	2.9E-04	9.0E-05	6.8E-05	1.4E-05	8.9E-02	5.8E-02
12.2	8.6E-03	6.5E-03	1.3E-03	4.1E-04	3.1E-04	6.2E-05	4.1E-01	2.6E-01
12.5	3.8E-03	2.9E-03	5.7E-04	1.8E-04	1.4E-04	2.7E-05	1.8E-01	1.2E-01
12.6	1.7E-02	1.3E-02	2.6E-03	8.2E-04	6.2E-04	1.2E-04	8.1E-01	5.3E-01

[a] sediment benthic half-life (days)

Table 2-94. Estimated Surface Water Concentrations of HBCD Modeled using PSC (Mean Flow 10th Percentile)

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
1.1	3.3E+00	2.5E+00	5.0E-01	3.3E-01	2.5E-01	5.0E-02	6.9E+02	3.0E+02
1.2	3.3E-01	2.5E-01	5.0E-02	2.7E-01	2.1E-01	4.1E-02	6.9E+02	3.0E+02
1.3	1.7E+01	1.3E+01	2.5E+00	1.7E+00	1.2E+00	2.5E-01	3.5E+03	1.5E+03
1.4	1.6E+00	1.2E+00	2.5E-01	1.3E+00	1.0E+00	2.0E-01	3.5E+03	1.5E+03
1.5	3.7E+00	2.8E+00	5.6E-01	3.7E-01	2.8E-01	5.6E-02	7.8E+02	3.4E+02
1.6	3.7E-01	2.8E-01	5.6E-02	3.0E-01	2.3E-01	4.6E-02	7.7E+02	3.3E+02
1.7	1.9E+01	1.4E+01	2.8E+00	1.9E+00	1.4E+00	2.8E-01	3.9E+03	1.7E+03
1.8	1.9E+00	1.4E+00	2.8E-01	1.5E+00	1.2E+00	2.3E-01	3.9E+03	1.7E+03
2.1	3.2E+00	2.4E+00	4.8E-01	1.6E-01	1.2E-01	2.4E-02	2.5E+02	1.2E+02
2.2	5.2E-01	3.9E-01	7.9E-02	1.0E-01	7.8E-02	1.6E-02	2.3E+02	1.0E+02

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
2.3	7.1E+00	5.4E+00	1.1E+00	3.5E-01	2.7E-01	5.3E-02	5.6E+02	2.6E+02
2.4	1.2E+00	9.1E-01	1.8E-01	2.4E-01	1.8E-01	3.6E-02	5.4E+02	2.3E+02
2.5	3.2E-01	2.4E-01	4.8E-02	1.6E-02	1.2E-02	2.4E-03	2.5E+01	1.2E+01
2.7	7.1E-01	5.4E-01	1.1E-01	3.5E-02	2.7E-02	5.3E-03	5.6E+01	2.6E+01
2.9	3.5E-01	2.7E-01	5.4E-02	1.8E-02	1.3E-02	2.6E-03	2.8E+01	1.3E+01
2.11	8.0E-01	6.0E-01	1.2E-01	3.9E-02	3.0E-02	6.0E-03	6.3E+01	2.9E+01
3.1	1.0E+01	7.8E+00	1.6E+00	5.0E-01	3.8E-01	7.5E-02	4.2E+02	3.2E+02
3.2	6.9E-01	5.2E-01	1.0E-01	3.4E-02	2.6E-02	5.2E-03	7.9E+01	3.5E+01
3.3	2.5E+01	1.9E+01	3.8E+00	1.2E+00	9.2E-01	1.8E-01	1.0E+03	7.7E+02
3.4	1.7E+00	1.3E+00	2.6E-01	8.5E-02	6.4E-02	1.3E-02	2.0E+02	8.6E+01
3.5	1.0E+00	7.8E-01	1.6E-01	5.0E-02	3.8E-02	7.5E-03	4.2E+01	3.2E+01
3.6	6.9E-02	5.2E-02	1.0E-02	3.4E-03	2.6E-03	5.2E-04	7.9E+00	3.5E+00
3.7	2.5E+00	1.9E+00	3.8E-01	1.2E-01	9.2E-02	1.8E-02	1.0E+02	7.7E+01
3.8	1.7E-01	1.3E-01	2.6E-02	8.5E-03	6.4E-03	1.3E-03	2.0E+01	8.6E+00
3.9	1.2E+00	8.7E-01	1.7E-01	5.6E-02	4.2E-02	8.4E-03	4.7E+01	3.5E+01
3.10	7.7E-02	5.8E-02	1.2E-02	3.9E-03	2.9E-03	5.8E-04	8.9E+00	3.9E+00
3.11	2.8E+00	2.1E+00	4.3E-01	1.4E-01	1.0E-01	2.1E-02	1.2E+02	8.6E+01
3.12	1.9E-01	1.4E-01	2.9E-02	9.5E-03	7.2E-03	1.4E-03	2.2E+01	9.7E+00
4.1	9.8E+00	7.4E+00	1.5E+00	4.7E-01	3.6E-01	7.2E-02	4.0E+02	3.0E+02
4.2	8.3E-01	6.2E-01	1.2E-01	4.1E-02	3.1E-02	6.2E-03	7.4E+01	3.3E+01
4.3	9.8E-01	7.4E-01	1.5E-01	4.7E-02	3.6E-02	7.2E-03	4.0E+01	3.0E+01
4.4	8.3E-02	6.2E-02	1.2E-02	4.1E-03	3.1E-03	6.2E-04	7.4E+00	3.3E+00
4.5	1.1E+00	8.3E-01	1.7E-01	5.3E-02	4.0E-02	8.0E-03	4.5E+01	3.4E+01
4.6	9.2E-02	7.0E-02	1.4E-02	4.6E-03	3.5E-03	6.9E-04	8.3E+00	3.6E+00
5.1	6.6E+02	5.0E+02	1.0E+02	3.3E+01	2.5E+01	5.0E+00	8.0E+04	3.5E+04
5.2	6.6E+01	5.0E+01	1.0E+01	3.3E+00	2.5E+00	5.0E-01	8.0E+03	3.5E+03
5.3	7.4E+01	5.6E+01	1.1E+01	3.7E+00	2.8E+00	5.6E-01	8.9E+03	4.0E+03
5.4	7.7E+01	5.8E+01	1.2E+01	2.6E+01	2.0E+01	4.0E+00	6.8E+04	2.9E+04
5.5	7.7E+00	5.8E+00	1.2E+00	2.6E+00	2.0E+00	4.0E-01	6.8E+03	2.9E+03
5.6	8.6E+00	6.5E+00	1.3E+00	3.0E+00	2.2E+00	4.5E-01	7.6E+03	3.3E+03
5.7	9.0E+02	6.8E+02	1.4E+02	4.5E+01	3.4E+01	6.8E+00	1.1E+05	4.8E+04
5.8	9.0E+01	6.8E+01	1.4E+01	4.5E+00	3.4E+00	6.8E-01	1.1E+04	4.8E+03
5.9	1.0E+02	7.6E+01	1.5E+01	5.0E+00	3.8E+00	7.6E-01	1.2E+04	5.4E+03
5.10	1.0E+02	7.9E+01	1.6E+01	3.6E+01	2.7E+01	5.4E+00	9.3E+04	4.0E+04
5.11	1.0E+01	7.9E+00	1.6E+00	3.6E+00	2.7E+00	5.4E-01	9.3E+03	4.0E+03
5.12	1.2E+01	8.9E+00	1.8E+00	4.1E+00	3.1E+00	6.1E-01	1.0E+04	4.5E+03
6.1	3.0E+00	2.3E+00	4.6E-01	1.5E-01	1.1E-01	2.3E-02	3.7E+02	1.6E+02
6.2	3.0E-01	2.3E-01	4.6E-02	1.5E-02	1.1E-02	2.3E-03	3.7E+01	1.6E+01
6.3	3.4E-01	2.6E-01	5.1E-02	1.7E-02	1.3E-02	2.6E-03	4.1E+01	1.8E+01

Scenario Label	Water Column 1 Day average	Water Column Dissolved 1 Day µg/L	Water Column Suspended 1 Day µg/L	Water Column µg/L 21 day average	Water Column 21 day Dissolved µg/L	Water Column 21 day Suspended µg/L	Sediment µg/kg 28 day average (128)[a]	Sediment µg/kg 28 day average (11)[a]
6.4	1.7E-01	1.3E-01	2.6E-02	1.5E-01	1.1E-01	2.2E-02	3.6E+02	1.6E+02
6.7	1.4E+01	1.0E+01	2.0E+00	6.7E-01	5.1E-01	1.0E-01	1.6E+03	7.2E+02
6.8	1.4E+00	1.0E+00	2.0E-01	6.7E-02	5.1E-02	1.0E-02	1.6E+02	7.2E+01
6.9	1.5E+00	1.1E+00	2.3E-01	7.6E-02	5.7E-02	1.1E-02	1.8E+02	8.1E+01
6.10	7.5E-01	5.7E-01	1.1E-01	6.5E-01	4.9E-01	9.8E-02	1.6E+03	7.0E+02
6.11	7.5E-02	5.7E-02	1.1E-02	6.5E-02	4.9E-02	9.8E-03	1.6E+02	7.0E+01
6.12	8.4E-02	6.4E-02	1.3E-02	7.3E-02	5.5E-02	1.1E-02	1.8E+02	7.8E+01
8.1	6.1E-03	4.6E-03	9.3E-04	3.1E-04	2.3E-04	4.7E-05	2.6E-01	1.9E-01
8.3	7.2E-01	5.4E-01	1.1E-01	3.7E-02	2.8E-02	5.6E-03	3.6E+01	2.3E+01
10.1	1.4E+01	1.1E+01	2.1E+00	6.8E-01	5.2E-01	1.0E-01	5.8E+02	4.3E+02
10.2	1.4E+00	1.1E+00	2.1E-01	6.8E-02	5.2E-02	1.0E-02	5.8E+01	4.3E+01
10.3	1.6E+00	1.2E+00	2.4E-01	7.6E-02	5.8E-02	1.2E-02	6.4E+01	4.8E+01
10.4	1.0E-01	7.8E-02	1.6E-02	3.5E-02	2.7E-02	5.4E-03	9.1E+01	3.9E+01
10.7	1.7E+01	1.3E+01	2.5E+00	8.1E-01	6.2E-01	1.2E-01	6.8E+02	5.2E+02
10.8	1.7E+00	1.3E+00	2.5E-01	8.1E-02	6.2E-02	1.2E-02	6.8E+01	5.2E+01
10.9	1.9E+00	1.4E+00	2.8E-01	9.1E-02	6.9E-02	1.4E-02	7.7E+01	5.8E+01
10.10	1.2E-01	9.2E-02	1.8E-02	4.2E-02	3.2E-02	6.4E-03	1.1E+02	4.7E+01
12.1	5.3E-02	4.0E-02	8.0E-03	2.6E-03	1.9E-03	3.9E-04	2.6E+00	1.6E+00
12.2	5.9E-02	4.5E-02	8.9E-03	2.9E-03	2.2E-03	4.4E-04	2.9E+00	1.8E+00
12.5	1.1E-01	8.0E-02	1.6E-02	5.1E-03	3.9E-03	7.8E-04	5.1E+00	3.3E+00
12.6	1.2E-01	8.9E-02	1.8E-02	5.8E-03	4.4E-03	8.7E-04	5.7E+00	3.6E+00

[a] sediment benthic half-life (days)

Table 2-95. Highly Exposed Group: Range of HBCD Fish Ingestion Dose by Scenario and Age Group, Acute Dose Rate (mg/kg/day)

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
1. Processing: Repackaging of Import Containers	NA	3.9E-03 - 2.7E-02	3.2E-03 - 2.2E-02	3.0E-03 - 2.0E-02	2.3E-03 - 1.6E-02	1.4E-03 - 9.5E-03	2.7E-03 - 1.8E-02
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	NA	2.3E-04 - 5.1E-03	1.9E-04 - 4.2E-03	1.7E-04 - 3.9E-03	1.3E-04 - 3.0E-03	8.0E-05 - 1.8E-03	1.5E-04 - 3.4E-03
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	NA	5.0E-05 - 1.8E-02	4.1E-05 - 1.5E-02	3.8E-05 - 1.3E-02	2.9E-05 - 1.0E-02	1.8E-05 - 6.3E-03	3.4E-05 - 1.2E-02
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	NA	5.9E-05 - 6.9E-03	4.9E-05 - 5.7E-03	4.5E-05 - 5.2E-03	3.5E-05 - 4.0E-03	2.1E-05 - 2.4E-03	4.0E-05 - 4.6E-03
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	NA	3.8E-02 - 6.5E-01	3.2E-02 - 5.4E-01	2.9E-02 - 4.9E-01	2.2E-02 - 3.8E-01	1.4E-02 - 2.3E-01	2.6E-02 - 4.4E-01
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	NA	2.2E-04 - 9.8E-03	1.8E-04 - 8.1E-03	1.7E-04 - 7.4E-03	1.3E-04 - 5.7E-03	7.8E-05 - 3.5E-03	1.5E-04 - 6.6E-03
7. Use: Installation of Automobile Replacement Parts	No water releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	NA	4.5E-06 - 5.3E-04	3.7E-06 - 4.4E-04	3.4E-06 - 4.0E-04	2.6E-06 - 3.1E-04	1.6E-06 - 1.9E-04	3.0E-06 - 3.6E-04
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	NA	5.1E-04 - 1.2E-02	4.2E-04 - 9.7E-03	3.9E-04 - 8.9E-03	3.0E-04 - 6.9E-03	1.8E-04 - 4.2E-03	3.5E-04 - 8.0E-03
11. Processing: Formulation of Coatings and solder	No water releases						
12. Use of Solder	NA	3.7E-05 - 8.3E-05	3.1E-05 - 6.9E-05	2.8E-05 - 6.3E-05	2.2E-05 - 4.9E-05	1.3E-05 - 3.0E-05	2.5E-05 - 5.6E-05

Table 2-96. Highly Exposed Group: Range of HBCD Fish Ingestion by Scenario and Age Group, Average Daily Dose (mg/kg/day)

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)	
							HE	CT
1. Processing: Repackaging of Import Containers	NA	1.7E-05 - 4.8E-04	1.4E-05 - 3.9E-04	1.2E-05 - 3.4E-04	1.1E-05 - 3.1E-04	6.3E-06 - 1.8E-04	1.1E-05 - 3.2E-04	4.4E-06 - 1.2E-04
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	NA	1.0E-06 - 2.2E-05	8.3E-07 - 1.9E-05	7.2E-07 - 1.6E-05	6.6E-07 - 1.5E-05	3.7E-07 - 8.2E-06	6.6E-07 - 1.5E-05	2.6E-07 - 5.8E-06
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	NA	2.2E-07 - 7.9E-05	1.8E-07 - 6.5E-05	1.5E-07 - 5.7E-05	1.4E-07 - 5.2E-05	8.0E-08 - 2.9E-05	1.4E-07 - 5.2E-05	5.6E-08 - 2.1E-05

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)	
							HE	CT
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	NA	2.6E-07 - 3.1E-05	2.1E-07 - 2.6E-05	1.9E-07 - 2.2E-05	1.7E-07 - 2.0E-05	9.5E-08 - 1.1E-05	1.7E-07 - 2.0E-05	6.7E-08 - 8.0E-06
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	NA	1.7E-04 - 2.8E-03	1.4E-04 - 2.3E-03	1.2E-04 - 2.0E-03	1.1E-04 - 1.9E-03	6.1E-05 - 1.0E-03	1.1E-04 - 1.9E-03	4.3E-05 - 7.4E-04
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	NA	9.5E-07 - 4.3E-05	7.9E-07 - 3.5E-05	6.8E-07 - 3.0E-05	6.3E-07 - 2.8E-05	3.5E-07 - 1.6E-05	6.3E-07 - 2.8E-05	2.5E-07 - 1.1E-05
7. Use: Installation of Automobile Replacement Parts	No water releases							
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	NA	5.9E-08 - 6.9E-06	4.9E-08 - 5.7E-06	4.2E-08 - 5.0E-06	3.9E-08 - 4.6E-06	2.2E-08 - 2.5E-06	3.9E-08 - 4.6E-06	1.5E-08 - 1.8E-06
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases							
10. Processing: Recycling of EPS Foam	NA	2.2E-06 - 5.3E-05	1.8E-06 - 4.4E-05	1.6E-06 - 3.8E-05	1.5E-06 - 3.5E-05	8.2E-07 - 1.9E-05	1.5E-06 - 3.5E-05	5.8E-07 - 1.4E-05
11. Processing: Formulation of Coatings and solder	No water releases							
12. Use of Solder	NA	1.7E-07 - 1.5E-06	1.4E-07 - 1.3E-06	1.2E-07 - 1.1E-06	1.1E-07 - 1.0E-06	6.1E-08 - 5.6E-07	1.1E-07 - 1.0E-06	4.3E-08 - 4.0E-07

For estimating exposures to suspended particulate associated with point sources to highly exposed populations, EPA used the IIOAC model as described in Section 2.3.2. These exposures result from air or incineration emissions associated with the scenario specific conditions of use. The results of all estimated inhalation ADRs and ADDs are presented in Table 2-97 and Table 2-98. A summary of the resulting inhalation doses are shown in Table 2-97 and Table 2-98 arrayed by scenario and age group.

Table 2-97. Highly Exposed Group: Range of HBCD Inhalation Dose by Scenario and Age Group, Acute Dose Rate (mg/kg/day)

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
1. Processing: Repackaging of Import Containers	3.9E-07 - 7.0E-03	3.8E-07 - 6.7E-03	3.3E-07 - 5.9E-03	2.5E-07 - 4.4E-03	1.7E-07 - 3.1E-03	1.3E-07 - 2.3E-03	9.5E-08 - 1.7E-03
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	5.8E-07 - 3.1E-05	5.6E-07 - 3.0E-05	5.0E-07 - 2.7E-05	3.7E-07 - 2.0E-05	2.6E-07 - 1.4E-05	1.9E-07 - 1.0E-05	1.4E-07 - 7.7E-06
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	2.2E-05 - 3.3E-03	2.1E-05 - 3.2E-03	1.9E-05 - 2.8E-03	1.4E-05 - 2.1E-03	9.7E-06 - 1.4E-03	7.3E-06 - 1.1E-03	5.4E-06 - 8.1E-04
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	2.8E-06 - 3.4E-03	2.7E-06 - 3.3E-03	2.4E-06 - 2.9E-03	1.8E-06 - 2.2E-03	1.2E-06 - 1.5E-03	9.1E-07 - 1.1E-03	6.8E-07 - 8.4E-04
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	2.5E-05 - 1.3E-02	2.4E-05 - 1.3E-02	2.1E-05 - 1.1E-02	1.6E-05 - 8.5E-03	1.1E-05 - 5.9E-03	8.2E-06 - 4.4E-03	6.1E-06 - 3.3E-03

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	7.1E-07 - 6.0E-04	6.8E-07 - 5.8E-04	6.0E-07 - 5.1E-04	4.5E-07 - 3.8E-04	3.1E-07 - 2.7E-04	2.3E-07 - 2.0E-04	1.7E-07 - 1.5E-04
7. Use: Installation of Automobile Replacement Parts	No releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	1.1E-07 - 1.1E-05	1.0E-07 - 1.0E-05	9.1E-08 - 9.1E-06	6.8E-08 - 6.7E-06	4.7E-08 - 4.7E-06	3.5E-08 - 3.5E-06	2.6E-08 - 2.6E-06
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	1.7E-08 - 2.0E-04	1.7E-08 - 1.9E-04	1.5E-08 - 1.7E-04	1.1E-08 - 1.3E-04	7.7E-09 - 8.8E-05	5.7E-09 - 6.6E-05	4.3E-09 - 4.9E-05
11. Processing: Formulation of Coatings and solder	3.5E-07 - 1.9E-04	3.4E-07 - 1.9E-04	3.0E-07 - 1.7E-04	2.2E-07 - 1.2E-04	1.5E-07 - 8.5E-05	1.1E-07 - 6.4E-05	8.5E-08 - 4.8E-05
12. Use of Solder	6.9E-09 - 1.5E-06	6.6E-09 - 1.4E-06	5.9E-09 - 1.2E-06	4.4E-09 - 9.2E-07	3.0E-09 - 6.4E-07	2.3E-09 - 4.8E-07	1.7E-09 - 3.6E-07

Table 2-98. Highly Exposed Group: Background and Air Modeling by Age Group, Average Daily Dose (mg/kg/day)

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)	
							HE	CT
1. Processing: Repackaging of Import Containers	1.8E-07 - 3.1E-06	1.8E-07 - 3.2E-06	1.7E-07 - 2.9E-06	1.4E-07 - 2.4E-06	9.7E-08 - 1.7E-06	6.9E-08 - 1.2E-06	3.0E-08 - 5.2E-07	1.2E-08 - 2.1E-07
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	2.9E-09 - 4.5E-09	2.9E-09 - 4.6E-09	2.7E-09 - 4.2E-09	2.3E-09 - 3.5E-09	1.5E-09 - 2.4E-09	1.1E-09 - 1.7E-09	4.8E-10 - 7.5E-10	1.9E-10 - 3.0E-10
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	2.7E-08 - 3.5E-08	2.8E-08 - 3.6E-08	2.5E-08 - 3.3E-08	2.1E-08 - 2.8E-08	1.5E-08 - 1.9E-08	1.0E-08 - 1.4E-08	4.6E-09 - 6.0E-09	1.8E-09 - 2.4E-09
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	3.4E-09 - 2.4E-07	3.5E-09 - 2.5E-07	3.2E-09 - 2.3E-07	2.7E-09 - 1.9E-07	1.8E-09 - 1.3E-07	1.3E-09 - 9.4E-08	5.7E-10 - 4.1E-08	2.3E-10 - 1.6E-08
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	4.7E-07 - 7.2E-06	4.8E-07 - 7.4E-06	4.4E-07 - 6.7E-06	3.7E-07 - 5.6E-06	2.5E-07 - 3.9E-06	1.8E-07 - 2.8E-06	7.9E-08 - 1.2E-06	3.1E-08 - 4.8E-07
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	2.4E-08 - 4.5E-06	2.4E-08 - 4.6E-06	2.2E-08 - 4.3E-06	1.9E-08 - 3.6E-06	1.3E-08 - 2.4E-06	9.2E-09 - 1.8E-06	4.0E-09 - 7.6E-07	1.6E-09 - 3.0E-07
7. Use: Installation of Automobile Replacement Parts	No releases							
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	1.1E-12 - 1.3E-08	1.2E-12 - 1.4E-08	1.1E-12 - 1.2E-08	9.0E-13 - 1.0E-08	6.2E-13 - 7.1E-09	4.5E-13 - 5.1E-09	1.9E-13 - 2.2E-09	7.6E-14 - 8.7E-10

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)	
							HE	CT
9. Demolition and Disposal of Insulation in Buildings	No site specific releases							
10. Processing: Recycling of EPS Foam	3.3E-10 - 3.1E-09	3.4E-10 - 3.2E-09	3.1E-10 - 2.9E-09	2.6E-10 - 2.5E-09	1.8E-10 - 1.7E-09	1.3E-10 - 1.2E-09	5.5E-11 - 5.3E-10	2.2E-11 - 2.1E-10
11. Processing: Formulation of Coatings and solder	4.6E-09 - 5.3E-08	4.8E-09 - 5.5E-08	4.4E-09 - 5.0E-08	3.6E-09 - 4.2E-08	2.5E-09 - 2.9E-08	1.8E-09 - 2.1E-08	7.8E-10 - 9.0E-09	3.1E-10 - 3.5E-09
12. Use of Solder	3.2E-09 - 3.5E-09	3.2E-09 - 3.6E-09	3.0E-09 - 3.3E-09	2.5E-09 - 2.8E-09	1.7E-09 - 1.9E-09	1.2E-09 - 1.4E-09	5.3E-10 - 6.0E-10	2.1E-10 - 2.4E-10

The approach for estimating general population exposures was discussed throughout Section 2.4.2 for the dust, soil, air, diet and dermal pathways and the resulting average daily doses, arrayed by pathway and age group are summarized in Table 2-99 (central tendency) and Table 2-101 (high end). The relative contribution of each pathway to the aggregated exposure is shown in Table 2-100 (central tendency) and Table 2-102 (high end). Based on these calculations, it can be seen that the predominant sources of exposure are from dust ingestion and diet, with the contribution of dust to the overall exposure being much more dominant in younger age groups. This is likely due to the exposure factors and behavior patterns of infants, young toddlers and children as they spend more time closer to sources of settled dust and are more likely to exhibit hand to mouth behaviors.

Table 2-99. General Population Central Tendency HBCD Exposure by Pathway and Age Group - Average Daily Dose (mg/kg/day)

Age Group	DUST	SOIL	AIR	DIET	DERMAL	ALL
Infant (<1 year)	2.4E-05	1.6E-07	5.4E-08	7.4E-06	6.7E-07	3.2E-05
Young Toddler (1-<2 years)	2.8E-05	1.8E-07	5.5E-08	9.0E-06	5.7E-07	3.8E-05
Toddler (2-<3 years)	1.4E-05	1.1E-07	5.0E-08	7.1E-06	4.9E-07	2.2E-05
Small Child (3-<6 years)	1.0E-05	8.1E-08	4.2E-08	5.1E-06	4.0E-07	1.6E-05
Child (6-<11 years)	6.0E-06	4.7E-08	2.9E-08	3.3E-06	3.2E-07	9.7E-06
Teen (11-<16 years)	2.2E-06	8.8E-09	2.1E-08	1.8E-06	2.9E-07	4.4E-06
Adult (16-<70 years)	1.6E-06	6.3E-09	1.5E-08	1.2E-06	3.1E-07	3.2E-06

Table 2-100. General Population Central Tendency Source Contribution by Pathway and Age Group (% Contribution to Total HBCD Exposure)

Age Group	DUST	SOIL	AIR	DIET	DERMAL
Infant (<1 year)	74.5%	0.5%	0.2%	22.8%	2.1%
Young Toddler (1-<2 years)	73.9%	0.5%	0.1%	23.9%	1.5%
Toddler (2-<3 years)	63.9%	0.5%	0.2%	33.1%	2.3%
Small Child (3-<6 years)	64.6%	0.5%	0.3%	32.1%	2.5%
Child (6-<11 years)	61.8%	0.5%	0.3%	34.1%	3.3%

Teen (11-<16 years)	51.1%	0.2%	0.5%	41.6%	6.6%
Adult (16-<70 years)	50.5%	0.2%	0.5%	39.1%	9.7%

Table 2-101. General Population High End HBCD Exposure by Pathway and Age Group, Average Daily Dose (mg/kg/day)

Age Group	DUST	SOIL	AIR	DIET	DERMAL	ALL
Infant (<1 year)	2.0E-04	8.9E-07	1.7E-06	2.1E-04	1.4E-05	4.3E-04
Young Toddler (1 - <2 years)	1.7E-04	7.9E-07	1.6E-06	1.5E-04	1.2E-05	3.4E-04
Toddler (2-<3 years)	1.4E-04	6.5E-07	1.4E-06	1.3E-04	1.0E-05	2.8E-04
Small Child (3-<6 years)	1.1E-04	4.8E-07	1.1E-06	9.2E-05	8.4E-06	2.1E-04
Child (6-<11 years)	6.1E-05	2.8E-07	7.5E-07	6.1E-05	6.7E-06	1.3E-04
Teen (11-<16 years)	2.1E-05	8.8E-08	5.5E-07	3.7E-05	6.1E-06	6.4E-05
Adult (16-<70 years)	1.5E-05	6.3E-08	3.9E-07	2.6E-05	6.5E-06	4.8E-05

Table 2-102. General Population High End Source Contribution by Pathway and Age Group (% Contribution to Total HBCD Exposure)

Age Group	DUST	SOIL	AIR	DIET	DERMAL
Infant (<1 year)	46.7%	0.2%	0.4%	49.3%	3.3%
Young Toddler (1-<2 years)	50.5%	0.2%	0.5%	45.2%	3.6%
Toddler (2-<3 years)	50.6%	0.2%	0.5%	44.9%	3.7%
Small Child (3-<6 years)	50.7%	0.2%	0.5%	44.4%	4.1%
Child (6-<11 years)	47.2%	0.2%	0.6%	46.9%	5.1%
Teen (11-<16 years)	32.2%	0.1%	0.9%	57.2%	9.5%
Adult (16-<70 years)	31.2%	0.1%	0.8%	54.1%	13.7%

Table 2-103. Range of HBCD Aggregate Exposure Acute Dose Rate (mg/kg/day) - Background and Modeled Fish Dose by Scenario and Age

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
1. Processing: Repackaging of Import Containers	NA	4.3E-03 - 2.7E-02	3.5E-03 - 2.2E-02	3.2E-03 - 2.1E-02	2.4E-03 - 1.6E-02	1.5E-03 - 9.6E-03	2.7E-03 - 1.8E-02
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	NA	5.7E-04 - 5.4E-03	4.7E-04 - 4.5E-03	3.8E-04 - 4.1E-03	2.6E-04 - 3.1E-03	1.4E-04 - 1.9E-03	2.0E-04 - 3.5E-03
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	NA	3.9E-04 - 1.8E-02	3.2E-04 - 1.5E-02	2.5E-04 - 1.4E-02	1.6E-04 - 1.1E-02	8.2E-05 - 6.3E-03	8.1E-05 - 1.2E-02
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	NA	4.0E-04 - 7.2E-03	3.3E-04 - 6.0E-03	2.5E-04 - 5.4E-03	1.6E-04 - 4.2E-03	8.5E-05 - 2.5E-03	8.7E-05 - 4.7E-03

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	NA	3.9E-02 - 6.5E-01	3.2E-02 - 5.4E-01	2.9E-02 - 4.9E-01	2.3E-02 - 3.8E-01	1.4E-02 - 2.3E-01	2.6E-02 - 4.4E-01
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	NA	5.6E-04 - 1.0E-02	4.6E-04 - 8.3E-03	3.8E-04 - 7.6E-03	2.6E-04 - 5.9E-03	1.4E-04 - 3.5E-03	1.9E-04 - 6.6E-03
7. Use: Installation of Automobile Replacement Parts	No water releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	NA	3.4E-04 - 8.7E-04	2.8E-04 - 7.2E-04	2.1E-04 - 6.1E-04	1.3E-04 - 4.4E-04	6.6E-05 - 2.5E-04	5.0E-05 - 4.1E-04
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	NA	8.5E-04 - 1.2E-02	7.0E-04 - 1.0E-02	6.0E-04 - 9.1E-03	4.3E-04 - 7.1E-03	2.5E-04 - 4.2E-03	3.9E-04 - 8.0E-03
11. Processing: Formulation of Coatings and solder	No water releases						
12. Use of Solder	NA	3.8E-04 - 4.2E-04	3.1E-04 - 3.5E-04	2.4E-04 - 2.7E-04	1.5E-04 - 1.8E-04	7.7E-05 - 9.4E-05	7.2E-05 - 1.0E-04

Table 2-104. Range of HBCD Aggregate Exposure Average Daily Dose (mg/kg/day): Background and Modeled Fish Dose by Scenario and Age

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
1. Processing: Repackaging of Import Containers	NA	3.6E-04 - 8.2E-04	2.9E-04 - 6.7E-04	2.2E-04 - 5.5E-04	1.4E-04 - 4.4E-04	7.0E-05 - 2.4E-04	5.8E-05 - 3.6E-04
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	NA	3.4E-04 - 3.6E-04	2.8E-04 - 3.0E-04	2.1E-04 - 2.3E-04	1.3E-04 - 1.4E-04	6.4E-05 - 7.2E-05	4.8E-05 - 6.2E-05
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	NA	3.4E-04 - 4.2E-04	2.8E-04 - 3.5E-04	2.1E-04 - 2.7E-04	1.3E-04 - 1.8E-04	6.4E-05 - 9.3E-05	4.7E-05 - 9.9E-05
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	NA	3.4E-04 - 3.7E-04	2.8E-04 - 3.1E-04	2.1E-04 - 2.3E-04	1.3E-04 - 1.5E-04	6.4E-05 - 7.5E-05	4.7E-05 - 6.7E-05
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	NA	5.1E-04 - 3.2E-03	4.2E-04 - 2.6E-03	3.3E-04 - 2.2E-03	2.4E-04 - 2.0E-03	1.3E-04 - 1.1E-03	1.6E-04 - 1.9E-03
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	NA	3.4E-04 - 3.8E-04	2.8E-04 - 3.2E-04	2.1E-04 - 2.4E-04	1.3E-04 - 1.6E-04	6.4E-05 - 8.0E-05	4.8E-05 - 7.5E-05
7. Use: Installation of Automobile Replacement Parts	No water releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	NA	3.4E-04 - 3.5E-04	2.8E-04 - 2.9E-04	2.1E-04 - 2.1E-04	1.3E-04 - 1.3E-04	6.4E-05 - 6.7E-05	4.7E-05 - 5.2E-05

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	NA	3.4E-04 - 3.9E-04	2.8E-04 - 3.2E-04	2.1E-04 - 2.5E-04	1.3E-04 - 1.6E-04	6.5E-05 - 8.3E-05	4.8E-05 - 8.2E-05
11. Processing: Formulation of Coatings and solder	No water releases						
12. Use of Solder	NA	3.4E-04 - 3.4E-04	2.8E-04 - 2.8E-04	2.1E-04 - 2.1E-04	1.3E-04 - 1.3E-04	6.4E-05 - 6.5E-05	4.7E-05 - 4.8E-05

Table 2-105. Range of HBCD Aggregate Exposure Acute Dose Rate (mg/kg/day): Background and Modeled Inhalation Dose by Scenario and Age

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
1. Processing: Repackaging of Import Containers	3.2E-05 - 7.0E-03	3.7E-05 - 6.8E-03	2.1E-05 - 6.0E-03	1.6E-05 - 4.4E-03	9.8E-06 - 3.1E-03	4.4E-06 - 2.3E-03	3.3E-06 - 1.7E-03
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	5.8E-07 - 3.1E-05	3.8E-05 - 6.7E-05	2.1E-05 - 4.8E-05	1.6E-05 - 3.6E-05	9.9E-06 - 2.3E-05	4.5E-06 - 1.5E-05	3.3E-06 - 1.1E-05
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	2.2E-05 - 3.3E-03	5.8E-05 - 3.2E-03	4.0E-05 - 2.8E-03	3.0E-05 - 2.1E-03	1.9E-05 - 1.5E-03	1.2E-05 - 1.1E-03	8.6E-06 - 8.1E-04
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	2.8E-06 - 3.4E-03	4.0E-05 - 3.4E-03	2.3E-05 - 3.0E-03	1.8E-05 - 2.2E-03	1.1E-05 - 1.5E-03	5.2E-06 - 1.1E-03	3.9E-06 - 8.5E-04
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	2.5E-05 - 1.3E-02	6.1E-05 - 1.3E-02	4.2E-05 - 1.1E-02	3.2E-05 - 8.5E-03	2.1E-05 - 5.9E-03	1.3E-05 - 4.4E-03	9.3E-06 - 3.3E-03
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	7.1E-07 - 6.0E-04	3.8E-05 - 6.2E-04	2.2E-05 - 5.4E-04	1.6E-05 - 4.0E-04	9.9E-06 - 2.8E-04	4.5E-06 - 2.0E-04	3.4E-06 - 1.5E-04
7. Use: Installation of Automobile Replacement Parts	No water releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	1.1E-07 - 1.1E-05	3.7E-05 - 4.7E-05	2.1E-05 - 3.0E-05	1.6E-05 - 2.3E-05	9.6E-06 - 1.4E-05	4.3E-06 - 7.8E-06	3.2E-06 - 5.8E-06
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	1.7E-08 - 2.0E-04	3.7E-05 - 2.3E-04	2.1E-05 - 1.9E-04	1.6E-05 - 1.4E-04	9.6E-06 - 9.7E-05	4.3E-06 - 7.0E-05	3.2E-06 - 5.2E-05
11. Processing: Formulation of Coatings and solder	3.5E-07 - 1.9E-04	3.7E-05 - 2.2E-04	2.1E-05 - 1.9E-04	1.6E-05 - 1.4E-04	9.8E-06 - 9.5E-05	4.4E-06 - 6.8E-05	3.3E-06 - 5.1E-05
12. Use of Solder	6.9E-09 - 1.5E-06	3.7E-05 - 3.8E-05	2.1E-05 - 2.2E-05	1.6E-05 - 1.7E-05	9.6E-06 - 1.0E-05	4.3E-06 - 4.8E-06	3.2E-06 - 3.6E-06

Table 2-106. Range of HBCD Aggregate Exposure Average Daily Dose (mg/kg/day): Background and Modeled Inhalation Dose by Scenario and Age

SCENARIO NAME	Infant (<1 yr)	Young Toddler (1-<2 yrs)	Toddler (2-<3 yrs)	Small Child (3-<6 yrs)	Child (6-<11 yrs)	Teen (11-<16 yrs)	Adult (16-<70 yrs)
1. Processing: Repackaging of Import Containers	3.2E-05 - 3.5E-05	3.7E-05 - 4.0E-05	2.1E-05 - 2.4E-05	1.6E-05 - 1.8E-05	9.7E-06 - 1.1E-05	4.4E-06 - 5.5E-06	3.2E-06 - 3.7E-06
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	2.9E-09 - 4.5E-09	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.6E-06	4.3E-06 - 4.3E-06	3.2E-06 - 3.2E-06
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	2.7E-08 - 3.5E-08	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.6E-06	4.3E-06 - 4.3E-06	3.2E-06 - 3.2E-06
4. Processing: Manufacturing of XPS Foam Using HBCD Powder	3.4E-09 - 2.4E-07	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.7E-06	4.3E-06 - 4.4E-06	3.2E-06 - 3.2E-06
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	4.7E-07 - 7.2E-06	3.7E-05 - 4.4E-05	2.1E-05 - 2.8E-05	1.6E-05 - 2.2E-05	9.9E-06 - 1.3E-05	4.5E-06 - 7.1E-06	3.3E-06 - 4.4E-06
6. Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	2.4E-08 - 4.5E-06	3.7E-05 - 4.2E-05	2.1E-05 - 2.5E-05	1.6E-05 - 2.0E-05	9.6E-06 - 1.2E-05	4.3E-06 - 6.1E-06	3.2E-06 - 4.0E-06
7. Use: Installation of Automobile Replacement Parts	No water releases						
8. Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and other Structures	1.1E-12 - 1.3E-08	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.6E-06	4.3E-06 - 4.3E-06	3.2E-06 - 3.2E-06
9. Demolition and Disposal of Insulation in Buildings	No site specific water releases						
10. Processing: Recycling of EPS Foam	3.3E-10 - 3.1E-09	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.6E-06	4.3E-06 - 4.3E-06	3.2E-06 - 3.2E-06
11. Processing: Formulation of Coatings and solder	4.6E-09 - 5.3E-08	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.6E-06	4.3E-06 - 4.3E-06	3.2E-06 - 3.2E-06
12. Use of Solder	3.2E-09 - 3.5E-09	3.7E-05 - 3.7E-05	2.1E-05 - 2.1E-05	1.6E-05 - 1.6E-05	9.6E-06 - 9.6E-06	4.3E-06 - 4.3E-06	3.2E-06 - 3.2E-06

2.4.2.9 Sensitivity Analysis - Human Exposure

Similar to the environmental exposure assessment, EPA conducted a targeted sensitivity analysis for human exposures.

2.4.2.9.1 Sensitivity Analysis – Infant Exposures

For the highly exposed general population, EPA further considered infant exposures and reports additional percentiles beyond the 95th percentile using different assumptions. In EPA's approach, the selection of which upper percentile is assigned to the high-end monitoring data is generally more sensitive than the selection of the geometric mean.

In this sensitivity analysis, EPA examined the effect of varying three assumptions related to the stochastic modeling of HBCD aggregate dose for infants (<1 year) in the general population:

1. In the baseline stochastic analysis of HBCD doses modeled above, only the 95th percentile estimate of modeled HBCD doses is reported as a high-end estimate. In this analysis, EPA also reported the 96th, 97th, 98th, 99th, and 99.5th percentiles of estimated HBCD dose.
2. In the baseline (previous) analysis, environmental concentrations were assumed to follow lognormal distributions, with the central tendency and high-end concentrations reported in monitoring data used to define the shape of the lognormal distribution. Specifically, the central tendency estimate from monitoring data was assumed to correspond to the median of the lognormal distribution, while the high-end estimate from monitoring data was assumed to correspond to either the 95th percentile (for soil and dust) or the 90th percentile (all other environmental and biotic media). In this analysis, EPA varied this assumption by allowing all high-end monitoring data values to represent the 90th, 95th, and 99th percentile of the underlying lognormal distribution.
3. In the baseline analysis, the central tendency estimate from monitoring data was assumed to correspond to the median of the lognormal distribution, which is equivalent to assuming that the central tendency estimate was equal to the geometric mean of the underlying distribution. In this analysis, EPA varied this assumption by 10% in either direction of the geometric mean to evaluate the sensitivity of the output to the central tendency estimate.

The results of varying assumptions 1 and 2 in the sensitivity analysis are visualized in Figure 2-6. The x-axis shows alternative percentiles that can be used to estimate the high-end dose, ranging from the 95th to the 99.5th percentile of the output dose distribution. The y-axis displays the estimated dose in mg/kg/day at each of these percentiles. The different curves each represent an alternative assumption with respect to the shape of the underlying environmental distributions. Specifically, each series presents an analysis based on assuming the reported high-end monitoring data value for environmental concentrations represented either the 90th, 95th, or 99th percentile of the underlying lognormal distribution; the baseline analysis is also pictured.

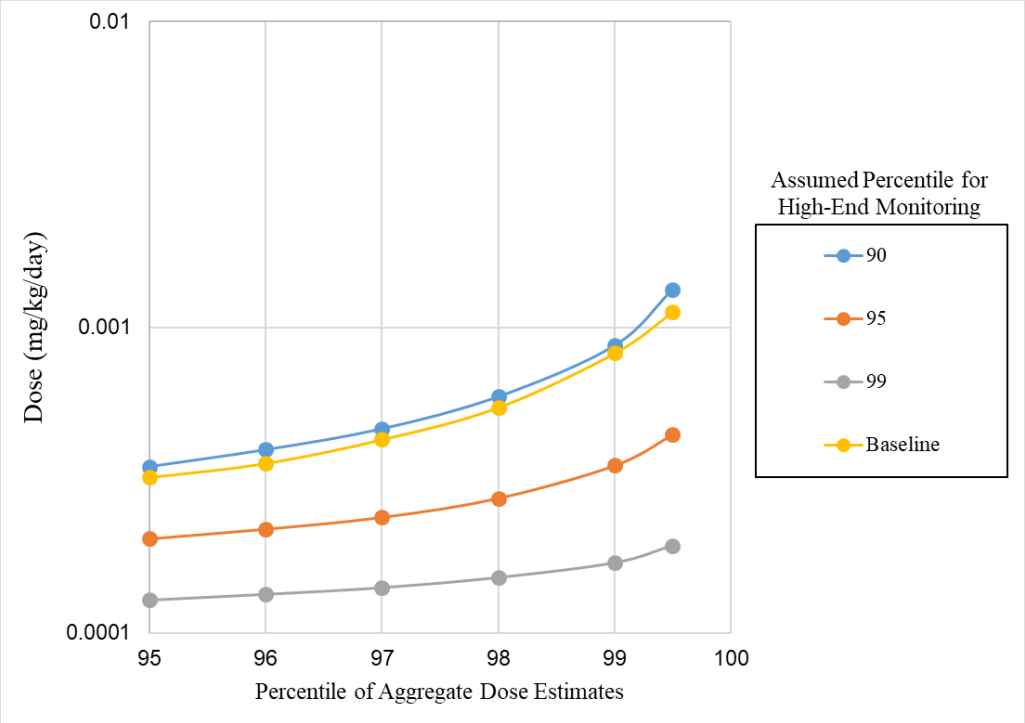

Figure 2-6. Comparison of HBCD Dose for Infants in the General Population from Different Sensitivity Analyses

Based on a review of Figure 2-6, it is possible to conclude:

- High-end aggregate dose estimates are sensitive to the choice of percentile used to represent high-end doses. Choosing the 99.5th percentile of the stochastic dose output instead of the 95th percentile can increase estimated high-end dose by a factor of 3. This is consistent with the theoretical expectation that dose estimates would be left skewed in their distribution with a long tail to the right.
- It is assumed that the reported high-end value from monitoring data represents a higher end percentile of the underlying distribution of environmental data (e.g. 99th percentile instead of 90th percentile), the estimated dose decreases. This is consistent with the theoretical expectation that a longer tail will result in larger estimated dose.
- The baseline analysis is very similar to the analysis in which the reported high-end value from monitoring data represents the 90th percentile of the underlying distribution of environmental data. This is because the baseline analysis assumes the reported monitoring high-end estimate represents the 90th percentile for all distributions except soil and dust for which it was assumed to represent the 95th percentile.

The results of varying assumption 3 in the sensitivity analysis are summarized in Table 2-107.

Table 2-107. Sensitivity Analysis of Central Tendency Estimate Assumptions in Monitoring Data

	Estimated Dose in mg/kg/day		
	Baseline GM	**Baseline GM + 10%**	**Baseline GM - 10%**
95th Percentile Dose	3.12E-04	3.23E-04	2.91E-04
% Change from Baseline	--	4%	-7%
GM = geometric mean			

The highest theoretical maximum aggregate exposure to infants is 3.59E-3 mg/kg-day, where the maximum modeled HBCD dose is combined with the lower (90th) assumed percentile of the underlying distribution of environmental data. This value is similar to the maximum modeled HBCD dose from the higher-end assumption (+10%) of the true central tendency value (3.45E-3 mg/kg-day).

2.4.2.9.2 Sensitivity Analysis – Variation in Production Volume

EPA considered releases using three production volumes acknowledging decreasing trends of releases. EPA notes that chronic doses decrease by a factor of approximately two to four when releases are similarly reduced by a factor of two to four. Acute doses are approximately the same because EPA inferred that reduced release days when the magnitude of releases decreases. EPA also considered three separate approaches to estimated fish doses and the overall magnitude and trends associated with all three approaches are similar.

A sensitivity analysis examining varying production volume and waste water treatment removal was conducted for human exposures, using a parallel approach as was described in Section 2.3.7 for environmental exposures. The results are summarized in the table below. The estimated surface water concentrations were used to derive fish ingestion doses as described previously in Section 2.4.2.3.

Table 2-108. Summary of Surface Water Concentrations from Sensitivity Analysis: Varying HBCD Production Volume and Waste Water Treatment Removal –Human Exposures (Fish Ingestion)

SCENARIO NAME	Production Volume (lbs / year)	% WWTP Removal for Direct Releases	Surface Water 21-Day Average Dissolved Concentration Range (µg/L)	
			Acute: 10th %-ile Flow	Chronic: 50th %-ile Flow
Scenario 1. Import and Re-packaging/ Processing: Repackaging of Import Containers	100,000	90%	2.1E-01 - 1.4E+00	6.9E-03 - 2.0E-01
	50,000	90%	1.2E-01 - 7.5E-01	4.1E-03 - 1.0E-01
	25,000	90%	6.0E-02 - 7.1E-01	2.0E-03 - 1.0E-01
Scenario 3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	100,000	0%	2.6E-03 - 9.2E-01	8.9E-05 - 3.2E-02
		75%	2.6E-03 - 2.3E-01	8.9E-05 - 1.5E-02
	50,000	0 %	1.3E-03 - 4.6E-01	4.4E-05 - 1.6E-02
		75 %	1.3E-03 - 1.2E-01	4.4E-05 - 7.5E-03
	25,000	0 %	6.5E-04 - 2.3E-01	2.2E-05 - 8.2E-03
		75%	6.5E-04 - 5.8E-02	2.2E-05 - 3.7E-03
Scenario 5. Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads	100,000	0 %	2.0E+00 - 3.4E+01	6.8E-02 - 1.2E+00
		75%	2.6E+00 - 1.1E+01	9.0E-02 - 7.0E-01
	50,000	0 %	4.4E-01 - 1.1E+02	1.7E-02 - 1.2E+00
		75 %	4.4E-01 - 5.3E+01	2.3E-02 - 7.0E-01

SCENARIO NAME	Production Volume (lbs / year)	% WWTP Removal for Direct Releases	Surface Water 21-Day Average Dissolved Concentration Range (µg/L)	
			Acute: 10th %-ile Flow	Chronic: 50th %-ile Flow
	25,000	0 %	5.0E-01 - 3.6E+01	7.4E-02 - 5.0E+00
		75 %	6.6E-01 - 1.1E+01	7.4E-02 - 2.5E+00

2.4.2.10 Assumptions and Key Sources of Uncertainty in the General Population, Highly Exposed, and Consumer Exposure Assessment

Estimates of general population exposures based on environmental monitoring and biomonitoring data represent the conditions present at the time the data was collected. It is unknown which combination of potential sources associated with conditions of use as described in this risk evaluation contribute to the monitoring data presented here. However, given the wide range of exposures shown within and across the monitoring data, there is a plausible contribution from some of the sources/conditions of use described within this document.

For the general population assessment, EPA used central tendency and high-end environmental monitoring data informed by all studies for a given media that passed evaluation. EPA also compared pathway specific estimates with completed assessments already reported in the literature. For example, EPA's dietary assessment is of similar magnitude to (Barghi et al., 2016). EPA also used all extracted biomonitoring data and estimated external doses based on assumptions of lipid-weight percentages and half-life in the body. While there are approximately 400 monitoring studies across all media, there are limited studies within the U.S. to characterize current and spatially diverse environmental levels. It is unknown whether the currently available HBCD concentrations in environmental media outside of the U.S. are representative of values in the U.S. While some media such as indoor dust and sediment have relatively more data, other matrices such as human biota and surface water are less well characterized. A qualitative assessment of the uncertainty, sensitivity, and variability associated with this approach is presented in the Table 2-109 below.

Table 2-109. Qualitative Assessment of the Uncertainty and Variability Associated with General Population Assessment

Variable Name	Data Source	Uncertainty (L, H)	Variability (L, H)
General Population Exposure Assessment (based on Environmental Monitoring)			
Environmental Monitoring Data	Extracted and evaluated data (all) plus key studies	L	H
Exposure Factors and Activity Patterns	Exposure Factors Handbook	L	L
General Population Exposure Assessment (based on Biomonitoring)			
Biomonitoring Data	Extracted and evaluated data (all) plus key studies	L	H
Half-life in the body	Select studies	H	H
Lipid weight in the matrix	Select studies	L	H

For the highly exposed group, EPA modeled three pathways: air, water to fish (fish ingestion), and consumer articles to indoor air and dust. There are more input parameters used across these three modeling approaches. EPA balanced a combination of central tendency and high-end inputs for these modeled scenarios. Further, each scenario was split into many sub-scenarios to fully explore potential variability. Modeled estimates were compared with monitoring data to ensure overlap and evaluate the overall magnitude and trends. For example fish ingestion doses were evaluated in three different ways (see section 2.4.2.3). A qualitative assessment of the uncertainty and variability associated with this approach is presented in Table 2-110 below.

Table 2-110. Qualitative Assessment of the Uncertainty and Variability Associated with Highly Exposed Population Assessment

Variable Name	Descriptor (data source)	Uncertainty (L, H)	Variability (L, H)
Environmental Exposure and Highly Exposed Groups Assessment (based on Exposure modeling)			
Environmental Releases Category			
Emission Factor	Range (EU RAR, OECD ESD)	M	H
Days of Release	Range (EU RAR, EU TGD, OECD ESD)	M	H
Production Volume	CDR volume threshold /Datamyne	H	L
Directly reported Releases	Reported values (TRI)	L	L
Environmental Fate Category			
Physical-Chemical Properties: KoC, Henry's Law Constant, etc	Point estimate (measured values, modeled estimates)	L	L
BAF	Point estimate based on lower end of range (measured studies)	L	H
Half-lives of HBCD in media	Range (measured studies)	L	H
Exposure Model Parameter Category			

Variable Name	Descriptor (data source)	Uncertainty (L, H)	Variability (L, H)
Environmental Exposure and Highly Exposed Groups Assessment (based on Exposure modeling)			
Water modeling defaults: river flow, dimensions, characteristics	Range CT and HE (PSC user guide)	L	H
Air modeling defaults: meteorological data, indoor/outdoor transfer,	Range CT and HE (IIOAC user guide)	L	H
Consumer Article modeling defaults: characterization of emissions from articles, characterization of residential and auto environments)	Range CT and HE (IECCU user guide	H	H
Exposure Factors and Activity Patterns	Range CT and HE (Exposure Factors Handbook	L	L
L = low; M = moderate; H=high			

EPA aggregated exposure across several pathways, in its general population assessment and found general agreement between different approaches. EPA also substituted modeled estimates for scenario-specific pathways for air, fish, and indoor air/dust for its assessment of highly exposed populations. There was a wide range of release estimates reported within and across scenarios which results in scenario-specific estimates that were lower than, of similar magnitude to, and higher than general population estimates. When considering pathway specific estimates and aggregate exposures, there is uncertainty associated with which pathways co-occur in a given population group. Further, there is variability within a given exposure pathway. For the same exposure scenarios, central tendency estimates are more likely to occur than high-end estimates. To address this, EPA used a stochastic approach to simulate the effect of aggregated exposures. EPA used different combinations of exposures sampling from the entire distribution for all pathways. This approach offers more clarity than static sensitivity analyses based on combining assorted high-end and/or central tendency estimates of the component distributions. For instance, combining the 95th percentile estimate of all component variables in an exposure equation in a static sensitivity analysis may produce a conservative high-end estimate of exposure that cannot be related to a specific percentile on the exposure distribution. Instead, EPA used a stochastic analysis, and selected the 95th percentile to approximate a high-end exposure estimate. The stochastic approach, however, is subject to uncertainty stemming from assumptions relating to the component distributions. If the true component distributions differ in terms of shape and/or parameters from the assumed distributions, the estimated exposure distribution may be potentially biased, especially in the tails of the distribution.

Finally, EPA did not consider all possible exposure pathways, but rather focused on pathways that were within the scope of its conceptual model. This may result in a potential underestimation of exposure in some cases. Examples of exposure pathways that were not considered include incidental ingestion of suspended sediment and surface water during recreational swimming and ingestion of non-fish seafood such as aquatic invertebrates or marine mammals. However, EPA expects these exposures to be less than those that were included in the aggregate assessment. As such, their impact will likely be minimal and would be unlikely to influence the overall magnitude of the results.

3 HAZARDS

3.1 Environmental Hazards

3.1.1 Approach and Methodology

During scoping and problem formulation, EPA reviewed potential environmental and health hazards associated with HBCD. EPA identified the following sources of environmental hazard data: Technical Review of HBCD (U.S. EPA, 2016c), Technical Review of Flame Retardant Alternatives for HBCD (U.S. EPA, 2014d), National Industrial Chemicals Notification and Assessment Scheme (NICNAS) Report on HBCD: Priority Existing Chemical Assessment (NICNAS, 2012a), Environment Canada and Health Canada Screening Assessment Report on HBCD (EC/HC, 2011), European Union (EU) Environmental Risk Assessment on HBCD (EINECS, 2008), EPA Risk-based Prioritization of HPV Chemicals (U.S. EPA, 2008a), and SIDS Assessment of HBCD (OECD, 2007b). These sources describe the hazards of HBCD to aquatic organisms including fish, aquatic invertebrates, aquatic plants and sediment invertebrates exposed to relevant media under acute and chronic exposure conditions. These publications report acute toxicity to aquatic invertebrates from HBCD, based on mortality and immobilization as well as chronic toxicity to aquatic invertebrates (growth and reproduction) when exposed to HBCD. Also, chronic toxicity was observed in sediment dwelling organisms based on reduced survivability when exposed to HBCD. In addition, these assessments summarize the hazards of HBCD to terrestrial organisms including soil invertebrates and avian species when exposed to relevant media under acute and chronic exposure conditions.

Although the assessment documents mentioned above provide detailed information regarding the environmental hazard of HBCD to aquatic and terrestrial organisms, they do not account for additional and latest information published on HBCD. Therefore, EPA completed the review of environmental hazard data/information sources during risk evaluation using the data quality review evaluation metrics and the rating criteria described in the *Application of Systematic Review in TSCA Risk Evaluations* document (U.S. EPA, 2018a). Studies that were considered "On Topic" were evaluated for acceptability. The acceptable studies were rated as high, medium, or low for quality. The data quality evaluation results are outlined in Tables 1 and 2 in Appendix G of this document and indicate most of the studies were rated high and moderate for quality. Only studies rated as high, medium, or low for quality during data evaluation were used during data integration. Any study rated as unacceptable was not used. Also, only clearly adverse signs of toxicity (e.g., lethality, immobility, effects on growth and reproduction, organ histopathology, abnormal behavior) were used to set toxicity effect levels such as lethal and effective concentrations (i.e., LC_{50}, EC_{50} values) no-observed-effect concentrations (NOECs) and lowest- observed-effect concentrations (LOECs).

3.1.2 Hazard Identification

EPA identified 50 acceptable studies (i.e., rated high medium or low) that contained aquatic toxicity data (i.e., fish, aquatic invertebrates, algae) and terrestrial toxicity data (i.e., plants, earthworms, avian species). Aquatic toxicity studies considered in this assessment are summarized in Table 3-1.
This assessment evaluated not only studies that followed standard test guidelines (e.g., Office of Chemical Safety and Pollution Prevention (OCSPP)), Organisation for Economic Co-operation and Development [OECD]), but also non-standard toxicity tests that followed procedures that were scientifically sound according to the *Application of Systematic Review in TSCA Risk Evaluations* document (U.S. EPA, 2018a). For this assessment, only clearly adverse signs of toxicity (e.g., lethality,

immobility, effects on growth and reproduction, organ histopathology, abnormal behavior) were used to set toxicity effect levels such as lethal and effective concentrations.

Table 3-1. Ecological Hazard Characterization of HBCD to Aquatic and Terrestrial Organisms

Test Organism	Duration	Endpoint	Hazard Value	Units	Effect Type	Reference
Aquatic Organisms						
Fish	Acute	96-hour LC_{50}	>0.0025	mg/L	mortality	(Wildlife Intl, 1997) (High)
	Chronic	28-day NOEC	>0.0037	mg/L	Growth and Reproduction	(Drottar et al., 2001) (High)
Invertebrates (*Surface Water*)	Acute	48-hour EC_{50}	>0.0032	mg/L	Immobilization	(Wildlife Intl, 1998; Wildlife Intl LTD, 1997) (High)
		96-hour LC_{50}	>0.8	mg/L	Mortality	(Shi et al., 2017)
	Chronic	21-day NOEC	0.0031	mg/L	Reproductive success; Growth; Weight; Length	(Wildlife Intl, 1998) (High)
		21-day LOEC	0.0056	mg/L		
		21-day MATC	0.0042	mg/L		
Invertebrates (*Sediment Dwelling*)	Chronic	28-day LOEC	>1,000	mg/kg dwt	Reduced survivability	Thomas et al.(ACC, 2003a, b) (High)
		28-day NOEC	3.1	mg/kg dwt	Population	(Oetken et al., 2001) (High)
		28-day LOEC	28.7	mg/kg dwt	Population	
		28-day MATC	15.4 (normalized)	mg/kg dwt	Population	
Algae	Acute	96-hour EC_{50}	>0.0037	mg/L	Abundance; Population Growth rate	(Wildlife Intl, 1997) (High)
		96-hour EC_{50}	0.08	mg/L	Population change	(Walsh et al., 1987) (High)
Terrestrial Organisms						
Vegetation	Chronic	21-day NOEC	>5,000	mg/kg dw	No treatment-related effects on emergence, survival or growth	(Wu et al., 2016b; Wu et al., 2012; Porch et al., 2002) (High)
Invertebrates	Chronic	21-day NOEC	20	mg/kg dw	Reduced pipping success	(Shi et al., 2017) (High)
Avian Species		22-day LOEC	0.001	mg/kg		(Crump et al., 2010) (High)
		6-week LOAEL	125	µg/L	reduction in hatchability	(MOEJ, 2009) (High)
			15	mg/L	reduced chick survival	
			2.1	mg/kg/day		
			5	mg/L		

Test Organism	Duration	Endpoint	Hazard Value	Units	Effect Type	Reference
		75-day LOAEL	164.3	ng/g wet weight of egg	reduced corticosterone response in males, reduced flying activities in juvenile males, delayed response time to predator avoidance in juvenile females	(Kobiliris, 2010) (High)
		21-day LOAEL	0.51 - 3.27	mg/kg/day	Delayed egg laying and laid smaller eggs with thinner eggshells.	(Marteinson et al., 2012; Fernie et al., 2011; Marteinson et al., 2011; Marteinson et al., 2010) (High)

Aquatic Toxicity

Acute Fish Toxicity

Short-term effects of HBCD to fish were identified in five high quality acceptable studies representing two different species, including one rainbow trout (*Oncorhynchus mykiss*) study and four zebrafish (*Danio rerio*) studies. As stated above, only clearly adverse signs of toxicity (e.g., lethality, immobility, effects on growth and reproduction, organ histopathology, abnormal behavior) were used to set toxicity effect levels, NOEC and LOEC values. Therefore, the rainbow trout study was used to characterize the toxicity of HBCD to fish. In this study (Wildlife Intl, 1997), rainbow trout were exposed to HBCD composed of α, β, and γ- diastereomers for 96 hours under flow-through conditions. The concentration of DMF in the solvent control and in the HBCD treatment groups was 0.1 ml/L. Rainbow trout were exposed to five measured concentrations of 0.0075, 0.0015, 0.0023, 0.0023, and 0.0025 mg//L, respectively. No mortalities or other effects were observed throughout the test. The results indicate that HBCD is not acutely toxic to rainbow trout up to concentrations of >0.0025 mg/L.

Chronic Fish Toxicity

There is one acceptable high-quality study that characterizes the chronic effects of HBCD to fish. In this study (Wildlife Intl, 1997), rainbow trout were exposed to HBCD at mean measured concentrations of 0.0025, 0.0047, 0.0083, 0.018, and 0.0037 mg/L under flow-through conditions for 88 days. Reagent grade acetone was used as a solvent control. The maximum nominal concentration was similar to the measured water solubility of 0.0086 mg/L. No effects were found at the water solubility limit of HBCD. The reported 88-day NOEC was >0.0037 mg/L. There were other studies that conducted sub-chronic or chronic effects of HBCD to fish and are summarized in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables of Environmental Hazard Studies (U.S. EPA, 2019b).*

Acute Invertebrate Toxicity

There are three acceptable studies that represents the acute toxicity of HBCD to aquatic invertebrates. These studies include two water flea (*Daphnia magna*) studies and one copepod (*Tigriopus japonicus*)

study. The results of these high quality studies show that HBCD is not acutely toxic to aquatic invertebrates at the chemical's water solubility limit.

In one study (Wildlife Intl LTD, 1997), *D. magna* were exposed to mean measured concentrations of 0, 0, 0.0018, 0.0021, 0.0023, 0.0024, 0.0032 mg/L under flow-through conditions for 48 hours. No effects were observed at the highest exposure concentration. In another study by Drottar (Drottar and Krueger, 1998), *D. magna* were exposed to mean measured concentrations of 0, 0, 0.00087, 0.0016, 0.0031, 0.0056, 0.011 mg/L for 48 hours under flow-through conditions. No effects on mortality or immobilization were observed at the highest exposure concentration. Finally, *T. japonicus* were exposed to measured concentrations of 0, 0, 0.08, 0.3, 0.8 mg/L of HBCD for 96-hours (Shi et al., 2017). Although the exposure concentrations were tested above the water solubility limit, a solvent control (DMSO) was used. No effects were observed at the highest exposure concentration.

Chronic Invertebrate Toxicity

There are four high-quality studies that represents the chronic toxicity of HBCD to aquatic invertebrates representing freshwater and saltwater species in the water and sediment compartment. These studies included one water flea (*D. Magna*) study, two amphipods (*Hyalella azteca*) studies, one black worm (*Lumbriculus variegatus*) study and one copepod (*Tigriopus japonicus*) study. There were effects on growth and reproduction in *D. magna* after 21 days of exposure to HBCD. The organisms were exposed to mean-measured concentration of 0, 0, 0.00087, 0.0016, 0.0031, 0.0056 and 0.011 mg/L HBCD under flow-through conditions (Wildlife Intl, 1998). A MATC of 0.042 mg/L was calculated from a NOEC of 0.0056 mg/L and a LOEC of 0.011 mg/L. Also, there were effects in survival in *L. variegatus* after exposure of 0.05, 0.5, 50, and 500 mg/kg dry weight (dwt) HBCD for 28-days (Oetken et al., 2001). The effects are relevant at the population level. In addition, HBCD induced developmental delay after 40 days of exposure to *T. japonicus*. (Shi et al., 2017). The marine copepods were expose to nominal concentrations of 0, 0, 0.08, 0.3, 0.8 mg/L under static conditions. DMSO was used as a solvent. After 20 days of exposure, HBCD caused growth delay to *T. japonicus nauplii*. The lowest-observable-effect concentrations of HBCD induced developmental delay were 0.030 and 0.008 mg/L for the F_0 and F_1 generations, respectively, which suggest that the F_1 generation was more sensitive to HBCD than the F_0 generation and warranted multiple-generation toxicity tests for future studies. A NOEC of 0.08 mg/L and a LOEC of 0.3 was reported for the F_0 generation (MATC = 0.15 mg/L) and a NOEC of 0.008 mg/L and a LOEC of 0.03 mg/L for the F_1 generation (MATC = 0.015 mg/L). However, no effects were found in *H. azteca* after exposures of 31, 63, 125, 250, 500 and 1,000 mg/kg dwt sediment (nominal concentrations) HBCD for 28 days in the presence of 2% and 5% total organic carbon (TOC) (ACC, 2003a, b).

Other Acute and Chronic Effects

As previously mentioned, only clearly adverse signs of toxicity (e.g., lethality, immobility, effects on growth and reproduction, organ histopathology, abnormal behavior) were used to set toxicity effect levels such as lethal and effective concentrations for this assessment (i.e., LC_{50}, EC_{50} values, NOECs and LOECs). However, a wide range of effects of HBCD have been reported in fish (e.g., developmental toxicity, embryo malformations, reduced hatching success, reduced growth, hepatic enzyme and biomarker effects, thyroid effects, DNA damage to erythrocytes, and oxidative damage) and invertebrates (e.g., degenerative changes, morphological abnormalities, decreased hatching success, and altered enzyme activity) in supporting studies that assessed endpoints beyond those evaluated in this assessment (Du et al., 2015; Hong et al., 2015; Foekema et al., 2014; Hong et al., 2014; Zhang et al.,

2014b; Wu et al., 2013; Du et al., 2012; Anselmo et al., 2011; Palace et al., 2010; Deng et al., 2009; Hu et al., 2009a; Smolarz and Berger, 2009; Aniagu et al., 2008; Palace et al., 2008; Zhang et al., 2008; Ronisz et al., 2004). Effects on the thyroid in fish (reduced thyroid hormone (triiodothyronine, T_3, and thyroxine, T_4) levels in rainbow trout (Palace et al., 2010; Palace et al., 2008; Kuiper et al., 2007; Lower and Moore, 2007), are similar to those observed in mammals. These studies were also evaluated using metrics and the rating criteria described in the Application of Systematic Review in TSCA Risk Evaluations document (U.S. EPA, 2018a). These studies were considered acceptable and are summarized in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables of Environmental Hazard Studies* document (U.S. EPA, 2019b).

Aquatic Plant Toxicity

For aquatic plants, two acceptable studies reported data on three species of algae, including fresh and saltwater species, and green algae and diatoms. Algae data were assessed as acute and chronic endpoints regardless of duration and not separated into acute and chronic, because durations normally considered acute for other species (e.g., 48, 72 hours) can encompass several generations of algae. Population changes were reported in the marine algae, *Skeletonema costatum* after 72 hours exposure to HBCD (Walsh et al., 1987). The EC_{50} values were determined in four of the five test media with different salinity for *S. costatum* and ranged from 0.009 to 0.012 mg/L. The geometric mean EC_{50} was 0.010 mg/L. Also, in the same study, *Thalassiosira pseudonana* were exposed to HBCD under the same conditions. The EC_{50} values were determined in all six-test media and ranged from 0.050 – 0.370 mg/L. The reported EC_{50} value for *T. pseudonana* was 0.08 mg/L. No effects on population changes were reported at the solubility limit of HBCD for this study. Also, there were no effects reported on abundances and population growth rate after 96-hour exposure to HBCD to *Selenastrum capricornutum* (currently known as *Raphidocelis subcapitata*) (Wildlife Intl, 1997). This freshwater green algae species was exposed to mean measured concentrations of 0.0013, 0.0022, 0.0033, 0.0042 and 0.0064 mg/L under static conditions for 96 hours. No dose response was found. Inhibition of around 10% based on AUC after 96-hour was observed in the highest tested treatment. Averaging the measured concentrations at the start and the end of the test for the highest test group resulted in a mean exposure concentration of 0.0037 mg/L.

Terrestrial Organisms

Toxicity to Soil Invertebrates

Two acceptable studies reported data on two species of earthworms. Both studies were rated high-quality. A short-term static earthworm (*Eisenia fetida*) study was conducted to examine the effects of HBCD on growth rate (Shi et al., 2017). The worms were exposed to nominal concentrations of 0, 50, 100, 200, 400 mg/kg dry soil and control (acetone). A significant ($P< 0.01$) up-regulation of superoxide dismutase SOD expression level was observed in earthworms exposed to HBCD at 400 mg/kg dry weight. The transcript level of Hsp70 gene was significantly up-regulated ($P < 0.01$) when earthworms exposed to HBCD at 400 mg/kg (2.61-fold). A LOAEL of 400 mg/kg dry soil was reported. The other study Li et al., 2016) examined the bioaccumulation potential of HBCD in *E. fetida* and *Metaphire guillelmi* (Li et al., 2016a). The values of α- and γ-HBCDs were substantially higher in *E. fetida* than those in *M. guillelmi*, with the higher lipid and protein contents in *E. fetida* as the primary reason for this difference. Other processes, such as uptake, depuration, metabolism and isomerization, also differed

between the two species and led to a difference in the bioaccumulation of β-HBCD. The β- and γ-HBCDs were bioisomerized to α-HBCD in the earthworms, but to a greater extent in *E. fetida*.

Toxicity to Avian Species

There are 11 studies that report data on three avian species. These studies include domestic chicken (*Gallus domesticus*), Japanese quail (*Coturnix coturnix japonica*), and American kestrel (*F. sparverius*). The results of these high-rated studies show that HBCD is toxic to these organisms effecting weight reduction, reproduction, development, behavior and thyroid hormone regulation. In one study, short-term exposer to HBCD in *G. domesticus* at nominal concentrations of 0, 0.006, 0.06, 0.6, 1.9, 6.4 mg/L resulted in a significant up-regulation of enzymes involved with metabolism of xenobiotic (Crump et al., 2008). Also, significant down-regulation of proteins associated with the thyroid hormone pathway and lipid regulation occurred in this concentration range. A 36-hour LOAEL of 0.06 mg/L was reported. A similar study reported HBCD's effects on embryo toxicity, isomer-specific accumulation in liver and cerebral cortex, and hepatic gene expression (Crump et al., 2010). Chicken eggs were injected with dose concentrations of 50, 100, 300, 1000, and 10, 000 ng/g. These doses were reported as 0.22, 0.43, 1.5, 4.98 and 50 mg/mL A 22-day LOAEL of 0.43 mg/mL was reported. In another study (MOEJ, 2009) adult mortality increased at 1,000 mg/L. Also, dietary exposure of HBCD in *C. japonica*, resulted in reproductive toxicity (MOEJ, 2009). Quails were fed diets containing 0, 125, 250, 500 or 1,000 mg/L of HBCD (a mixture of isomers: α, 27%; β, 30%; γ, 43%) for six weeks. HBCD caused a reduction in hatchability at all concentrations examined. Statistically significant reduction in egg shell thickness ($P \leq 0.05$) was also observed at concentrations above 125 mg/L. Also, HBCD exposer resulted in decrease egg weights and production rate and increase in cracked eggs at 500 and 1,000 mg/L. The NOEC for reproductive performance of quails was reported as 5 ppm (0.7 mg/kg bw/day) of HBCD. The effect on reproduction and develop are relevant for population effects. Four acceptable studies reported data on the reproductive, development and behavior effect of HBCD in *F. sparverius* (Marteinson et al., 2012; Fernie et al., 2011; Marteinson et al., 2011; Kobiliris, 2010; Marteinson et al., 2010).

Toxicity to Terrestrial Mammals

The toxicity of HBCD to mammals are characterized in Section 3.2 of this document. In rodents, HBCD isomers are biotransformed in the liver and are distributed in fat, liver, skeletal muscle and skin. Oral toxicity studies in rodents show that HBCD exposure can affect thyroid function. HBCD exposure can result in liver weight, steatosis, hypertrophy and inflammation. Reproductive toxicity in female rats included decreases in pregnancy, number of litters lost at high exposure dose to F1 dams and decrease primordial follicles. In male rats, no consistent effects were found relating to reproductive effects HBCD exposures. HBCD exposure to rats resulted developmental effects including reduced offspring viability, decreased pup body weight, altered development and skeletal system, and delayed eye opening. Neurological effects as reported in experimental studies in rats resulted in neurodevelopmental milestones, locomotor activity and executive function and neurological outcomes related to changes in auditory sensitivity, dopamine system function, and brain weight. Immune system effects in rats exposed to HBCD during development resulted in immune organ weights. The acute toxicity of HBCD in rodents, and rabbits via oral, dermal and inhalation exposures are low. Eye irritation effects in rabbits were low after 0.5 mL exposer. In summary, HBCD is not acutely toxic to rodents. However, prolong exposer to rodents resulted in effects to the liver, thyroid and reproductive organs.

Toxicity to Terrestrial Plants

For terrestrial plants, three acceptable studies reported data on six species. All studies have a high-quality rating. Phytotoxicity was reported in a 21-day exposure to HBCD to six species of plants (Porch et al., 2002). Mean measured test concentrations were 31.2, 97.7, 297.1, 764.6, 2,230 and 6,200 mg/kg dry weight. In one study, three monocots (corn, onion and rye grass) and three dicots (cucumber, soybean and tomato) were tested. For each species, a control group, and the five treatments were maintained. Each group consisted of four replicates each containing 10 seeds. During the 21-day test, weekly observations of seedling emergence and a qualitative assessment of the condition of each seedling were made. Onion showed significant (P>0.05) differences between the control and the 276 mg/kg group mean survival. There were no signs of treatment-related phytotoxicity observed on seedlings of any species at any test concentration. In another study, the accumulation and toxicity of α, β, and γ-HBCDs in maize were examined after exposer of 0, 0.002, 0.005, 0.01, 0.02, 0.05 mg/L (Wu et al., 2012). In another study, Wu et al, 2016(Wu et al., 2016b) investigated the accumulation of HBCD in maize. Young seedlings were exposed to HBCD at concentrations of 0, 0.002, 0.005, 0.01, 0.02, 0.05 mg/L. The uptake kinetics showed that the HBCD concentration reached an apparent equilibrium within 96 hours, and the accumulation was much higher in roots than in shoots. HBCD effected growth, biomass, length, and germination (LOAEL= 0.0002 mg/L). A LOAEL= 0.0002 mg/L was reported.

3.1.3 HBCD Trophic Transfer in the Environment

EPA initially assessed the PBT characteristics of HBCD in accordance with the U.S. EPA TSCA Work Plan Chemicals: Methods Document (U.S. EPA, 2012e). The potential of HBCD trophic transfer in both aquatic and terrestrial ecosystems was evaluated in this risk evaluation by using the *U.S. EPA Final Water Quality Guidance for Great Lakes System* (U.S. EPA, 1995), *U.S. EPA Wildlife Exposure Factors Handbook* (U.S. EPA, 1993b) and European Chemicals Agency (ECHA) Guidance on Information Requirements and Chemical Safety Assessment (Chapter R.16: Environmental exposure estimate; ECHA, 2016). Different methodologies of predicting potential HBCD trophic transfer were utilized because each method focuses on predators with different feeding habits; organisms were chosen for each of the methods based on data availability and method-specific requirements.

EPA has assessed the available studies collected in accordance with *The Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a) relating to the bioaccumulation and bioconcentration (BAF/BCF) of HBCD. To evaluate HBCD uptake via dietary and media exposure, different approaches were used to incorporate various sources (*i.e.,* environmental monitoring and modeled surface water and sediment concentrations) and types of exposure media (*i.e.,* uptake via diet or environmental media).

Ingestion rates from the *U.S. EPA Wildlife Exposure Factors Handbook* (U.S. EPA, 1993b) are used in the *U.S. EPA Final Water Quality Guidance for Great Lakes System* (U.S. EPA, 1995), thus the calculations used to predict Mink (*Neovison vison*) HBCD ingestion, via trout ingestion, are presented in Table 3-2. One limitation of the *U.S. EPA Final Water Quality Guidance for Great Lakes System* (U.S. EPA, 1995) is that the prediction of chemical uptake is limited to aquatic ecosystems. Estimations for HBCD trophic transfer as presented in Table 3-2 were calculated using exposure factors from the *U.S. EPA Wildlife Exposure Factors Handbook* (U.S. EPA, 1993b) and HBCD biomonitoring data. The American Kestrel was selected as a model terrestrial avian predator because they primarily consume prey that inhabit terrestrial ecosystems; American Kestrel serve as a terrestrial predator counterpart to Mink, where the comparison of HBCD from either only terrestrial and aquatic prey, respectively, can be compared. As mentioned above, there is also toxicity data available for American

Kestrel, and a body weight conversion can also be conducted to estimate HBCD body burdens that would result in similar toxicity to other avian species. Mink was selected to represent a higher trophic level mammal because a majority of their diet is composed of fish and other aquatic prey. Specifically Mink diet consists of 56, 26, 3, and 4% of trout, non-trout fish, unidentified fish, and crustaceans (U.S. EPA, 1993b), respectively, which is comparable to the 90% of mink diet attributed to aquatic prey in trophic level 3 (U.S, 1995). The potential trophic transfer of HBCD from aquatic ecosystems is more easily estimated than that from terrestrial ecosystems due to the greater amount of both environmental and biomonitoring information and hazard data for aquatic ecosystems and organisms, respectively.

The *ECHA Guidance on Information Requirements and Chemical Safety Assessment* (Chapter R.16: Environmental Exposure Estimate) (ECHA, 2008a) was used to estimate HBCD uptake via fish- and earthworm-consuming predators. Rainbow trout and earthworm bioconcentration factors (BCF) and HBCD exposure concentrations in water and soil, respectively, were used to derive $C_{organism}$ values, as presented in Table 3-3. The BCF for rainbow trout was used to remain consistent with taxa used in Table 3-2, despite the availability of more conservative BCFs for other fish species (i.e., fathead minnows). As compared to BAFs, BCFs can often underestimate HBCD uptake because only media exposure concentrations are accounted for. BCFs are used per methodologies provided in the *ECHA Guidance on Information Requirements and Chemical Safety Assessment* (ECHA, 2008a). The body burden of HBCD in rainbow trout and earthworms, as presented in Table 3-3 does not represent the predicted environmental concentration in food $PEC_{oral,\ predator}$ for predators of rainbow trout or earthworms, respectively. Total HBCD BMFs for rainbow trout and earthworms were unavailable, and isomer-specific HBCD BMFs for rainbow trout were not used to derive $PEC_{oral,\ predator}$ for predators of rainbow trout because of uncertainties due to processes (*i.e.*, bioisomerization, degradation) that would significantly impact HBCD isomer uptake and depuration. There is additional uncertainty due to the use of BCFs that are not normalized to the amount of lipids present in the samples of tissues used for the referenced studies; there is additional uncertainty in using earthworms and rainbow trout as representative organisms for their respective trophic levels using this analysis as lipid normalization generally accounts for specie differences (*i.e.,* size, age, seasonal variations in diet, sex).

Given the higher likelihood that HBCD is present in the environment due to its persistent and bioaccumulative characteristics, chronic exposures are of greater relevance to higher trophic level organisms. HBCD uptake can be used to evaluate potential HBCD trophic transfer, however as there is limited toxicity data on higher trophic level organisms, it is difficult to surmise whether the amount of HBCD one is exposed to will result in toxicological effects. The currently available data on HBCD toxicity to higher trophic level organisms are limited to a few avian species that do not consume prey from aquatic ecosystems (*i.e.,* Japanese Quail and American Kestrel), where the greatest releases of HBCD are expected.

The abovementioned methodologies used to estimate HBCD uptake via prey consumption and media exposure only use available biomonitoring and hazard data. As compared to biomonitoring and environmental monitoring data, which provides real time information on HBCD concentrations found in wildlife and various media, these data cannot be specifically attributed to a condition of use of HBCD that is evaluated in this risk assessment. As described below in Section 4.1, a two tiered approach was used to predict HBCD concentrations in various compartments (*i.e.,* surface water, pore water, sediment) as a result of HBCD release scenarios expected from different model sub-scenarios of each condition of use. In addition to the HBCD concentrations predicted to be in each of the compartments using the Point Source Calculator, HBCD physical chemical properties (*i.e.,* K_{oc}=100,000; $\log K_{ow}$=5.62; Water solubility=66 µg/L) were used as input parameters for the K_{OW} (based) Aquatic BioAccumulation Model

(KABAM) version 1.0 (U.S. EPA, 2009b), which estimates the bioconcentration, bioaccumulation, and biomagnification of HBCD in aquatic food webs. Specifically, mammal and avian uptake of HBCD through diet and water intake were estimated and attributed to predicted surface water, pore water, and sediment concentrations for modeled sub-scenarios of conditions of use (COU) 3.3 (Processing: Manufacturing of XPS Foam using XPS Masterbatch) and 5.7 (Processing: Manufacturing of EPS Foam from Imported EPS Resin beads). As explained below in Section 4.1, a sensitivity analysis was conducted to evaluate whether production volume and percent of HBCD removed from facility direct releases would impact the predicted concentrations of HBCD in various media for three COUs (two of which are selected for evaluation for trophic transfer) that have the highest releases of HBCD. The two model sub-scenarios (3.3 and 5.7) within COU 3 and 5 were selected because between the COUs that were targeted in the sensitivity analysis, these two COUs represent three types of water treatment of releases from facilities (*i.e.,* direct release, POTW, and WWTP) and generally have the highest predicted surface water and sediment concentrations. KABAM predictions of HBCD bioavailability through diet and water is used to categorize exposure and predicts body burdens and the contribution to body burden due to diet. Predicted bioaccumulation, bioconcentration and biomagnification factors can also be predicted for representative organisms within each trophic level. American kestrel and Sprague Dawley rats are used as proxy organisms for terrestrial avian and mammalian wildlife organisms that may be exposed to HBCD through trophic transfer and various media exposure. Specifically for this model, based on the assumption that the modeled organisms have the same effect or response to the same effect concentration as those of the proxy organisms, hazard data on the proxy organisms are also input parameters for KABAM. All KABAM outputs (predicted body burdens, BAF, BCFs, etc.) are provided in Appendix G.3.

Numerous sources have demonstrated the likelihood of HBCD presence and bioaccumulation in various taxa in both aquatic in terrestrial ecosystems. However, greater uncertainty lies in estimating trophic transfer potential for predators that consume prey from numerous trophic levels and reside in different ecosystems. Thus, these approaches use higher trophic level organisms that have well characterized diet compositions to represent organisms that will be consistently exposed to HBCD in the environment. There is a general data gap regarding the ecological hazard of HBCD for apex predators, specifically those that solely prey on terrestrial organisms. Despite HBCD being found predominantly in aquatic media (e.g., sediment), HBCD trophic transfer may result in HBCD source fluxes between aquatic and terrestrial ecosystems. Specifically, HBCD source movement from aquatic to terrestrial ecosystems, via trophic transfer, is another area that was briefly explored by estimating HBCD trophic transfer to a terrestrial mammal (e.g., Mink) that primarily consumes aquatic prey (e.g., trout) (U.S. EPA, 1993b). Mink and American Kestrel were chosen as the apex predators of interest with different dietary habits, as to understand how HBCD sources contribute to HBCD trophic transfer in different food webs. Using exposure factors are limited however because only about 31 and 56% of American kestrel and Mink diet are accounted for, which likely underestimates HBCD uptake by these top predators from their diet.

Methods used to estimate HBCD trophic transfer demonstrate HBCD uptake solely via prey ingestion do not account for media exposure to HBCD, whereas the use of KABAM relates potential BAF, BCFs, and other indications of trophic transfer to water releases of HBCD that can be tied to a specific COU. Although methods that only evaluate dietary uptake of HBCD likely underestimate HBCD uptake quantifying body burdens due to diet as compared to environmental media will provide additional insight on how species-specific dietary preferences impacts HBCD trophic transfer. Environmental monitoring data, as presented above, demonstrates the higher likelihood that aquatic organisms are exposed to greater concentrations of HBCD than terrestrial organisms, especially near facilities that process waste containing HBCD (Zhu et al., 2017). Furthermore, the data from both monitoring and

modeled predictions suggest that not only can HBCD undergo trophic transfer, but that organisms that not only reside in aquatic ecosystems, but prey on aquatic organisms, will also be exposed to HBCD. This suggests that terrestrial organisms living within close proximity to aquatic ecosystems may be exposed to HBCD through their diet. Although not explicitly addressed in this section, the potential for HBCD trophic transfer may also depend on diastereomer-specific uptake, metabolism, bioaccumulation and excretion; diastereoisomer-specific metabolism and biotransformation may account for diastereoisomer-specific accumulation observed in higher trophic level organisms (Du et al., 2015). Finally, HBCD excretion will also determine predator exposure to HBCD through prey consumption; following an aqueous exposure to 1.8 µg HBCD/L and a depuration period of 19 days, exposed rainbow trout were able to eliminate 50% of their HBCD body burden (Drottar and Krueger, 2000). The equations used to derive HBCD ingestion in Table 3-2 and Table 3-3 are provided in Appendix G.2.

Table 3-2. Potential Trophic Transfer of HBCD in Aquatic and Terrestrial Ecosystems Using the U.S. EPA Final Water Quality Guidance for Great Lakes System and U.S. EPA Wildlife Exposure Factors Handbook

Organism's Attribute	Assumption	Reference	ng HBCD consumed/day
Deer mouse ingestion rate (female)	0.45 g food/ g bw-d	Millar, 1979[1]	Deer Mouse 0.35 (via fruit) + 200 (via arthropods) = 200.4
Deer mouse % diet of fruit in summer	25%	Wolff et al., 1985[1]	
Deer mouse body weight (female)	24.5 g	Millar and Innes, 1983[1]	
HBCD in fruits (biomonitoring data: food basket study in South Korea)	0.127 µg HBCD/kg ww	Barghi (2016)	
HBCD in grasshopper (biomonitoring data: near electronic-waste dismantling facilities in China)	32.4 ng HBCD/g bw	Zhu (2017)	
Deer mouse % diet of arthropods in summer	56%	Wolff et al., 1985[1]	
American kestrel ingestion rate (vertebrates-winter)	0.18 g/g bw-d	Koplin et al., 1980[1]	American kestrel 64.4 (via Deer mouse)
American kestrel % diet of mammals	31.7%	Meyer and Balgooyen, 1987[1]	
American kestrel body weight (female-winter)	138 g	Gessaman and Haggas, 1987[1]	
Mink ingestion rate	0.16 g/g bw-d	Bleavins & Aulerich, 1981[1]	Mink 700.7 (via trout)
Mink weight	1,734 g	Hornshaw et al., 1983[1]	
Mink % diet of trout	56%	Alexander, 1977[1]	
HBCD in trout	4.51 ng HBCD/g	Tomy (2004)	

[1]Exposure factors, as indicated, were derived from the U.S. EPA Wildlife Exposure Factors Handbook. (U.S. EPA, 1993b)

Table 3-3. Potential Trophic Transfer of HBCD in Aquatic and Terrestrial Ecosystems using the ECHA Guidance on Information Requirements and Chemical Safety Assessment (Environmental Exposure Assessment)

Organism's Attribute	Assumption	Reference	HBCD in organism
Rainbow trout (whole body BCF)	8,974	Drottar and Kruger (2000)	HBCD Rainbow trout concentration (C_{fish}) = 16,154 µg/kg
HBCD exposure concentration to Rainbow trout	1.8 µg/L	Drottar and Kruger (2000)	
Rainbow trout whole body lipid percentage	0.083	Drottar and Kruger (2000)	Lipid normalized HBCD Rainbow trout concentration (C_{fish}) = 60,067 µg/kg
Rainbow trout (whole body lipid normalized BCF)	108,120.5	Drottar and Kruger (2000)	
Earthworm bioconcentration factor (BCF)	4.5	Aufterheide (2003)	Earthworm concentration ($C_{earthworm}$) = 18,855 mg/kg
HBCD exposure concentration to earthworm	4,190 mg/kg dry soil	Aufterheide (2003)	

The estimated HBCD bioaccumulation as presented in Appendix Sections G.3.1 and G.3.2, based on either the 10th or 50th percentile predictions for surface and pore water HBCD concentrations associated with COU-related releases, respectively, are within the same magnitude as measured BAFs (both lipid normalized) for upper trophic level fish (He et al., 2013) Wu et al., 2011).

3.1.4 Weight of Evidence

During data integration stage of systematic review EPA analyzed, synthesized, and integrated the environmental data/information for HBCD. This involved weighing scientific evidence for quality and relevance, using a Weight of Evidence (WoE) approach (U.S. EPA, 2018a).

During data evaluation of the relevant HBCD studies, a rating of high, medium, or low for quality based on the TSCA criteria described in the *Application of Systematic Review in TSCA Risk Evaluations* was applied(U.S. EPA, 2018a). While integrating environmental hazard data for HBCD, EPA gave more weight and consideration to relevant data/information rated high or medium for quality. Only data/information rated as high, medium, or low for quality was used for the environmental risk assessment. Any information rated as unacceptable was not used to characterize the hazard of HBCD. The factors for determining if environmental data/information were relevant, were based on whether the source had biological, physical/chemical, and environmental relevance (U.S. E.PA, 1998):

- **Biological relevance –** correspondence among the taxa, life stages, and processes measured or observed and the assessment endpoint.
- **Physical/chemical relevance –** correspondence between the chemical or physical agent tested and the chemical or physical agent constituting the stressor of concern.
- **Environmental relevance –** correspondence between test conditions and conditions in the region of concern. (U.S. E.PA, 1998)

This WoE approach was used to assess the environmental hazard data of HBCD and develop concentrations of concern (COCs). Where high or medium quality studies were available for a taxonomic group, low quality studies were not used to derive COCs.

To assess aquatic toxicity from acute exposures, data for three taxonomic groups were available: algae, aquatic invertebrates (i.e., surface water and sediment dwelling) and fish. For each taxonomic group, data were available for these species as shown in Table 3-1. There were no acute toxicity to aquatic from HBCD exposure. However, other short-term effects were reported that indicate that HBCD exposure resulted in developmental

To assess aquatic toxicity from chronic exposures, data for three taxonomic groups were described in the acceptable literature: fish, and aquatic invertebrates. Therefore, the endpoints for fish and aquatic invertebrates including surface water and sediment-dwelling organisms (MATC, NOEC, and an LOEC) were more biologically relevant, because they measured a toxic effect. Of these values, the most sensitive species were a 21-day MATC of 0.042 mg/L measuring reproduction in aquatic invertebrates (*Daphna magna*) and a 28-day MATC of 15.7 mg/kg dwt measuring worm survival in *Lumbriculus variegatus*.

To assess the toxicity of HBCD to algae, data for two species were available from studies rated high for quality. The most sensitive endpoint reported for algae (*Skeletonema costatum*) was a 72-hour EC_{50} of 0.010 mg/L from Walsh et al. (1987). As stated in Section 3.1, algae data were assessed together with acute and chronic endpoints regardless of duration and not separated into acute and chronic, because durations normally considered acute for other species (e.g. 48, 72 hours) can encompass several generations of algae.

To assess terrestrial toxicity from chronic exposures, data for three taxonomic groups were described in the acceptable literature: terrestrial plants, soil invertebrates and avian species. Therefore, the endpoints for terrestrial plants, soil invertebrates and avian species (EC_{50}, MATC, LOEC, NOEC, NOAEL, LOAEL) and an LOEC) were more biologically relevant, because they measured a toxic effect. Of these values, the most sensitive species were a 4-day Maize (*Zea mays*) measuring growth reduction and reporting a LOAEL of 0.002 mg/L, a 14-day earthworm (*Eisenia fetida*) reporting a MATC of 200 mg/kg/day measuring reproduction effects and a 21-day LOAEL in American kestrel (*F. sparverius*) measuring reproduction reporting a LOAEL of 3.27 ng/g ww.

3.1.5 Concentrations of Concern

The concentrations of concern (COCs) for aquatic species were calculated based on the environmental hazard data for HBCD, using the weight of evidence approach described above and EPA methods (Suter, 2016; U.S. EPA, 2013c, 2012d). For HBCD, EPA derived an acute COC, a chronic COC, and an algal COC. Algae was assessed separately and not incorporated into acute or chronic COCs, because durations normally considered acute for other species (e.g. 48, 72 hours) can encompass several generations of algae.

After weighing the evidence and selecting the appropriate toxicity values from the integrated data to calculate an acute, chronic, and algal COC, an uncertainty factor (UF) is applied according to EPA methods (Suter, 2016; U.S. EPA, 2013c, 2012d). The application of AFs provides a lower bound effect level that would likely encompass more sensitive species not specifically represented by the available experimental data. AFs also account for differences in inter- and intra-species variability, as well as laboratory-to-field variability. These AFs are dependent on the availability of datasets that can be used to characterize relative sensitivities across multiple species within a given taxa or species group. However, they are often standardized in risk assessments conducted under TSCA, since the data available for most industrial chemicals are limited. For fish and aquatic invertebrates (e.g., daphnia) the

acute COC values are divided by an AF of 5. For chronic COCs, an AF of 10 is used (U.S. EPA, 2013c, 2012d).

Table 3-2. Concentrations of Concern (COCs) for Aquatic Toxicity

Environmental Toxicity	Concentration of Concern (COC)	Species	Effect	Reference
Acute toxicity to aquatic organism	2.5 µg/L	Marine Algae (*S. costatum*)	Growth Rate	(Walsh et al., 1987)
Chronic toxicity to aquatic organisms	0.42 µg/L	Water flea (*D. magna*)	Reduced length of surviving young	(Drottar and Krueger, 2000)(Drottar and Krueger, 2000)(Drottar and Krueger, 2000)(Drottar and Krueger, 2000)
Chronic toxicity to sediment-dwelling organisms	1.57 mg/kg/dwt.	California blackworm (*Lumbriculus variegatus*)	Reduction in worm number	(Oetken et al., 2001)

Evaluating data from acute studies of fish, aquatic invertebrates and algae, the marine algae (*S. costatum*) 72-hour EC_{50} of 0.01 (MATC of 0.009 – 0.012) mg/L resulted in the lowest value and EPA divided this 96-hour EC_{50} value by an uncertainty factor (UF) of 4 for acute tests using aquatic plants, as per established EPA methods (EPA, 2013, 2012) to give an acute COC of 0.025 mg/L (or 2.5 µg/L).

For chronic concerns, the Daphnia magna 21-day MATC chronic value of 0.0042 mg/L based on reduced length of surviving young is the most sensitive value. When divided by an uncertainty factor (UF) of 10 for chronic effects, as per established EPA methods (EPA, 2013, 2012), the resulting chronic COC is 0.00042 mg/L (or 0.4 µg/L).

The *L. variegates* 28-day MATC of 15.7 mg/L, based on reduction in worm number, was divided by an uncertainty factor (UF) of 10 for chronic effects, as per established EPA methods (EPA, 2013, 2012), to give a chronic COC of 1.57 mg/kg/dwt (or 1,570 µg/kg/dwt).

Table 3-3. Terrestrial Effect Concentrations (Hazard) used to Evaluate Toxicity to Terrestrial Organisms

Environmental Toxicity	Effect concentration	Effect	Reference	Data Evaluation Score
Maize 4-d LOAEL	2 µg/L	Growth (root and shoot)	(Wu et al., 2016b)	High
Earthworm 14-d LOAEL	200 mg/kg	Oxidative stress	(Shi et al., 2018)	High
American Kestrel 21-d LOAEL	3.27 ng/g ww	Reproduction (clutch size, egg production timing)	(Fernie et al., 2009)	High
Rat 2-generation NOAEL	10 mg/kg bw	Thyroid	(Ema et al., 2008)	High

Studies where terrestrial organisms were exposed to HBCD were evaluated and those with high data evaluation scores (using either environmental and human health Systematic Review metrics) and relevant environmental exposure pathways were used to assess risk to terrestrial organisms. The studies identified in Table 3-3 provides a summary of reported lowest observed adverse effect levels where chronic exposures to HBCD were conducted with terrestrial organisms. The organisms identified in the abovementioned studies were chosen to represent their respective taxa classifications (*i.e.,* vegetation, invertebrate, vertebrate). Out of the four terrestrial vegetation studies (all rated with high data evaluation scores), (Wu et al., 2016b) represents the most highly relevant study because the exposure is not diastereomer-specific and has a discrete effect concentration; maize exposed to HBCD through spiked water resulted in significant reductions in root and shoot growth. Despite the sparse amount of available terrestrial invertebrate toxicity data, Shi et al., 2015 was the only highly evaluated study that demonstrated potential toxicity due to chronic exposure to HBCD; although growth was not significantly reduced, an upregulation of superoxide dismutase (SOD) and heat shock protein (Hsp70) gene expression suggests that a longer exposure to HBCD may result in organism-level toxicological effects. In the ten highly evaluated studies, three avian species (Chicken, Japanese Quail and American Kestrel) were mainly used to study reproductive effects resulting from HBCD exposure, where there were observations of reduced hatching time, smaller egg production, and the presence of HBCD in eggs where parents were chronically exposed to HBCD.

3.1.6 Summary of Environmental Hazard

HBCD presents a significant concern for adverse effects on the environment. This conclusion is based on the observed potential for bioaccumulation, biomagnification, altered reproductive behavior, as well as high acute and chronic toxicities. Bioconcentration factors BCFs) and biomagnification factors (BMFs) as high as 18,100 and 29.7 respectively have been observed in fish (Zhang et al., 2014a; Du et al., 2012; Law et al., 2006). BMF values of 26 (lipid-weight) and 1.6 - 3 have also been observed in birds (Haukås et al., 2010b) and mammals (Shaw et al., 2012) respectively. Observed acute toxicity values as low as 0.009 mg/L for a 72 hour EC_{50} based on reduced growth in the marine algae, *Skeletonema costatum*) (Walsh et al., 1987), and observed chronic aquatic toxicity values as low as 0.0042 mg/L (maximum acceptable toxicant concentration (MATC)) for reduced size (length) of surviving young in *Daphnia magna* (Drottar and Krueger, 1998), indicate high acute and chronic aquatic toxicity. Reduced chick survival in Japanese quails (*Coturnix coturnix japonica*) fed a 15 ppm HBCD diet (2.1 mg/kg body weight-day) (MOEJ, 2009) and altered reproductive behavior (reduced courtship and brood-rearing activity) and reduced egg size in American kestrels (*Falco sparverius*) fed 0.51 mg/kg body weight-day (Marteinson et al., 2012; Fernie et al., 2011; Marteinson et al., 2011; Marteinson et al., 2010) indicate high terrestrial toxicity as well.

Assessment of HBCD aquatic toxicity is complicated by the low water solubility of the chemical and differences in the solubility of the three main HBCD isomers, which makes testing difficult and interpretation uncertain for studies conducted above the water solubility. Studies conducted at concentrations above the water solubility of HBCD are essentially testing the effects at the maximum HBCD concentration possible. In contrast with the studies cited above, other acute and chronic aquatic toxicity studies conducted using methods, test species, and endpoints recommended by the EPA reported no effects at or near the limit of water solubility. However, water solubility is not considered a limiting factor for hazard determination for aquatic species since there are studies showing adverse effects at or below the water solubility of HBCD. In addition, the potential for HBCD to bioaccumulate, bio-magnify, and persist in the environment, significantly increases concerns for effects on aquatic organisms.

A wide range of effects of HBCD have been reported in fish (e.g., developmental toxicity, embryo malformations, reduced hatching success, reduced growth, hepatic enzyme and biomarker effects, thyroid effects, DNA damage to erythrocytes, and oxidative damage) and invertebrates (e.g., degenerative changes, morphological abnormalities, decreased hatching success, and altered enzyme activity) in supporting studies that assessed endpoints beyond those evaluated in this assessment (Du et al., 2015; Hong et al., 2015; Foekema et al., 2014; Hong et al., 2014; Zhang et al., 2014b; Wu et al., 2013; Du et al., 2012; Anselmo et al., 2011; Palace et al., 2010; Deng et al., 2009; Hu et al., 2009a; Smolarz and Berger, 2009; Aniagu et al., 2008; Palace et al., 2008; Zhang et al., 2008; Ronisz et al., 2004). Effects on the thyroid in fish (reduced thyroid hormone (triiodothyronine, T3, and thyroxine, T4) levels in rainbow trout (Palace et al., 2010; Palace et al., 2008; Kuiper et al., 2007; Lower and Moore, 2007). Effects on the thyroid in fish (reduced thyroid hormone (triiodothyronine, T_3, and thyroxine, T_4) levels in rainbow trout (Palace et al., 2010; Palace et al., 2008), are similar to those observed in mammals. These studies were also evaluated using metrics and the rating criteria described in the Application of Systematic Review in TSCA Risk Evaluations document (U.S. EPA, 2018a).

The COCs and derived for aquatic organisms are summarized in Table 3-3. EPA calculated the chronic COC for HBCD based on two high quality studies at 4.2 ppb and 157 µg/kg dwt, based on an MATC for *D. magna* and *L. variegatus*, respectively.

Also, the terrestrial effect concentrations to derived terrestrial organisms are summarized in Table 3-4. EPA calculated terrestrial effect levels for HBCD based on three high quality studies at 2 ppb and 200 µg/kg dwt and 3.27 ng/g ww based on a LOAEL for Maize, a LOAEL for earthworm, a LOAEL for American kestrel and a NOAEL for rats, respectively (Table 3-5).

As stated previously, algae were assessed separately from other aquatic organisms, because durations normally considered acute for other species (e.g. 48, 72 hours) can encompass several generations of algae. EPA calculated an algal COC for HBCD at 2.5 ppb, based on a geometric mean of a LOEC and NOEC for growth in *S. costatum* from Walsh et al. (1987), a study rated high for quality.

Table 3-5 Summary of the Environmental Concern Levels of HBCD

Environmental Aquatic Toxicity	Concentration of Concern
Aquatic Toxicity	
Toxicity from Chronic Exposure	4.2 µg/L
	157 ug/kg dwt
Toxicity for Algae:	
	2.5 µg/L
Terrestrial Toxicity	
Toxicity from Chronic Exposure	2 µg/L
	200 mg/kg
	3.27 ng/g ww
	10 mg/kg bw

3.1.7 Assumptions and Key Sources of Uncertainty for the Environmental Hazard Assessment

In characterizing the environmental hazard of HBCD, some uncertainty in the analysis of environmental exposure is due to the inherent nature that the proportion of diastereomers in HBCD mixtures will differ based on commercial and consumer products used, and the changes of such proportions that may occur following environmental release. Similarly, the environmental hazard of HBCD will depend on the exposure to varying proportions and concentrations of HBCD diastereomers; most studies reported exposure and effects concentration in total HBCD, however studies that concentrated on bioisomerization generally parsed out exposure based on individual diastereomer. The sole use of HBCD diastereomer-specific partitioning and toxicity data may result in the underestimation of overall HBCD environmental hazard because diastereomer proportions will continue to change in the environment.

For evaluating the potential trophic transfer of HBCD in the environment, many assumptions and uncertainties were taken into consideration due to the complexity of food web dynamics. In general, there is an inherent uncertainty when using proxy organisms to represent all terrestrial and aquatic prey and predators; the selection was based on data availability, thus making it difficult to represent more than three levels of prey-predator relationships. Organism selection for this evaluation was exclusively from the available exposure factors in the *U.S. EPA Wildlife Exposure Factors Handbook* (also incorporated in the *U.S. EPA Final Water Quality Guidance for Great Lakes System*). Variations in diet categories due to life stage, gender, and seasonal differences are not addressed in this evaluation because the specificity of each exposure factor differed based on the methodologies used in their respective original references. Further, the inability to account for complete diets and the potential variations in diet may have resulted in the under- or overestimation of HBCD uptake. Specifically, in regard to Mink diet, HBCD uptake calculations using methodologies from the *U.S. EPA Final Water Quality Guidance for Great Lakes System* and *U.S. EPA Wildlife Exposure Factors Handboo*k, and trout HBCD biomonitoring data could only account for 56% of Mink diet; an additional 26% and 18% of their diet was labeled "non-trout" fish, and miscellaneous items, respectively. Like the other organisms used to calculate potential HBCD uptake via ingestion, large portions of Mink diet are unaccounted for due to a lack of reasonably available information on either the diet composition, or HBCD body burden in prey organisms. Further underestimations of HBCD uptake by terrestrial predators, as compared to aquatic predators in this assessment (*i.e.,* calculated by evaluating Kestrel ingestion of mice) may also be due to the use of fruit and grasshopper HBCD biomonitoring data as the original source of HBCD for Kestrel, as opposed to smaller mammals with a higher body fat composition. The limited data regarding HBCD in terrestrial organisms contributes to the uncertainty regarding HBCD trophic transfer in terrestrial food webs.

The uncertainties regarding the ingestion of HBCD also do not take into consideration physiological processes that impact the absorption, metabolism, distribution and elimination of HBCD, once ingested. The available literature regarding how HBCD is absorbed, metabolized, distributed and eliminated are largely evaluations of the bioisomerization of HBCD once ingested.

The above analysis focuses on HBCD uptake via prey ingestion as an indicator for potential HBCD trophic transfer in aquatic and terrestrial food webs, and does not take into consideration the uncertainties regarding the physiological processes that impact the absorption, metabolism, distribution and elimination of HBCD, once ingested. Specifically, the available literature primarily focuses on

HBCD diastereomer-specific body burdens as a function of the potential bioisomerization of α-, β-, and γ-HBCD. However, as there is no consensus on the uptake, biotransformation, and elimination of HBCD diastereomers once ingested, it is difficult to ascertain whether HBCD diastereomer-specific uptake and exposure is a function of environmental concentrations and/or bioisomerization of HBCD once ingested. There is also speculation on whether aquatic or terrestrial ecosystem conditions differentially result in diastereoisomer-specific isomerization and degradation. As mentioned in Section C.2, α-HBCD is bioaccumulated and biomagnified to a greater extent than either β- and γ- diastereomers in aquatic food webs, despite γ-HBCD being the isomer primarily found in commercial mixtures. Furthermore, the bioisomerization of γ-HBCD to α-HBCD in fish (Du et al., 2012) and the higher water solubility of α-HBCD (as compared to the other diastereomers) suggest that regardless of the percentages of diastereomers in commercial mixtures, once released into the environment, there is a higher likelihood of organisms being exposed to α-HBCD. Diastereomer-specific excretion will also influence whether higher trophic level predators will be exposed to HBCD via prey ingestion. In rats that were orally exposed to all three HBCD diastereomers, through both feces and urine, HBCD diastereomer excretion was greater for β- and γ- diastereomers, than α-HBCD (Hakk, 2016). Species-specific differences in physiological processes will also greatly impact predator-specific uptake of HBCD. Due to the higher lipid and protein found in the earthworm, *Eisenia fetida,* as compared to *Metaphire guillelmi,* as well as differences in in HBCD uptake, depuration, metabolism and isomerization, the biota soil accumulation factor for HBCD was higher in *E. fetida*. Furthermore, the bioisomerization of β- and γ-HBCD to α-HBCD was observed to a greater extent in *E. fetida* than in *M. guillelmi.* In addition to having a longer half-life than β- and γ-HBCD, α-HBCD also bioaccumulated to a greater extent than the other two diastereomers in both earthworms exposed to soil samples individually containing HBCD diastereomers (Li et al., 2016a). In general, evaluating the trophic transfer of HBCD using any method will not be able to account for all sources of physiological differences (*i.e.,* age, gender, and seasonal impacts on prey availability) that will ultimately affect HBCD exposure and bioavailability.

3.2 Human Health Hazards

3.2.1 Approach and Methodology

EPA used the approach described in Section 1.5 to evaluate, extract and integrate HBCD's human health hazard and dose-response information.

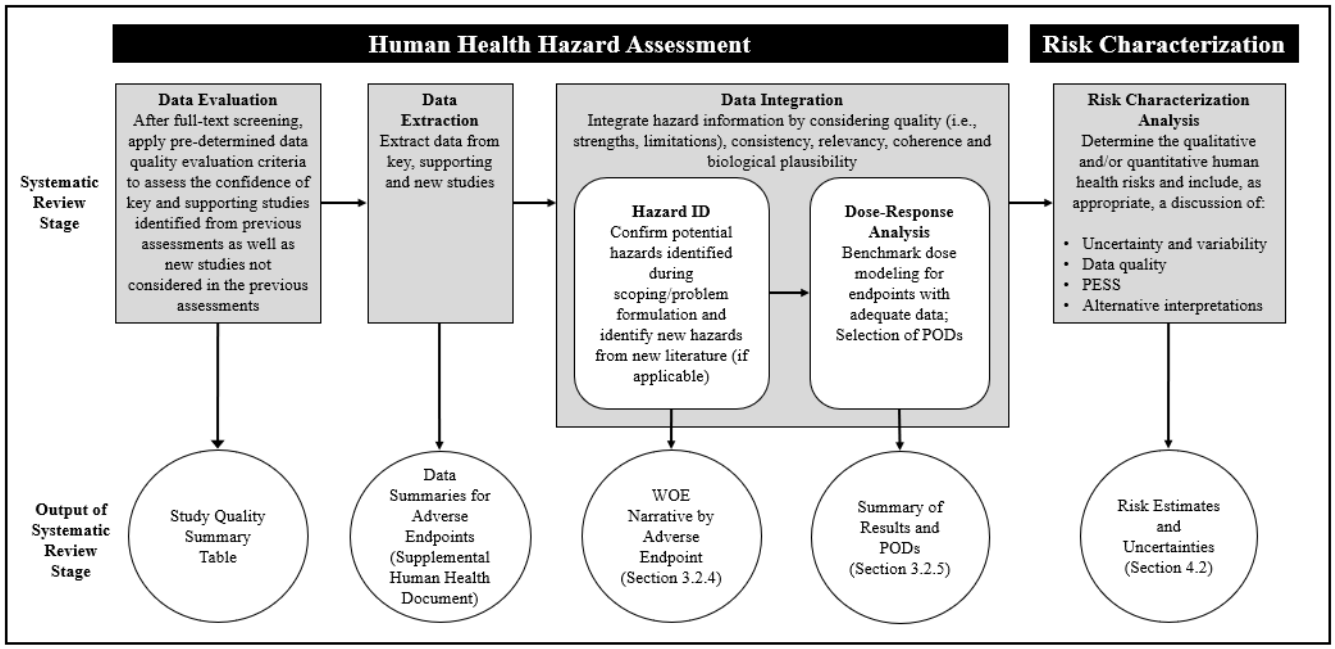

Figure 3-1. EPA Approach to Hazard Identification, Data Integration, and Dose-Response Analysis for HBCD

Specifically, EPA reviewed key and supporting information from previous hazard assessments as well as the existing body of knowledge on HBCD's human health hazards. These data sources[13] included the TRI Technical Review of HBCD (U.S. EPA, 2016c), the *TSCA Work Plan Problem Formulation and Initial Assessment*, (U.S. EPA, 2015), *Preliminary Materials for the IRIS Toxicological Review of HBCD* (U.S. EPA, 2014f) as well as other publications (U.S. EPA, 2016c, 2014d; NICNAS, 2012a; EC/HC, 2011; EINECS, 2008; U.S. EPA, 2008a; OECD, 2007b). Additional scientific support from the Office of Research and Development subsequent to these publications also contributed to this human health hazard assessment.

All non-cancer health hazards of HBCD previously identified in these reviews were described and reviewed in this risk evaluation, including: acute toxicity, liver toxicity, thyroid effects, reproductive/ developmental toxicity, neurotoxicity, immunotoxicity, sensitization and irritation. EPA relied heavily on the aforementioned existing reviews along with scientific support from the Office of Research and Development in preparing this risk evaluation. Development of the HBCD hazard and dose-response assessments considered EPA and National Research Council (NRC) risk assessment guidance.

The new literature was screened against inclusion criteria in the PECO statement and the relevant studies (e.g., useful for dose-response)[14] were further evaluated using the data quality criteria for human, animal, and *in vitro* studies described in the *Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a) (see Section 1.5). EPA skipped the PECO screening step of the key and supporting studies and entered them directly into the data quality evaluation step based on their previously identified relevance to the risk evaluation.

[13] HBCD does not have an existing EPA IRIS Assessment.
[14] Some of the studies that were excluded based on the PECO statement were considered later during the systematic review process as needed. For example, EPA reviewed mode of action information to qualitatively support the health hazard assessment.

EPA considered studies of low, medium, or high confidence for hazard identification and dose-response analysis. Information from studies that were rated unacceptable were only discussed on a case-by-case basis for hazard ID and weight-of-evidence assessment but were not considered for dose-response analysis. EPA considered the specific reasons for the unacceptable scoring in determining whether unacceptable studies could remain useful for hazard ID or weight-of-evidence.

EPA has not developed data quality criteria for all types of hazard information. This is the case for toxicokinetics and many types of mechanistic data which EPA typically uses for qualitative support when synthesizing evidence. As appropriate, EPA evaluated and summarized these data to determine their utility for supporting the risk evaluation (e.g. ADME data).

Following the data quality evaluation, EPA integrated the toxicological information from each relevant study. In the last step, the strengths and limitations of the data were evaluated for each endpoint and a weight-of-the-scientific evidence narrative was developed. Data for each selected hazard endpoint was modeled to determine the dose-response relationship (Appendix I). Finally, the results were summarized, and the uncertainties were presented. The process is described in Figure 3-1.

The weight of evidence analysis included integrating information from toxicokinetics and toxicodynamics in relation to the key hazard endpoints: acute toxicity, liver toxicity, thyroid effects, reproductive/ developmental toxicity, neurotoxicity, immunotoxicity, sensitization and irritation. EPA selected human health studies that were of the highest quality and relevance to move forward for dose-response analysis in order to quantitatively assess each key hazard endpoint. Dose-response analyses using benchmark dose modeling (BMD) was performed for each hazard endpoint of concern where possible. In an effort to address some of the limitations of the NOAEL/LOAEL approach, the BMD approach was developed as a more robust alternative that considers all the data in the dose-response relationship (U.S. EPA, 2012a). Supplemental studies were evaluated in considering the mode of action (MOA) for these endpoints in relation to hazard characterization.

A summary table which includes all endpoints considered for this assessment, the no-observed- or lowest-observed-adverse-effect levels (NOAEL and LOAEL) for non-cancer health endpoints by target organ/system, the incidence for cancer endpoints, and the results of the data quality evaluation is provided in *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies. (U.S. EPA, 2019n)*.

EPA considered points of departure (POD) from studies that were PECO relevant, scored acceptable in the data quality evaluation, and contained adequate dose-response information. The POD is a dose or concentration near the lower end of the observed range without significant extrapolation to lower doses. It is used as the starting point for subsequent dose-response (or concentration-response) extrapolations and analyses. PODs can be a no-observed-adverse-effect level (NOAEL), a lowest-observed-adverse-effect level (LOAEL) for an observed incidence, or change in level of response, or the lower confidence limit on the dose at the benchmark dose (BMD)[15]. PODs were adjusted as appropriate to conform to the specific exposure scenarios evaluated.

The only available repeat-dose toxicity studies available on HBCD were conducted via the oral route of exposure (except for a single 14-day inhalation study (Song et al., 2016)). These studies were evaluated

[15] The benchmark dose (BMD) is a dose or concentration that produces a predetermined change in response range or rate of an adverse effect (called the benchmark response or BMR) compared to baseline.

for dose-response assessment, and oral PODs were extrapolated for use via the inhalation route because it is assumed that inhaled HBCD will be absorbed either through the lungs or via the GI tract following incidental ingestion. Limited toxicological data are available by the dermal route and physiologically based pharmacokinetic/ pharmacodynamic (PBPK/PD) models that would facilitate route-to-route extrapolation have not been identified for HBCD. Therefore, oral PODs were also extrapolated for use via the dermal route, with adjustments made for absorption. The PODs estimated based on effects in adult animals were converted to Human Equivalent Doses (HEDs) employing a standard dosimetric adjustment factor (DAF) consistent with EPA guidance (U.S. EPA, 2011d).

Section 3.2.5 describes the dose-response assessment guiding the selection of PODs for non-cancer endpoints. The benchmark dose analysis is discussed in Appendix I, and the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard. (U.S. EPA, 2019e).*

3.2.2 Toxicokinetics

This section describes the available information on absorption, distribution, metabolism and excretion (ADME). See Appendix H for further discussion, including citations.

As discussed above in Section 3.2.1, EPA has not published systematic review criteria applicable to toxicokinetic studies, however all relevant toxicokinetic information was either obtained from previous regulatory and non-regulatory chemical assessments and/or was informally evaluated for overall data quality and relevance. HBCD isomers in commercial HBCD mixtures (α-, β-, and γ-HBCD) are rapidly and extensively absorbed in orally-exposed laboratory animals, with many studies demonstrating absorption ratios approaching or above 90%. Data on the rate or extent of oral absorption in humans are not available, but absorption in the human gastrointestinal (GI) tract is expected given the detection of HBCD in samples of human milk, maternal blood/cord blood, and fetal tissue. Dermally, absorption of HBCD is affected by the relative ratio of sweat to sebum, with greater partitioning into sebum. While a substantial percentage of HBCD has been shown to be bioaccessible (locally available within dermal layers) within skin, dermally applied HBCD is quite poorly absorbed systemically into the bloodstream. For the purposes of this risk evaluation, an upper estimate of 100% gastrointestinal absorption will be used. It is assumed that any inhaled HBCD particles will be either absorbed through the lungs or swallowed and absorbed through the GI tract. Based on available *ex vivo* and *in vitro* data, the higher-end estimate of 6.5% dermal absorption of HBCD is used as a conservative assumption. The actual percentage of HBCD absorbed dermally is variable based on multiple factors including the relative percentage of each isomer in the mixture and the relative ratio of sweat to sebum on skin.

In laboratory animals, absorbed HBCD isomers and metabolites distribute to tissues, with the highest levels found in fat, liver, skeletal muscle, and skin. Isomers of HBCD accumulate differentially in tissues, with α-HBCD showing greater potential to accumulate in fat than γ-HBCD or β-HBCD. Biomonitoring studies indicate that HBCD is transferred to breast milk in humans and crosses the placenta. Animal and in vitro studies show that HBCD isomers undergo metabolism by hydroxylation and debromination, and that the β- and γ-isomers, but not the α-isomer, can undergo isomerization. Cytochrome P450 enzymes appear to be involved in the hydroxylation of HBCD isomers and are induced in rats following repeated oral exposure. HBCD isomers and their metabolites are excreted in feces (via biliary excretion) and in urine. γ-HBCD and β-HBCD are more rapidly metabolized and eliminated from laboratory animal tissues (especially fat) than α-HBCD. HBCD has a derived elimination half-life as high as 64 days in humans based on data from breast milk and rat adipose tissue. The toxicokinetics of inhaled HBCD have not been investigated.

No physiologically based pharmacokinetic (PBPK) models are available for HBCD. An unpublished, empirical two-compartment open kinetic model for orally-administered 14C-HBCD was developed from data in Sprague-Dawley rats (Yu and Atallah, 1980). The model did not explicitly describe HBCD metabolism but did estimate an elimination constant for HBCD. (Aylward and Hays, 2011a) derived a simple first-order elimination model to estimate the steady-state lipid concentration of HBCD in the body (in ng/g lipid) corresponding to a given daily HBCD intake (in mg/kg-day). They proposed the use of lipid-adjusted tissue concentrations of HBCD as an internal dose metric to reduce uncertainties associated with inter- and intraspecies extrapolation based on external dose, however the simplistic model introduces significant other uncertainties that reduce the value of its use. Based on the absence of a robust, peer reviewed PBPK model, EPA relied on traditional route-to-route extrapolation, uncertainty factors, and dosimetric adjustment factor in the derivation of HEDs. See Appendix H for further discussion of these models.

3.2.3 Hazard Identification

The HBCD database includes six epidemiological studies that examined associations between HBCD exposure and endpoints related to effects on the thyroid, nervous system, and male reproductive system. The evaluation of HBCD epidemiology studies by each of the five aspects of study design – study population characteristics and representativeness, exposure measures, outcome measures, confounding, and analysis – is discussed below; a summary of the results from these studies and the data quality evaluation of individual studies is provided in *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard. (U.S. EPA, 2019e)* and *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S. EPA, 2019n).* Overall, EPA determined that the epidemiological database was insufficient for dose-response assessment,

Experimental animal studies of HBCD that underwent study evaluation consisted of studies designed to examine repeat-dose oral toxicity and specialized studies of various non-cancer hazards. The majority of the experimental animal studies were considered informative and useful for characterizing the health hazards associated with exposure to HBCD, and results from these studies were extracted into evidence tables in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)* and [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables for Human Health Hazard Studies (U.S. EPA, 2019g)*]. Some limitations were noted for each study (see the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S. EPA, 2019n).* Any study evaluation concerns that may have meaningfully influenced the reliability or interpretation of the results were brought forward into the synthesis of evidence for a given hazard. Two studies were considered for dose-response assessment of all endpoints (Ema et al., 2008; WIL Research, 2001), both of which scored a High in data evaluation.

Animal studies of ingested HBCD reported effects on the thyroid, liver, development, reproduction, nervous system, and immune system, in addition to limited studies demonstrating overt toxicity following acute exposure and sensitization/irritation. The potential health effects of inhaled HBCD have not been adequately investigated in humans or animals. There is not adequate available information to assess the carcinogenic potential of HBCD.

3.2.3.1 Non-Cancer Hazards

Data evaluation results for all studies can be found in the [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S. EPA, 2019n)*] and data extraction results including author-reported PODs can be found in the [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables for Human Health Hazard Studies (U.S. EPA, 2019g)]*.

For additional, more detailed information on toxicity information, weight of evidence, and mechanistic data see Section 3.2.4 and [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*].

3.2.3.1.1 Thyroid Effects

In humans, (Eggesbø et al., 2011) reported elevated but non-statistically significant odds ratios for increased thyroid stimulating hormone (TSH) in relation to increased HBCD levels in breast milk, but confidence intervals (CIs) around point estimates were relatively wide and a clear dose-response was not observed. Similarly, other studies in humans (Kiciński et al., 2012; Roze et al., 2009; Johnson et al., 2013) also did not observe any statistically significant correlations with HBCD exposure and thyroid effects among populations of various lifestages.

Although the human evidence was inconclusive, oral toxicity studies in rodents provide evidence that HBCD exposure can result in dose-related perturbations of thyroid function. In studies of HBCD-induced perturbation of serum thyroid hormone levels (i.e., TSH, T4, and T3), TSH was elevated in three studies (Saegusa et al., 2009; Ema et al., 2008; WIL Research, 2001), two of which also reported decreases in serum T4 (Ema et al., 2008; WIL Research, 2001). Of the several studies that measured T3 (Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008; van der Ven et al., 2006; WIL Research, 2001), only one reported a treatment-related effect (Saegusa et al., 2009), with a statistically significant reduction observed at the highest dose. Exposure to HBCD was also associated with histopathological changes, including decreased thyroid follicle size (Ema et al., 2008; van der Ven et al., 2006), follicular cell hypertrophy (Saegusa et al., 2009; WIL Research, 2001), and colloid depletion (WIL Research, 1997), and increased thyroid weight (Saegusa et al., 2009; Ema et al., 2008; van der Ven et al., 2006; WIL Research, 2001). These changes were observed across multiple rat strains, sexes, exposure durations, and study designs.

3.2.3.1.2 Liver Effects

There are no epidemiological studies that investigated the potential for an association between HBCD exposure and liver outcomes; however, some evidence for liver toxicity was identified in several rodent studies. The most consistently observed liver outcome was liver weight changes. Dose-related increases were consistently observed across species, sexes, and age from multiple studies of various designs and exposure durations (Maranghi et al., 2013; Saegusa et al., 2009; Ema et al., 2008; WIL Research, 2001, 1997). Limited support for HBCD effects on the liver are provided by histopathological examination. A subset of the rat studies (Saegusa et al., 2009; WIL Research, 2001, 1997) and one mouse study (Maranghi et al., 2013) reported increased vacuolation (generally of minimal to mild severity) in HBCD-exposed animals, but these responses were not dose-related. Other histological findings were less frequently observed and included some additional evidence of fatty change (steatosis) (Yanagisawa et al., 2014), hypertrophy (Yanagisawa et al., 2014; WIL Research, 1997), and inflammation (Maranghi et al., 2013). Of note, (Yanagisawa et al., 2014) scored Unacceptable in data quality evaluation due to relying on an intermittent 1x/week dosing schedule, however observations from that study still

contribute to hazard identification. Statistically or biologically significant elevations in serum liver enzymes were not consistently associated with HBCD exposure in rats or mice (Yanagisawa et al., 2014; WIL Research, 1997), although a dose-responsive increase in alanine aminotransferase (ALT) was observed in female rats (WIL Research, 2001).

3.2.3.1.3 Reproductive Effects

Female reproductive effects

There are no epidemiological studies evaluating female reproductive outcomes. In animals, some evidence for an association between HBCD exposure and female reproductive system effects comes from findings of effects on fertility and pregnancy outcome as reported in a two-generation reproductive toxicity study for HBCD in rats (Ema et al., 2008); signs of reproductive toxicity included dose-related decreases in pregnancy incidence in F0 and F1 generations, and a statistically significant incidence of total litter loss in multiple high-dose F1 dams. Decreased primordial follicles were also observed in the F1 dams (this endpoint was not evaluated in F0 females).

Male reproductive effects

Two epidemiological studies investigated reproductive endpoints in male subjects from a birth cohort and adult males seeking infertility treatments (Johnson et al., 2013; Meijer et al., 2012); these studies provide some evidence of a weak to moderate negative correlation between HBCD exposure and serum testosterone or sex hormone binding globulin (SHBG) levels, but not other hormones.

In animal studies, no consistent effects on male reproductive organ weights, reproductive development, hormone concentrations, or spermatogenic measures were associated with 28-day, 90-day, or developmental exposure to HBCD (Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008; van der Ven et al., 2006; WIL Research, 2001).

3.2.3.1.4 Developmental Effects

There are no epidemiological studies evaluating developmental-specific outcomes. However, several studies in animals exposed during gestation and lactation provide some evidence of developmental effects associated with HBCD, including reduced offspring viability (Ema et al., 2008), decreased pup body weight (Maranghi et al., 2013; Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008), altered development of the skeletal system, and delayed eye opening (Ema et al., 2008). Evidence of adverse developmental effects is based on findings of reduced offspring survival and decreased pup body weight. Reduced viability was observed in F2 pups of the two-generation study by (Ema et al., 2008); the decreases in viability were dose-related and observed on both post-natal day (PND) 4 and 21. The fact that effects were seen only in F2 offspring is consistent with decreased viability manifesting after multigenerational exposure, although that hypothesis cannot be established based on the current developmental literature for HBCD (i.e., a single two-generation study). Effects on pup body weight were demonstrated in several studies in rats using different strains and exposure durations (Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008). Other developmental effects, including changes in bone development and delayed eye opening, were only reported in a single study and with a less clear dose-response relationship (van der Ven et al., 2009; Ema et al., 2008).

3.2.3.1.5 Neurological Effects

Developmental exposure

The two available epidemiological studies did not find consistent effects on the nervous system following developmental exposure. In animals, there is some evidence to support HBCD-mediated neurotoxicity following developmental exposure. Early-life exposure in rodents affected several measures of neurotoxicity, including neurodevelopmental milestones (Miller-Rhodes et al., 2014; Ema

et al., 2008), locomotor activity and executive function (Miller-Rhodes et al., 2014; Ema et al., 2008; Eriksson et al., 2006), and other neurological outcomes related to changes in auditory sensitivity, dopaminergic system function (Lilienthal et al., 2009), and brain weight (van der Ven et al., 2009; Ema et al., 2008). (Eriksson et al., 2006) evaluated effects in young adult (3-month-old) mice that were administered a single dose of HBCD on PND 10, which corresponds with a period of rapid growth and maturation for motor and sensory neural networks in mice.

Adult exposure

There are no epidemiological studies evaluating nervous system effects following adult exposure. In animals, four studies in rats or mice exposed only as adults found no changes in the nervous system endpoints evaluated (i.e., striatal levels of dopamine, FOB, locomotor activity, brain weight, or gross brain pathology) (Genskow et al., 2015; van der Ven et al., 2006; WIL Research, 2001, 1997). Results on locomotor activity indicated that mice failed to habituate to the novel environment of the testing arena, however this result was not confirmed in a longer duration study (Miller-Rhodes et al., 2014; Ema et al., 2008).

3.2.3.1.6 Immune System Effects

There are no epidemiological studies evaluating immune system effects. In animals, there is some evidence of HBCD-mediated immune system effects. The strongest evidence comes from alterations in IgG antibodies, a functional measure of immune system response, in rats exposed to HBCD during development (Hachisuka et al., 2010; van der Ven et al., 2009). Changes in other indicators of immunomodulation, including changes in immune organ weights, hematology, and histopathology, were variable and inconsistent in both developing and adult animals. Recent mechanistic studies (Almughamsi and Whalen, 2016; Anisuzzaman and Whalen, 2016; Canbaz et al., 2016a; Koike et al., 2016) along with bioassays from the EPA ToxCast Dashboard (https://actor.epa.gov/dashboard/#chemical/3194-55-6) demonstrate changes in cytokine secretion from immune cells following HBCD exposure, however these changes were not always consistent and could not be directly linked to any particular toxicological outcome.

3.2.3.1.7 Overt Toxicity Following Acute/Short Term Exposure

Acute/short term studies in animals consist of either single or short-term exposures (14-days or less) at high doses specifically designed for assessing the dose at which lethality occurs or for examining overt toxicity. Several acute lethality studies in rodents and rabbits by the oral, dermal, and inhalation routes with HBCD are available (GSRI, 1994; Momma et al., 1993; BASF, 1990; IRDC, 1978a, b, c; Lewis and Palanker, 1978a). The acute lethality of HBCD is relatively low via the oral, dermal and inhalation routes. Oral LD50 values are equal to or greater than 680 mg/kg-bw, in rats and mice. Various neurotoxic signs observed in oral studies included ptosis (upper eyelid drooping), apathy, trembling, and hypoactivity. Additional effects included lacrimation (tears), diarrhea, and inflammation (U.S. EPA, 2015). No lethality was observed in rabbits following acute dermal exposure to doses as high as 8.0 g/kg (Lewis and Palanker, 1978a). Several inhalation studies have demonstrated no mortality in rats following exposure to up to 200 mg/L (200,000 mg/m^3) HBCD for 1-4h (U.S. EPA, 2015), with only minor symptoms observed (such as eye squint, slight dyspnea, salivation, lacrimation, and nasal discharge). A recent study confirmed that the HBCD LC50 for 4-h inhalation exposure in rats is greater than 5000 mg/m^3 (Song et al., 2016). In that same study, HBCD also did not produce any adverse effects (clinical signs or organ-specific pathology) up to 2000 mg/m^3 administered 6h/day for 14 days.

3.2.3.1.8 Sensitization/Irritation

The available literature indicates that HBCD is not a dermal irritant in guinea pigs (Lewis and Palanker, 1978b). Acute eye irritation studies in rabbits showed HBCD to be a mild transient ocular irritant (Lewis and Palanker, 1978b), (Gulf South Research Institute, 1988). One study (Momma et al., 1993) found HBCD to be a mild skin allergen in guinea pigs, however (Microbiological Associates, 1996b) did not observe any sensitization reaction at the same dose (5%) or neat in corn oil (~100%) (NRC, 2000b). Two mechanistic studies suggest that HBCD enhances the allergenic response to dust-mites (Canbaz et al., 2016a; Canbaz et al., 2016b)], and there is some evidence of HBCD stimulating the release of various pro-inflammatory cytokines that may promote allergic responses (Almughamsi and Whalen, 2016; Anisuzzaman and Whalen, 2016; Canbaz et al., 2016a; Koike et al., 2016).

3.2.3.2 Genotoxicity and Cancer Hazards

Genotoxicity

A limited number of studies have investigated the genotoxicity of HBCD. Most standard Ames tests conducted with HBCD yielded negative results (Huntingdon Research Center, 1990; IBT Labs, 1990; Litton Bionetics, 1990; Pharmakologisches Institut, 1990; SRI International, 1990; Zeiger et al., 1987). Among the few assays performed to determine the genotoxicity of HBCD in eukaryotic systems, a reverse mutation assay in yeast (Litton Bionetics, 1990), one assay detecting chromosomal aberrations in human peripheral lymphocytes in vitro (Microbiological Associates, 1996a), and an *in vivo* mouse micronucleus test following intraperitoneal (i.p.) injections of HBCD (BASF, 2000) were negative, even when tested at cytotoxic concentrations.

Some positive results have been reported in both bacteria (Ethyl Corporation, 1990b; IBT Labs, 1990) and mammalian cells (Helleday et al., 1999),(Ethyl Corporation, 1990a). It is noteworthy that in the mammalian cell study (Helleday et al., 1999), observed positive results for intragenic recombination were dose-dependent, observed at nontoxic doses, and in two assays, specific for detecting mutations. However, the Ames tests in the same microbial strains that showed positive results (TA1535 and TA100) were negative in seven other studies, while he positive mutagenicity results observed in mammalian cells (Helleday et al., 1999) have not been confirmed by another group. There is also only limited evidence in the literature indicating that HBCD exposure may induce oxidative stress (An et al., 2013; Hu et al., 2009b).

Carcinogenicity

The carcinogenic potential of HBCD was not evaluated in any epidemiological studies. The only experimental animal study to examine cancer endpoints is an 18-month dietary study in mice that was only available as an incomplete report (Kurokawa et al., 1984). That study concluded that HBCD was not carcinogenic at dietary concentrations of 100, 1000 and 10,000 ppm.

3.2.4 Weight of Evidence

For more detailed discussion on weight of evidence and mode of action, see *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*.

3.2.4.1.1 Thyroid Effects

The human database was considered too limited for drawing conclusions regarding the relationship between HBCD exposure and thyroid effects. Several human epidemiological studies investigated the association between HBCD exposure and alteration of thyroid hormones at various lifestages. (Eggesbø et al., 2011) reported an elevated but non-statistically significant odds ratio for increased TSH in relation to increased HBCD levels in breast milk, but confidence intervals around point estimates were relatively

wide and a clear dose-response was not observed. Other studies also found no significant correlations with HBCD exposure and thyroid effects. In general, these HBCD studies were limited by small sample sizes (Kim and Oh, 2014; Johnson et al., 2013; Roze et al., 2009) or HBCD exposure quantification methods (Kim and Oh, 2014; Kiciński et al., 2012).

Animal toxicity studies provided evidence of thyroid perturbation associated with HBCD exposure, including altered levels of thyroid hormones, histological changes, and increased thyroid weight, with effects observed across multiple lifestages. A pattern of increased TSH, a sensitive early indicator of decreased thyroid hormone reserve, and decreased T4 that was observed in a two-generation reproductive study (Ema et al., 2008) is consistent with the multi-loop feedback system of the HPT-axis (Fisher and Nelson, 2012). A similar pattern of effect in TSH and T4 was reported by (WIL Research, 2001); however, confidence in these results is low because while the study scored a High overall in data evaluation based on other endpoints, the reported control levels for TSH measurements were 10- to 25-fold lower than the control levels measured in other studies. Although these two studies did not observe significant changes in T3, this finding is not surprising given that T4 is the major thyroid hormone in the blood and most T3 is created by deiodination of T4 in the peripheral tissues (Rosol et al., 2013). In addition to changes in serum hormone levels, evidence of thyroid activation, including histopathological changes (Saegusa et al., 2009; Ema et al., 2008; van der Ven et al., 2006; WIL Research, 2001, 1997) and increased thyroid weight (Saegusa et al., 2009; Ema et al., 2008; van der Ven et al., 2006; WIL Research, 2001), were observed in both sexes and across studies of different exposure durations (subchronic, short-term, and one- and two-generations).

Regulation of thyroid hormones is complex and homeostasis is largely maintained via hypothalamic-pituitary-thyroid (HPT) axis feedback mechanisms. Reductions in serum T3 or T4 triggers release of TSH from the pituitary, which stimulates the thyroid gland to increase secretion of T3 and T4 stores from the colloid (Fisher and Nelson, 2012). Decreased T4 is expected to be the primary driver of HBCD-mediated thyroid effects that triggers release of TSH. Indeed, this is supported by mechanistic studies that indicate that that observed decreases in T4 may be largely driven by hepatic induction of enzymes that metabolize this hormone (Shelby et al., 2003; Vansell and Klaassen, 2002; Kelly, 2000). Furthermore, reduced T4 levels can also play a key role in other downstream effects such as liver toxicity, developmental neurotoxicity, as well as other developmental processes (Finken et al., 2013; Julvez et al., 2013a; Román et al., 2013; Henrichs et al., 2010; Haddow et al., 1999). A few studies demonstrate that HBCD may induce human health hazards downstream of thyroid hormone dysregulation through activation of the DNA-binding thyroid receptor (Hamers et al., 2006; Schriks et al., 2006)

There is debate as to whether rodents are more sensitive than humans to thyroid hormone disruption. A review on thyroid disruption by perchlorate by the National Academies of Science (NAS) (NRC, 2005) concludes that while thyroid function and regulation are qualitatively similar in rats and humans, differences in clearance rates and thyroid stimulation require careful consideration for interpreting thyroid hormone or histopathology changes in quantitative risk assessment. This NAS assessment also states that humans are less susceptible than rats to disruption of thyroid hormone based on these differences. This review was targeted to the effects of perchlorate however, with all conclusions caveated in that they apply specifically to perchlorate exposure and the formation of thyroid tumors, which is not an expected outcome of HBCD exposure. The mode of action (MOA) for perchlorate involves inhibition of sodium-iodide symporter (NIS)-mediated iodide uptake in the thyroid, and NAS recommends use of this effect as the basis for the perchlorate point of departure (POD). There is no evidence that HBCD modulates thyroid hormones through inhibition of iodide uptake. Available

mechanistic evidence suggests that HBCD is likely to function at least partially indirectly through upregulation of the enzyme uridine diphosphate glucuronyl transferase (UGT) (Crump et al., 2010; Cantón et al., 2008; Crump et al., 2008; Palace et al., 2008; van der Ven et al., 2006) resulting in increased thyroid hormone metabolism and excretion (Kato et al., 2008; Klaassen and Hood, 2001). This mechanism would be expected to act on thyroid hormone levels directly, unlike the MOA for perchlorate. Additionally, a review of the HPT axis across species published more recently than the NAS review (Zoeller et al., 2007) states that there is minimal evidence linking biochemical and metabolic differences in thyroid hormones (due primarily to reduce serum binding proteins in rodents) to differences in sensitivity among rodents and humans except on a MOA-specific basis. The review concludes that "total T4 in rodents is a valid measure of thyroid function if serum binding proteins are not being affected by the treatment under study". While there is conflicting limited mechanistic evidence investigating whether HBCD may affect transcription of the serum binding protein transthyretin (TTR) (Crump et al., 2008; Hamers et al., 2006), the majority of mechanistic data supports an MOA involving increased thyroid hormone clearance through induction of UGT.

A review by the National Institute of Environmental Health Sciences (NIEHS) (Choksi et al., 2003) concludes that while the thyroid system is highly conserved between rodents and humans in general, differences that need to be considered in extrapolating results from animal data include: "metabolic turnover rates, basal TSH levels, sodium-iodide symporter sensitivities, windows of susceptibility, the role of the thyroid system on reproductive tract development and function, and the magnitudes of thyroid system changes that result in adverse health effects", among others. Additionally, thyroid hormone glucuronidation by UGT is only a minor pathway in humans under euthyroid conditions. Therefore, overall the weight-of-evidence indicates that rodents are an adequate model for assessment of thyroid disruption by HBCD, however it is possible that quantitative extrapolation may overestimate the adversity of effects in humans.

Perturbations in thyroid hormones observed in animal studies following HBCD exposure as well as effects observed in mechanistic studies [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*], support EPA conducting dose- response analysis on this endpoint. In addition, the other hazards associated with HBCD toxicity are likely downstream results of the dysregulation of thyroid hormones and the HPT axis, key events in the associated adverse outcome pathway leading to multiple adverse outcomes (Forhead and Fowden, 2014; Gilbert and Zoeller, 2010; Hulbert, 2000). Therefore, this hazard was carried forward for dose-response analysis.

3.2.4.1.2 Liver Effects

No epidemiological studies are available to inform potential liver effects of HBCD. In laboratory animals, there is evidence for liver toxicity. The most consistent hepatic change was increased liver weight, which was observed in the majority of studies, in both sexes, in both rats and mice, and following both adult and developmental exposures (Maranghi et al., 2013; Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008; van der Ven et al., 2006; WIL Research, 2001, 1997). Although the toxicological significance of increased liver weight is not clear, these data are supported by some histological and mechanistic data. Vacuolation was observed in several rat studies (Saegusa et al., 2009; WIL Research, 2001, 1997) and one mouse study (Maranghi et al., 2013). The content of the hepatocellular vacuoles was investigated by (WIL Research, 2001) and characterized as lipid. Studies reported evidence of inflammatory effects in the liver of mice following HBCD exposure through a standard chow diet (Maranghi et al., 2013) and enhancement of hepatic fatty changes (steatosis) in mice when HBCD was added to a high-fat diet (Yanagisawa et al., 2014). Statistically or biologically significant elevations in serum liver enzymes were not associated with HBCD exposure in rats or mice

(Yanagisawa et al., 2014; WIL Research, 2001, 1997). Mechanistic studies and histopathological data suggest that HBCD may dysregulate lipid metabolism and transport (Wheater and Burkitt, 1996). Mechanistic evidence also suggests a potential role of HBCD in the induction of hepatic microsomal enzymes, a proposed key event in initiating the perturbation of the HPT axis that leads to reduced T4 levels (see Thyroid section above) [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*]. Liver toxicity appears to be especially apparent following a high-fat diet, which may represent a susceptibility factor for HBCD toxicity (Bernhard et al., 2016).

Liver toxicity following HBCD exposure is supported by observations in animal studies. Therefore, this hazard was carried forward for dose-response analysis.

3.2.4.1.3 Reproductive Effects

Female Reproductive Effects

The potential for HBCD to affect the female reproductive system has not been investigated in humans. There is evidence for female reproductive hazard in animals, primarily based on effects observed in a two-generation reproductive toxicity study (Ema et al., 2008). (Ema et al., 2008) reported dose-related decreased incidence of pregnancy in the F0 and F1 generations and a reduced pool of primordial follicles in the F1 generation. The only other study that looked at a measure of pregnancy incidence was a one-generation study (van der Ven et al., 2009) that reported no significant dose-response trend on successful matings (i.e., the rate of matings that results in offspring). Because (van der Ven et al., 2009) used a lower dose range than (Ema et al., 2008), the lack of effects on reproductive performance from this study is only informative of an absence of effects at lower doses and does not contradict the outcomes observed in (Ema et al., 2008) at higher doses. HBCD exposure did not affect other fertility and pregnancy outcomes (e.g., gestational duration, number of implantation sites, litter size) (Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008). Investigation of other female reproductive outcomes provides little supportive evidence of reproductive toxicity. Statistically significant changes in hormone levels were limited to increased FSH as reported by (Ema et al., 2008) and increased testosterone as reported by (Maranghi et al., 2013); levels of other hormones showed no dose-related changes. Evidence of changes in time to vaginal opening, a measure of reproductive differentiation and development, were inconsistent across studies. No consistent effects were observed on measures of reproductive organ weight. A limited number of mechanistic studies [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*] focused on potential effects related to sex hormone homeostasis are inadequate to support an understanding of the potential mode of action for changes in fertility and pregnancy outcomes as observed in (Ema et al., 2008). Although supporting evidence is limited, there are no studies that contradict the findings in (Ema et al., 2008), the only study that used a two-generation study design.

Evidence for female reproductive toxicity following HBCD exposure is supported by observations in animal studies. Therefore, this hazard was carried forward for dose-response analysis.

Male Reproductive Effects

Both human and animal evidence for male reproductive effects were insufficient for drawing conclusions regarding the relationship between HBCD exposure and male reproductive toxicity. Two epidemiological studies (Johnson et al., 2013; Meijer et al., 2012) provided limited evidence of male reproductive effects (effects on serum testosterone and SHBG levels) associated with HBCD exposure in humans, and animal studies revealed inconsistent effects in all measures of male reproductive endpoints. Limited mechanistic data on male reproductive toxicity are available [*Draft Risk Evaluation*

for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)].

Evidence for male reproductive toxicity following HBCD exposure in animal studies was limited and inconsistent. Therefore, this hazard was not considered further for dose-response analysis.

3.2.4.1.4 Developmental Effects

Studies were not identified that looked at developmental-specific outcomes in humans. Note that epidemiological studies pertaining to other organ-/system-specific hazards following developmental exposure are discussed in Sections 3.2.3.1.1 (thyroid), 3.2.3.1.3 (male reproduction), and 3.2.3.1.5 (nervous system).

Animal toxicity studies provide evidence of a developmental hazard. These data suggest that early life exposure to HBCD can affect various developmental outcomes, including reduced offspring viability (Ema et al., 2008) and decrements in pup weight (Maranghi et al., 2013; Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008). Developmental landmarks were either unaffected (i.e., incisor eruption or pinna unfolding) or effected inconsistently (i.e., eye opening) (Ema et al., 2008). The support for developmental toxicity is strongest in F2 animals, with effects seen in both sexes in the high-dose group. Data in zebrafish suggest that early life exposure to HBCD may result in malformations and mortality in association with increased reactive oxygen species production and altered cardiac function. Although there is limited mechanistic data overall regarding HBCD-mediated effects on development, perturbations in thyroid hormones could lead to developmental toxicity because of the role thyroid hormones play during development (Zoeller et al., 2007; (Forhead and Fowden, 2014; Gilbert and Zoeller, 2010; Hulbert, 2000) [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*].

Evidence for developmental toxicity following HBCD exposure is supported by observations in animals. Therefore, this hazard was carried forward for dose-response analysis.

3.2.4.1.5 Neurological Effects

Developmental Exposure

In a birth cohort study in the Netherlands (Roze et al., 2009), the associations between maternal HBCD levels (week 35 of pregnancy) and multiple neuropsychological domains were inconsistent across the measured domains. A second study in adolescents in Belgium (Kiciński et al., 2012) did not observe associations between HBCD levels and six neurobehavioral measures. Therefore, the available human evidence ranges from equivocal to negative.

Some evidence of potential nervous system effects of HBCD comes from early-life exposure studies in rodents. Perinatal HBCD exposure altered neurodevelopmental milestones (Miller-Rhodes et al., 2014; Ema et al., 2008), elicited changes in locomotor activity and executive function that persisted into adulthood (Miller-Rhodes et al., 2014; Ema et al., 2008; Eriksson et al., 2006), and affected other neurological endpoints related to changes in auditory sensitivity, dopamine system function (Lilienthal et al., 2009), and brain weight (van der Ven et al., 2009; Ema et al., 2008). Across the database, nervous system effects were observed in both sexes and across a wide range of doses and exposure durations (ranging from acute to multigenerational). However, interpretation of these data was complicated by study quality issues, including lack of blinding, poor health in the animals, pooling of data across timepoints, and failure to measure potential confounders. Furthermore, there were considerable inconsistencies in outcomes across studies that evaluated similar neurodevelopmental endpoints,

including development of sensorimotor reflexes, locomotor activity, learning ability in swim maze tests, and brain weight.

Animal toxicity data are supported by mechanistic studies, indicating that HBCD interferes with thyroid hormone-mediated neurogenesis and differentiation, calcium homeostasis, and neurotransmitter release [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*]. Normal neurodevelopment is dependent on tight regulation of all of these systems and perturbations are associated with persistent changes in behavior and neurological function (Finken et al., 2013; Julvez et al., 2013b; Román et al., 2013; Henrichs et al., 2010; Haddow et al., 1999).

Overall, there is evidence from animal studies to support potential nervous system effects associated with HBCD exposure during development. However, although the data support a qualitative assessment of developmental neurotoxicity, there are notable inconsistencies and/or limitations with the database. Treatment-related effects were observed in all but one study that evaluated the effects of developmental exposure on nervous system function, but there was no consistent pattern of effect across studies. Furthermore, study quality issues (i.e., lack of blinding, health issues in the animals, pooling of data, failure to measure potential confounders, wide variation in response, and questions regarding the statistical methodology) were identified in several studies. In light of these uncertainties, selection of data sets from the available developmental neurotoxicity studies for dose-response analysis was not supported.

Adult Exposure

Neurotoxicity following HBCD exposure during adulthood was not supported by observations in animal studies (Genskow et al., 2015; van der Ven et al., 2006; WIL Research, 2001, 1997). Therefore, this hazard was not carried forward for dose-response analysis.

3.2.4.1.6 Immune System Effects

The potential immunotoxicity of HBCD has not been investigated in human populations. The effects of HBCD on both functional and structural immune endpoints were evaluated in animal models. Of the endpoints evaluated, measures of T cell-dependent antibody responses—functional immune endpoints and therefore more sensitive and predictive indicators of potential immunotoxicity (Luster et al., 2005)—were given more weight.

Developmental Exposure

In studies in rats, early-life HBCD exposure altered antibody responses to sheep red blood cells (SRBC) (increased) (van der Ven et al., 2009) and keyhole limpet hemocyanin (KLH) (decreased) (Hachisuka et al., 2010). Healthy immune function is maintained as a delicate balance between: (1) an immune response adequate to provide protection from certain types of cancers and infectious diseases, and (2) pathological loss of immune system control resulting in conditions such as autoimmunity, hypersensitivity, and chronic inflammation. Unintended immunomodulation in either direction (i.e., immunosuppression or immunostimulation) may be considered adverse (WHO, 2012). Therefore, the difference in direction of effect in the only two measures of antibody response does not necessarily minimize the validity of the findings in early lifestage animals.

Adult Exposure

HBCD did not cause changes in functional immune endpoints in adult rats or mice (Watanabe et al., 2010; van der Ven et al., 2006). The database does not provide a clear and consistent pattern of effect on immune organ weights, hematology, or histopathology. Mechanistic data suggests that HBCD stimulates

pro-inflammatory cytokines, however some of these responses are not consistently observed [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)]*. Given the diversity of study designs, exposure conditions, and analytical methods represented in this database, it is difficult to identify the underlying reasons for the differences in observations across studies.

Overall, while there is some evidence to support immune system effects following HBCD exposure, that data are inconclusive. Therefore, this hazard was not carried forward for dose-response analysis.

3.2.4.1.7 Overt Toxicity Following Acute/Short Term Exposures

Studies examining the toxicity of HBCD in humans following acute exposures have not been identified. There is limited evidence from acute toxicity studies in both rodents and rabbits exposed to high levels of HBCD for some minor and reversible neurological effects via the oral route, and mortality via the oral, dermal, and inhalation routes. Mortality or clinical signs of toxicity were not observed in rats following inhalation exposure to 2000 mg/m^3 HBCD administered 6h/day for 14 days (Song et al., 2016). While this study conflicts with data from repeat-dose oral studies, the study is of too-short of a duration to examine any chronic effects. Additionally, the study did not examine the critical effects of thyroid hormone regulation or any reproductive/developmental outcomes.

Evidence for overt toxicity or mortality is not supported by the available data from high dose acute exposure studies. Additionally, since these shorter-term oral exposure studies were either acute lethality studies or studies involving only single doses, they were not considered amenable to quantitative analysis. Therefore, this hazard was not carried forward for dose-response analysis.

3.2.4.1.8 Sensitization/Irritation

No studies have been identified examining the irritation or sensitization potential of HBCD in humans. A few studies in animals have found evidence for sensitizing potential of HBCD (Canbaz et al., 2016a; Momma et al., 1993) and HBCD stimulated release of pro-inflammatory cytokines, however, dermal sensitization has not been consistently observed (NRC, 2000b; Microbiological Associates, 1996b). Overall, there is insufficient evidence of irritation and inconsistent data regarding skin sensitization from HBCD exposure. In addition, there is only qualitative information available on these hazards. Therefore, they were not carried forward for dose-response analysis.

3.2.4.1.9 Genotoxicity/Carcinogenicity

Overall, given the limited data, negative results in the majority of mutation assays and the negative results in two assays for chromosomal aberrations (BASF, 2000; Microbiological Associates, 1996a), there is indeterminate evidence to make a conclusion on the genotoxicity of HBCD.

The only experimental animal study to examine cancer endpoints concluded that HBCD was not carcinogenic, however, this study was only available as an incomplete report (Kurokawa et al., 1984). Therefore, according to the U.S. EPA Guidelines for Carcinogen Risk Assessment (U.S. EPA, 2005), there is "inadequate information to assess the carcinogenic potential" of HBCD. As a result, this hazard was not carried forward for dose-response analysis.

3.2.4.1.10 Summary of Human Health Hazards Used to Evaluate Acute and Chronic Exposures

The EPA considered adverse effects for HBCD across organ systems. A comprehensive systematic review table can be found [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S.*

EPA, 2019n)]. The full list of human health effects was screened to those that are relevant, sensitive, and found in multiple studies. The HBCD human health hazard systematic review process screened 1,890 studies and obtained 53 studies that were relevant and applicable to the PECO statement. Only two of these studies were unacceptable based on data evaluation criteria. The remaining database of 51 studies included epidemiological studies that examined associations between HBCD exposure and endpoints related to effects on the thyroid, nervous system, and female reproductive system as well as repeat-dose experimental animal studies examining dose-responses for the endpoints of thyroid effects, liver effects, male and female reproductive effects, developmental toxicity, neurotoxicity, and immunotoxicity. EPA additionally considered data on toxicity following acute exposures, irritation, sensitization, genotoxicity, and carcinogenicity. From these effects, the EPA selected endpoints supported by the evidence for non-cancer that were amenable to quantitative analysis for dose-response assessment as discussed in more detail below in Section 3.2.5. In the following sections, the EPA identifies the appropriate toxicological studies to be used for acute and chronic exposure scenarios.

3.2.5 Dose-Response Assessment

3.2.5.1 Selection of Studies for Non-Cancer Dose-Response Assessment

As discussed in Section 3.2.4, studies in humans were not adequate to support conclusions regarding the relationship between HBCD exposure and effects on the thyroid, male reproduction, or nervous system, and accordingly do not support dose-response analysis. In the absence of adequate human data, animal toxicity studies were used for dose-response analysis.

The EPA evaluated data from studies described above (Section 3.2.3.1) to characterize the dose-response relationships of HBCD and selected studies and endpoints to quantify risks for specific exposure scenarios. One of the additional considerations was that the selected key studies had adequate information to perform dose-response analysis for the selected PODs. The EPA defines a POD as the dose-response point that marks the beginning of a low-dose extrapolation. This point can be the lower bound in the dose for an estimated incidence, or a change in response level from a dose-response model (i.e., BMDL), a NOAEL or a LOAEL for an observed incidence or change in the level of response.

Based on the weight of the evidence evaluation, four health effect domains were selected for non-cancer dose-response analysis: (1) thyroid; (2) liver; (3) female reproductive; and (4) developmental. These hazards have been carried forward for dose-response analysis. While there is also evidence to support nervous system toxicity following exposure to HBCD during development, these data sets were not carried forward for dose-response analysis. Data sets for male reproductive effects, adult neurological effects, immune system effects, genotoxicity, and cancer were also not carried forward for dose-response analysis. For a complete discussion, see Section 3.2.4.

Studies that evaluated each of the four health effect domains were identified in Section 3.2.3, and are considered in this section for dose-response analysis. In order to identify studies for dose-response analysis, several attributes of the studies were reviewed. Preference was given to studies using designs reasonably expected to detect a dose-related response. Chronic or subchronic studies are generally preferred over studies of less-than-subchronic duration for deriving chronic and subchronic reference values. Studies with a broad exposure range and multiple exposure levels are preferred to the extent that they can provide information about the shape of the exposure-response relationship. Additionally, with respect to measurement of the endpoint, studies that can reliably measure the magnitude and/or degree of severity of the effect are preferred.

Experimental animal studies considered for each hazard and effect were evaluated using systematic review quality considerations discussed in the Systematic Review Methods section. Only studies that scored an acceptable rating in data evaluation were considered for use in dose-response assessment. For HBCD, all evaluated repeated-dose studies that were considered acceptable received a Medium or High rating in data evaluation (*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S. EPA, 2019n)*. In addition to the data quality score, considerations for choosing from among these studies included study duration, relevance of study design, and the strength of the toxicological response. Details on these considerations for each endpoint are provided below. For all endpoints other than liver toxicity, (Ema et al., 2008) was considered the best study for dose-response assessment. The study was an OECD Guideline 2-generation reproductive toxicity study and scored a High in data evaluation. The 90-day repeat-dose oral study (WIL Research, 2001) also scored a High and was additionally considered for use in dose-response assessment only for the liver toxicity endpoint. See Section 3.2.5.2 for a more detailed explanation of EPA's basis for selection of these studies and derivation of PODs for each endpoint.

Given the different HBCD exposures scenarios considered (both acute and chronic), different endpoints were used based on the expected exposure durations. For non-cancer effects and based on a weight-of-evidence analysis of toxicity studies from rats, risks for developmental effects that may result from a single exposure were evaluated for both acute (short-term) exposures and chronic (long-term, repeated/continuous) exposures, whereas risks for other adverse effects (e.g., thyroid toxicity, liver toxicity, and female reproductive toxicity) were evaluated only for chronic exposures to HBCD. Although developmental studies typically involve multiple exposures, they are considered relevant for evaluating single exposures when the adverse effect may plausibly may result from a single exposure during a critical window of development (Davis et al., 2009; Van Raaij et al., 2003b; U.S. EPA, 1991). This is consistent with EPA's Guidelines for Reproductive Toxicity Risk Assessment (U.S. EPA, 1996) which state that repeated exposure is not a necessary prerequisite for the manifestation of developmental toxicity.

While there is uncertainty whether postnatal effects such as neonatal pup loss and decreased body weight can result from single developmental exposures, there is increased risk following acute exposures for HBCD, which is a persistent and bioaccumulative toxicological agent with a long half-life. Unlike many other chemicals with short half-lives (on the order of hours or less), HBCD has a derived elimination half-life as high as 64 days in humans (Geyer et al., 2004), indicating that even a single exposure may result in a retained body burden for an extended period of time. Consequently, in this risk evaluation EPA concluded that single or acute exposures to HBCD could result in detrimental and potentially irreversible effects on postnatal growth and viability, while acknowledging that risk for these endpoints is dependent on the specific timing of exposure. There is strong evidence that HBCD can reduce thyroid hormone levels in pregnant rats (Ema et al., 2008) and evidence from other thyroid disruptors suggests that acute or short-term exposure can result in thyroid hormone effects (Paul et al., 2010; Hedge et al., 2009; Zhou et al., 2001), including in weanlings. These changes would presumably result in downstream effects on developmental endpoints (Forhead and Fowden, 2014; Gilbert and Zoeller, 2010; Hulbert, 2000). Using the developmental endpoints as acute PODs is a health protective approach as it takes the results from a chronic two-generation study, where exposures lasted throughout pregnancy of the animal through weaning and sexual maturity, and assumes that a single acute exposure could lead to the same effects if that exposure occurs during a critical window within the pregnancy term. Nonetheless, this approach has a biologically supported basis.

Overt toxicity studies (Section 3.2.3.1.7) were not used for derivation of an acute POD because they often only tested a single dose level and the doses at which acute toxic effects or lethality were observed were significantly higher than the doses resulting in the previously described developmental endpoints.

3.2.5.2 Derivation of Points of Departure and Uncertainty Factors

A set of dose-response models were applied to empirically model the dose-response relationship in the range of the observed data. The models in EPA's Benchmark Dose Software (BMDS, version 2.6) were applied. Consistent with EPA's *Benchmark Dose Technical Guidance Document* (U.S. EPA, 2012a), the benchmark dose (BMD) and 95% lower confidence limit on the BMD (BMDL) were estimated using a benchmark response (BMR) to represent a minimal, biologically significant level of change, when possible. The BMR is represented by a specified percentage change, or relative deviation (RD), for continuous data. The BMR for dichotomous data is represented by a specified incidence, or extra risk (ER). In the absence of information regarding the level of change that was considered biologically significant, a BMR of 1 standard deviation (SD) from the control mean for continuous data or a BMR of 10% ER for dichotomous data was used to estimate the BMD and BMDL, and to facilitate a consistent basis of comparison across endpoints, studies, and assessments. Endpoint-specific BMRs are described further below. Where modeling was feasible, the estimated BMDLs were used as points of departure (PODs); the PODs are summarized in Table 3-7. Further details, including the modeling output and graphical results for the model selected for each endpoint, can be found in Appendix I and [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard (U.S. EPA, 2019e)*. Where dose-response modeling was not feasible, NOAELs or LOAELs were also identified and are summarized.

Selecting the model to use for POD computation

The following approach is recommended for selecting the model(s) to use for computing the BMDL to serve as the POD for a specific dataset according to EPA Benchmark Dose Guidance (U.S. EPA, 2012a). Some of these decisions are best performed by or in collaboration with personnel expert in the statistical procedures and potential pitfalls of this type of analysis.

1) Assess goodness-of-fit, using a value of $\alpha = 0.1$ to determine a critical value (or $\alpha = 0.05$ or $\alpha = 0.01$) if there is reason to use a specific model(s) rather than fitting a suite of models.
2) Further reject models that apparently do not adequately describe the relevant low- dose portion of the dose-response relationship, examining residuals and graphs of models and data.
3) As the remaining models have met the recommended default statistical criteria for adequacy and visually fit the data, any of them theoretically could be used for determining the BMDL. The remaining criteria for selecting the BMDL are necessarily somewhat arbitrary and are suggested as defaults.
4) If the BMDL estimates from the remaining models are sufficiently close (given the needs of the assessment), reflecting no particular influence of the individual models, then the model with the lowest AIC may be used to calculate the BMDL for the POD. This criterion is intended to help arrive at a single BMDL value in an objective, reproducible manner. If two or more models share the lowest AIC, the simple average or geometric mean of the BMDLs with the lowest AIC may be used. Note that this is not the same as "model averaging", which involves weighing a fuller set of adequately fitting models. In addition, such an average has drawbacks, including the fact that it is not a 95% lower bound (on the

average BMD); it is just the average of the particular BMDLs under consideration (i.e., the average loses the statistical properties of the individual estimates).

5) If the BMDL estimates from the remaining models are not sufficiently close, some model dependence of the estimate can be assumed. Expert statistical judgment may help at this point to judge whether model uncertainty is too great to rely on some or all of the results. If the range of results is judged to be reasonable, there is no clear remaining biological or statistical basis on which to choose among them, and the lowest BMDL may be selected as a reasonable conservative estimate. Additional analysis and discussion might include consideration of additional models, the examination of the parameter values for the models used, or an evaluation of the BMDs to determine if the same pattern exists as for the BMDLs. Discussion of the decision procedure should always be provided.

6) In some cases, modeling attempts may not yield useful results. When this occurs and the most biologically relevant effect is from a study considered adequate but not amenable to modeling, the NOAEL (or LOAEL) could be used as the POD. The modeling issues that arose should be discussed in the assessment, along with the impacts of any related data limitations on the results from the alternate NOAEL/LOAEL approach.

3.2.5.2.1 PODs for Acute Exposure

Developmental Effects

Acute exposure in humans is defined for occupational settings as exposure over the course of a single 8-hour work shift and for the general population as a single 24-hour day. Consistent with EPA's Guidelines for Reproductive Toxicity Risk Assessment, as discussed in Section 3.2.5.1, developmental toxicity is considered relevant for calculating risks associated with acute occupational or general population exposure.

Reduced offspring viability is a sensitive endpoint that is considered a marker for developmental toxicity. A single study reported reductions in offspring viability (Ema et al., 2008) and was judged to support dose-response analysis of viability as a measure of developmental effects.

Reduced offspring body weight is a sensitive endpoint that is considered a marker for fetal growth restriction. Decreased pup body weight was reported in four studies (Maranghi et al., 2013; Saegusa et al., 2009; van der Ven et al., 2009; Ema et al., 2008). (Maranghi et al., 2013) only used a single dose level. Observed effects were not consistently dose-responsive in (van der Ven et al., 2009). Additionally, the magnitude of decreased pup body weight reported by (Ema et al., 2008) was substantially greater than (Saegusa et al., 2009). Finally, (Ema et al., 2008) examined a larger number of animals per group than other studies and covered a broader dose range than all other studies except (Saegusa et al., 2009). For the above reasons, (Ema et al., 2008) was selected for dose-response analysis of pup body weight as a measure of developmental effects following acute exposures. Table 3-4 summarizes study design features considered in evaluating the strength of each study that reported changes in pup weight for purpose of dose-response analysis.

Table 3-4. Study Design Features of Developmental Toxicity Studies

Study reference	Route	Exposure duration	Number of dose groups[a]	Number of animals/group	Dose range (mg/kg-d)	Data Quality
(Ema et al., 2008)	Diet	Two-generation	3	13−24 rat litters	10−1,570[b]	High (1.0)

Study reference	Route	Exposure duration	Number of dose groups[a]	Number of animals/group	Dose range (mg/kg-d)	Data Quality
(van der Ven et al., 2009)	Diet	One-generation	7	≥14 rats	0.1−100	High (1.2)
(Saegusa et al., 2009)	Diet	Gestation and lactation (~42 d)	3	10−14 rats/sex[c]	15−1,505	High (1.2)
(Maranghi et al., 2013)	Diet	28 days	1	10−15 female mice	199	High (1.3)

[a]Excludes the control group.
[b]Doses differed by sex and generation (see, for example, Table 1-4).
[c]For PND 0 data, exact number of animals examined per dose group was unclear based on the published study.

In a study by (van Raaij et al., 2003a) a comparison between repeated and single dose studies across a range of chemicals showed that the NOAELs and LOAELs for fetal body weight were 2-4 fold lower than those for single-dose studies, thereby indicating that fetal body weight is more sensitive to repeated exposures. Body weight reduction in pups is therefore generally most applicable to estimating risks for chronic exposures (at least for short half-life chemicals). Nonetheless, there remains uncertainty regarding the applicability of the limited dataset examined in (van Raaij et al., 2003a) to persistent chemicals with long half-lives such as HBCD as well as the relevance of this finding for humans. It is uncertain whether the dose-duration relationships identified in (van Raaij et al., 2003a) for fetal body weight are also applicable to postnatal effects observed following HBCD exposure, however it can be expected that a similar relationship would apply. While offspring loss was only observed in the F2 generation (Ema et al., 2008), suggesting a multigenerational effect (possibly due to increasing bioaccumulation) over repeated exposures, the data does not exclude the possibility of this effect occurring following acute exposures during a critical window of development.. As discussed in Section 3.2.3.1, evidence from other thyroid disruptors suggests that acute or short-term exposure can result in thyroid hormone effects (Paul et al., 2010; Hedge et al., 2009; Zhou et al., 2001), including in weanlings, and these hormonal changes could result in downstream effects on developmental endpoints (Forhead and Fowden, 2014; Gilbert and Zoeller, 2010; Hulbert, 2000). Therefore, in order to be health protective given the persistence of HBCD in the body and the absence of any other usable PODs from other potential acute endpoints (such as neurotoxicity) for considering acute exposure scenarios, EPA considered the developmental endpoints of both F2 offspring loss and reduced F2 pup body weight as the basis for the dose-response analysis for acute exposures to HBCD.

Offspring loss

Increased offspring loss in the F2 generation from the (Ema et al., 2008) study was amenable to BMD nested modeling, using individual animal data obtained from the study authors (personal communication) (Makris, 2016). Two datasets were modeled: offspring loss (indicating decreased offspring viability) from implantation through PND 4 and offspring loss from PND 4 (post-culling) through PND 21. Maternal gestational doses (10, 100, and 995 mg/kg-day) were used to model offspring loss from the implantation through PND 4 dataset and modeling for the PND 4 post-culling through PND 21 dataset was performed using the maternal lactational doses (20, 179, and 1,724 mg/kg-day).

From a statistical standpoint, most reproductive and developmental studies with nested study designs typically support a BMR of 5% extra risk (ER) (U.S. EPA, 2012a). A smaller BMR of 1% ER was used in this case to address the severity of this endpoint (i.e., offspring loss), in accordance with EPA Benchmark Dose Guidance (U.S. EPA, 2012a), which supports use of smaller BMRs for more severe or

"frank" effects. For purposes of comparison, a POD based on the NOAEL is presented in addition to the $BMDL_{01}$ (see Section 3.2.5.3). The NCTR/Rai and Van Ryzin model was used for offspring loss from implantation through PND 4 based on selection of the lowest BMDL (see step 5 in BMD guidance), and the NLogistic model was used for PND 4 through PND 21 loss based on selection of the lowest AIC (see step 4 in BMD guidance).

Pup body weight

Changes in F2 pup body weight as reported in the two-generation reproductive toxicity study by (Ema et al., 2008) were amenable to BMD modeling. A BMR of 5% RD from control mean was applied in modeling pup body weight changes under the assumption that it represents a minimal biologically significant response. In adults, a 10% decrease in body weight in animals is generally recognized as a biologically significant response associated with identifying a maximum tolerated dose; during development, however, identification of a smaller (5%) decrease in body weight is consistent with the assumptions that development represents a susceptible lifestage and that the developing animal is more adversely affected by a decrease in body weight than the adult. In humans, reduced birth weight is associated with numerous adverse health outcomes, including increased risk of infant mortality as well as heart disease and type II diabetes in adults (Barker, 2007; Reyes and Mañalich, 2005). The selection of a 5% BMR is additionally supported by data from (Kavlock et al., 1995) which found that a BMR of 5% RD for fetal weight reduction was statistically similar to several other BMR measurements as well as to statistically-derived NOAEL values, however EPA acknowledges the uncertainty in extrapolating this fetal data to postnatal effects. For these reasons, a BMR of 5% RD was selected for decreased pup weight. The exponential (M4) model was used for male weanlings based on lowest BMDL (see step 5 in BMD guidance) and the linear model was used for female weanlings based on lowest AIC (see step 4 in BMD guidance).

3.2.5.2.2 PODs for Chronic Exposures

Chronic exposure was defined for occupational settings as exposure reflecting a 40-hour work week. Chronic exposure to the general population represents exposure averaged over 24 hours/day, 365 days/year, for the number of years living near a facility (either 13 or 33 years). Non-cancer endpoints selected as most relevant for calculating risks associated with chronic (repeated) occupational exposures to HBCD included toxicity to the thyroid, liver, female reproductive, and developmental effects.

Table 3-10 summarizes the hazard studies and health endpoints by target organ/system that the EPA considered suitable for the risk evaluation of chronic exposure scenarios for HBCD. Key studies in Table 3-10 are briefly described in Non-Cancer Hazards, Section 3.2.3.1, along with other toxicity and epidemiological studies. BMD modeling was performed for these endpoints in a manner consistent with EPA Benchmark Dose Technical Guidance. BMR were selected for each endpoint.

Thyroid Effects

Changes in serum thyroxine (T4) was selected as the endpoint representative of thyroid effects based on the following: (1) changes in T4 were observed in multiple studies; (2) T4 is likely to be the primary driver of HBCD-mediated thyroid effects; and (3) it is well established that perturbations in T4 are associated with biologically significant health effects. Specifically, adequate levels of T4 are necessary for normal growth and development, and altered thyroid homeostasis has the potential to affect numerous organ systems, including neuronal, reproductive, hepatic, and immune systems (Forhead and Fowden, 2014; Gilbert and Zoeller, 2010; Hulbert, 2000).

Based on considerations of study design and magnitude of T4 response, T4 data sets from (Ema et al., 2008) were selected for dose-response analysis. The 2-generation study design used by (Ema et al., 2008) involved a longer exposure duration and larger group size than (van der Ven et al., 2006), while inadequate reporting of thyroid hormone measurement methods and questionable control data reduced the confidence in the thyroid hormone results from (WIL Research, 2001).. Table 3-5 provides an overview of the study designs for those studies reporting T4 levels that were evaluated for dose-response analysis of thyroid effects.

Table 3-5. Study Design Features of Studies that Examined T4 Levels

Study reference	Route	Exposure duration	Number of dose groups[a]	Number of animals/group	Dose range (mg/kg-d)	Data Quality
(Ema et al., 2008)	Diet	Two-generation	3	8 rats/sex	10−1,363[a]	High (1.0)
(WIL Research, 2001)	Gavage	90 days	3	5–10 rats/sex	100−1,000	High* (1.0)
(van der Ven et al., 2006)	Gavage	28 days	7	4−5 rats/sex	0.3−200	High (1.3)

[a]Doses differed by sex and generation
*This study received a High overall, however the data is considered inadequate only for thyroid hormone measurements.

Specifically, T4 data from F0 male and female rats and from F1 female rats in (Ema et al., 2008) were used for quantitative analysis. Because the magnitude of response in F1 male rats was smaller than the response in these generations (by one-third to one-half), T4 data from F1 male rats was not modeled. Based on the data observed in both humans and animals demonstrating downstream health effects associated with a reduction of 10% or more in T4 levels (Gilbert et al., 2014; Gilbert et al., 2013; Gilbert, 2011; Liu et al., 2010; Ausó et al., 2004), a BMR of 10% RD from control mean was determined to be a minimally biologically significant degree of change when performing BMD modeling using female rat data. The available thyroid literature does not support identification of a biologically significant change in T4 levels in adult males as decreases in T4, and more generally thyroid function, have not been conclusively linked to similarly severe outcomes as in females. Nevertheless, males with depressed T4 values are part of the subpopulation that experiences thyroid dysfunction. Consistent with EPA's *Benchmark Dose Technical Guidance Document* (U.S. EPA, 2012a), a BMR of one control SD change from the control mean was applied in modeling T4 data from male rats in the absence of a biological basis for selecting a BMR. Additionally, a BMR of 10% RD from control means, supported by the literature on the effects of thyroid insufficiency in pregnant females and their offspring, was also applied in modeling the male T4 data. Under the assumption that differences in thyroid hormone response in male and female rats exposed to HBCD are not sex-specific but rather a reflection of hormone variability, using a BMR of 10% RD was also considered appropriate for this dataset. The exponential (M4) model was selected for derivation of all BMDLs for the thyroid endpoint (based on lowest AIC for males [step 4 in BMD guidance] and based on lowest BMDL for females [step 5 in BMD guidance]).

Liver Effects

Although the adversity of increased liver weight was ambiguous in some studies, it serves as an effective and sensitive toxicological indicator for liver toxicity, especially within a susceptible population. Increased liver weight was therefore selected as the representative endpoint for dose-response analysis of liver effects based on being the most consistently observed toxicological effect. Increased liver weight was reported in six studies in rats (Saegusa et al., 2009; Ema et al., 2008; van der

Ven et al., 2006; WIL Research, 2001, 1997) and mice (Maranghi et al., 2013). Increased liver weight was also accompanied by increased hepatocellular vacuolization in (Maranghi et al., 2013; Saegusa et al., 2009; WIL Research, 2001, 1997), hypertrophy in (WIL Research, 1997), and inflammation in (Maranghi et al., 2013).

(Ema et al., 2008) consistently observed increased liver weights in rats across multiple generations (i.e., F0, F1, and F2), lifestages (i.e., postnatal day [PND] 26 offspring and adults), and in both sexes, particularly at the high dose. Elevated liver weight was also observed along with increased serum alanine aminotransferase (ALT) and hepatocellular vacuolization in both sexes of rats across all dose groups in a 90-day study by (WIL Research, 2001). Both studies were selected for dose-response analysis because they provided robust dose-related responses that were consistent across sex and generations (for (Ema et al., 2008), unlike (Saegusa et al., 2009)) and following longer exposure durations than other studies. Table 3-6 provides an overview of the study designs for those studies reporting relative liver weight that were evaluated for dose-response analysis.

Table 3-6. Study Design Features of Studies that Examined Liver Weight

Study reference	Route	Exposure duration	Number of dose groups[a]	Number of animals/group	Dose range (mg/kg-d)	Data Quality
(Ema et al., 2008)	Diet	Two-generation	3	13–24 rats/sex	10–1,570[a]	High (1.0)
(WIL Research, 2001)	Gavage	90 days	3	10 rats/sex	100–1,000	High (1.0)
(van der Ven et al., 2006)	Gavage	28 days	7	4–5 rats/sex	0.3–200	High (1.3)
(WIL Research, 1997)	Gavage	28 days	3	6 rats/sex	125–1,000	High (1.3)
(Saegusa et al., 2009)	Diet	Gestation and lactation (~42 d)	3	10 rats/sex	15–1,505	High (1.2)
(Maranghi et al., 2013)	Diet	28 days	1	10–15 female mice	199	High (1.3)

[a]Doses differed by sex and generation

Liver effects as reported in the (Ema et al., 2008) and (WIL Research, 2001) studies were evaluated using BMD modeling. Liver weight data from (Ema et al., 2008) were amenable to modeling. For weanling (PND 26) datasets, the average exposures across gestation and lactation (F1 = 16.5, 168, and 1,570 mg/kg-day; F2 = 14.7, 139, and 1,360 mg/kg-day) were used for modeling because there was no evidence to indicate whether this effect was the result of prenatal exposure, postnatal exposure, or a combination of both. The exponential (M4) model was selected for derivation of all BMDLs for the liver endpoint from (Ema et al., 2008) based on visual fit and lowest AIC (steps 3 and 4 in BMD guidance). The linear model was additionally applied to data from F1 rat adults. A BMR of 10% RD from the control mean was applied in modeling relative liver weight changes under the assumption that it represents a minimal biologically significant change, with liver weight changes considered analogous to the 10% change in body weight that has been used to identify a maximum tolerated dose. Data on liver effects derived from (WIL Research, 2001) could not be modeled because none of the models provided adequate fit; therefore, LOAELs were chosen for the PODs derived from these data (step 6 in BMD guidance).

Female Reproductive Effects

Pregnancy incidence and primordial follicle count were selected for dose-response analysis as endpoints representative of female reproductive effects. These effects were reported in a two-generation reproductive toxicity study by (Ema et al., 2008) that included three dose groups in addition to the control. Pregnancy incidence was measured in two generations with exposure durations ranging from approximately 13 weeks (F0) to continuous lifetime exposure (F1); primordial follicle count was only evaluated in the F1 generation. (Ema et al., 2008), the only study to evaluate effects on pregnancy incidence and primordial follicle count, was selected for dose-response analysis of these measures of female reproductive toxicity.

Primordial follicle count

Decreased primordial follicle count as reported in the two-generation reproductive toxicity study by (Ema et al., 2008) was amenable to BMD modeling. Because primordial follicles are formed during gestation, the average dose during this critical window was used for BMD modeling. While there is no consensus regarding the degree of change considered to be adverse, a BMR of 10% RD from control levels was applied in modeling this endpoint under the assumption that it represents a minimal biologically significant effect based on what may be considered a reasonably detectable decrease in follicle number (Heindel, 1998). The exponential (M4) model was selected for derivation of all BMDLs for decreased follicle count based on being the only model with adequate fit (step 1 in BMD guidance).

Pregnancy incidence

In the study by (Ema et al., 2008), the increased incidence of non-pregnancy (indicating reduced female fertility index) in HBCD-exposed F0 or F1 rats alone was not statistically significant with either pairwise test (as reported by authors) or Cochran-Armitage trend test (conducted by EPA). Dose-response curves were shallow and never reached a high response percentage. Nevertheless, EPA considered this change to be biologically relevant. To increase statistical power and obtain a more precise estimate of the BMD and BMDL, consideration was given to combining F0 and F1 datasets. Cochran-Mantel-Haenszel statistics on F0 and F1 data stratified by dose groups were not significant ($p = 0.59$, $\alpha = 0.05$), indicating no statistical association between generation and response after adjusting for dose. Equality of responses in F0 and F1 rats was also not rejected ($p > 0.2$, $\alpha = 0.05$) by the Breslow-Day test for homogeneity of the odds ratios, and their background response percentages were not detectably different (Fisher's exact, $p = 1.00$). The results of these statistical tests indicated that F0 and F1 datasets were compatible for combining. The log-logistic model (which only demonstrated adequate fit after dropping the highest dose) from the combined dataset was selected to derive the BMD and BMDL for increased incidence of non-pregnancy based on lowest AIC (step 4 in BMD guidance) .

A BMR of 5% ER was applied in modeling this endpoint under the assumption that it represents a minimal biologically significant degree of change. Selection of a BMR took into consideration the limited sensitivity of rodent species to effects on fertility and pregnancy outcomes (U.S. EPA, 1996). Rather than applying an additional uncertainty factor to the POD based on reduced fertility in rats, a BMR of 5%, rather than 10%, was selected. A BMR of 5% ER was also consistent with the functional severity of the endpoint (i.e., reduced fertility).

Developmental Effects

As described above, developmental effects may result from single as well as repeated exposures at a developmentally critical period; therefore, decreased pup body weight and decreased viability (Ema et al., 2008) were the endpoints selected as most relevant to calculating risks associated with developmental toxicity following chronic as well as acute exposures. A smaller BMR of 1% ER was

used in this case to address the severity of this endpoint (i.e., offspring loss). A BMR of 5% RD from control mean was applied in modeling pup body weight changes under the assumption that it represents a minimal biologically significant response.

3.2.5.2.3 Human Equivalent Doses

Human equivalent doses (HEDs) for oral exposures were derived from the PODs according to the hierarchy of approaches outlined in EPA guidance (U.S. EPA, 2011d). The preferred approach is physiologically-based pharmacokinetic (PBPK) modeling. Other approaches can include using chemical-specific information in the absence of a complete PBPK model. As discussed in Section 3.2.2 and Appendix H, an appropriate toxicokinetic model for HBCD is not available. In the absence of either chemical-specific models or data to inform the derivation of human equivalent oral exposures, body weight scaling to the ¾ power (i.e., $BW^{3/4}$) was applied to extrapolate toxicologically equivalent doses of orally administered agents from adult laboratory animals to adult humans.

Consistent with EPA guidance (U.S. EPA, 2011d), the PODs estimated based on effects in adult animals were converted to HEDs employing a standard dosimetric adjustment factor (DAF) derived as follows:

$$DAF = \left(\frac{BW_A}{BW_H}\right)^{0.25}$$

Where

BW_a = animal body weight
BW_h = human body weight

Using BW_a of 0.25 kg for rats and BW_h of 80 kg for humans (U.S. EPA, 2005), the resulting DAF for rats is 0.24. Applying this DAF to the POD_{ADJ} identified for HBCD effects in adult rats, a POD_{HED} was derived as follows (see Table 2-3):

$$POD_{HED} = Laboratory\ animal\ dose\ (mg/kg\text{-}day) \times DAF$$

$BW^{3/4}$ scaling was not employed for deriving HEDs for increased relative liver weight in pups, offspring loss, or decreased pup weight as reported by (Ema et al., 2008) where doses were administered to early postnatal animals. There is uncertainty as to whether allometric (e.g., $BW^{3/4}$) scaling, derived from data in adult animals, holds when extrapolating doses in neonatal animals. This uncertainty arises because of the absence of quantitative information to characterize the toxicokinetic and toxicodynamic differences between animals and humans in early lifestages (U.S. EPA, 2011d).

3.2.5.2.4 Uncertainty Factors

Four areas of uncertainty and variability were considered in benchmark MOE derivation, as summarized below.

A UF for extrapolation from a LOAEL to NOAEL, UF_L, of 1 was applied when the POD was based on a BMDL, and the BMR was selected under the assumption that it represented a minimal biologically significant response level. A UF_L of 1 was applied to offspring loss where the POD was based on a NOAEL, and a value of 10 was applied to relative liver weight data from (WIL Research, 2001) because the POD was based on a LOAEL.

A subchronic to chronic UF, UF_S, was applied to account for the possibility that longer exposure may induce effects at a lower dose when data are derived from less-than-lifetime exposures. (Ema et al., 2008) is a multigenerational study where the parental generation is exposed for approximately 15-18 weeks and the offspring are exposed for approximately 21-24 weeks. Given HBCD's propensity to bioaccumulate it is also expected that internal exposure could increase with longer external exposure durations. For thyroid hormone effects, a UF_S of 10 was applied when effects were observed in parental (F0) animals because exposure was subchronic in duration. UFs was reduced to 1 for PODs for thyroid effects derived from F1 offspring, which have already experienced bioaccumulation across generations following up to 42 weeks of chronic exposure. A UFs of 1 was also applied to liver weight and both reproductive endpoints from (Ema et al., 2008), which incorporate data from the F1 generation, for the same reasoning. A UFs of 3 was applied for liver effects from (WIL Research, 2001), a subchronic 90-day study. UFs was reduced from 10 to 3 for that endpoint because the feedback interaction between liver metabolism and the HPT axis along with inconsistently observed histopathological or biochemical changes in other studies (see Section 3.2.4.1.2) suggests that there may only be limited adversity with increasing exposure. For pup weight and offspring loss, which are developmental endpoints, a UF_S of 1 was applied because the developmental period is recognized as a susceptible lifestage where exposure during certain time windows during development is more relevant to the induction of developmental effects than lifetime exposure (U.S. EPA, 1991).

With the exception of endpoints measured in neonatal animals, a UF for interspecies extrapolation, UF_A, of 3 ($10^{1/2} = 3.16$, rounded to 3) was applied to all PODs because $BW^{3/4}$ scaling was used to extrapolate oral doses from laboratory animals to humans. Although $BW^{3/4}$ scaling addresses some aspects of cross-species extrapolation of toxicokinetic and toxicodynamic processes, some residual uncertainty remains. In the absence of chemical-specific data to quantify this uncertainty, EPA's guidance on $BW^{3/4}$ scaling (U.S. EPA, 2011d) recommends the use of a UF_A of 3. $BW^{3/4}$ scaling was not used to derive HEDs for relative liver weight in weanling rats, decreased pup weight, or offspring loss because of the absence of information on whether allometric (i.e., body weight) scaling holds when extrapolating doses from early postnatal animals to adult humans due to presumed toxicokinetic and/or toxicodynamic differences between lifestages (U.S. EPA, 2011d; Hattis et al., 2004). For these developmental endpoints, interspecies extrapolation was based on administered dose, and an UF_A of 10 was applied to account for the lack of quantitative information to characterize toxicokinetic and toxicodynamic differences between animals and humans at this lifestage.

An intraspecies UF, UF_H, of 10 was applied to account for variability and uncertainty in toxicokinetic and toxicodynamic susceptibility within the subgroups of the human population that are most sensitive to the health hazards of HBCD (U.S. EPA, 2002b). In the case of HBCD, the PODs were derived from studies that used an inbred rat strain and that is not considered sufficiently representative of the exposure and dose-response of the most susceptible human subpopulations. In certain cases, the toxicokinetic component of this factor may be replaced when a PBPK model is available that incorporates the best available science on variability in toxicokinetic disposition in the human population (including sensitive subgroups). For HBCD, the available information is insufficient to quantitatively estimate variability in human susceptibility; therefore, the full value for the intraspecies UF was applied.

3.2.5.3 Points of Departure for Human Health Hazard Endpoints

Table 3-7 summarizes the oral PODs (and sequence of adjustments leading to the derivation of a human equivalent POD or POD_{HED}) by target organ/system. All of the PODs except for liver toxicity to be used for risk characterization were derived from the study by (Ema et al., 2008). This study is a well-conducted two-generation reproductive toxicity study, performed using Organisation for Economic Co-

operation and Development (OECD) testing guidelines, used a commercial mixture of isomers that was 99.7% pure, and included three dose groups (plus control) that covered a dose range of approximately 2.5 orders of magnitude. The study scored a High in OPPT's data quality evaluation (*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S. EPA, 2019n)* and was of longer duration than all other reproductive/developmental toxicity studies assessed in this risk evaluation, with health effects observed consistently and with a stronger response throughout the study duration.

For liver toxicity, the POD selected for risk characterization was obtained from (WIL Research, 2001), a 90-day oral toxicity study conducted according to OECD testing guidelines. Liver effects in (WIL Research, 2001) included hepatocellular vacuolization and increased serum alanine aminotransferase (ALT) levels as well as increased liver weight. Increased liver weight was the only effect detected in (Ema et al., 2008). Additionally, while F0 and F1 generations in (Ema et al., 2008) were exposed for greater than 10 weeks, dosing for (WIL Research, 2001) was administered continuously for 13 weeks on adult rats without the potentially confounding factors of pregnancy and weaning. This study also scored a High in OPPT's data quality evaluation (*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies (U.S. EPA, 2019n)* and was of a longer duration than other subacute studies receiving a High score that identified both liver weight and histopathological changes. Data from this study was of inadequate fit for BMD modeling, and the POD is based on a LOAEL resulting in a large benchmark MOE (3000), indicating high uncertainty. This study was used for risk estimation for the reasons stated above, however EPA acknowledges that the POD exhibits large uncertainty in its precision and may potentially overestimate risk. This POD remains less sensitive than the robust endpoint of thyroid hormones effect however, so uncertainty surrounding the liver POD and benchmark MOE is unlikely to have any significant effect on risk characterization.

Table 3-7. Summary of BMDL Results and Derivation of HEDs for HBCD

Endpoint and Reference	Species/ Sex	Model[a]	BMR	BMD (mg/kg-d)	BMDL (mg/kg-d)	POD_{ADJ}[b] (mg/kg-d)	POD_{HED}[c] (mg/kg-d)
Thyroid							
Decreased T4 (Ema et al., 2008)	**F0 rats (Sprague-Dawley)/ male, adults**	**Exponential (M4)**	**10% RD**	**23.9**	**6.99**	**6.99**	**1.68**
Decreased T4 (Ema et al., 2008)	F0 rats (Sprague-Dawley)/ male, adults	Exponential (M4)	1 SD	101	29.5	29.5	7.08
Decreased T4 (Ema et al., 2008)	F0 rats (Sprague-Dawley)/ female, adults	Exponential (M4)	10% RD	334	93.8	93.8	22.5
Decreased T4 (Ema et al., 2008)	F1 rats (Sprague-Dawley)/female, adults	Exponential (M4)	10% RD	448	127	127	30.5
Liver[d]							
Relative liver weight (Ema et al., 2008)	F1 rats (CRL)/male	Exponential (M4)	10% RD	163	109	109	109

Endpoint and Reference	Species/ Sex	Model[a]	BMR	BMD (mg/kg-d)	BMDL (mg/kg-d)	POD_{ADJ}[b] (mg/kg-d)	POD_{HED}[c] (mg/kg-d)
	weanlings, PND 26						
Relative liver weight (Ema et al., 2008)	F1 rats (CRL)/weanlings, PND 26	Exponential (M4)	10% RD	165	115	115	115
Relative liver weight (Ema et al., 2008)	F1 rats (CRL)/, adults	Linear	10% RD	680	573	573	138
Relative liver weight (Ema et al., 2008)	F1 rats (CRL)/, adults	Exponential (M4)	10% RD	569	184	184	44.2
Relative liver weight (Ema et al., 2008)	F2 rats (CRL)/, weanlings	Exponential (M4)	10% RD	215	116	116	116
Relative liver weight (Ema et al., 2008)	F2 rats (CRL)/, weanlings	Exponential (M4)	10% RD	286	166	166	166
Relative liver weight and hepatocellular vacuolization (WIL Research, 2001)	**Rats (Sprague-Dawley)/, male adults**	**No model fit**	**LOAEL = 100 (19% RD liver weight, 300% RD vacuolization)**			**100**	**24**
Relative liver weight and hepatocellular vacuolization (WIL Research, 2001)	**Rats (Sprague-Dawley)/, female adults**	**No model fit**	**LOAEL = 100 (24% RD liver weight, 200% RD vacuolization)**			**100**	**24**
Reproductive							
Primordial follicles (Ema et al., 2008)	**F1 parental rat (Sprague-Dawley)/, adults**	**Exponential (M4)**	**10% RD**	**10.1**	**2.87**	**2.87**	**0.689**
Incidence of non-pregnancy (Ema et al., 2008)	**F0 parental and F1 offspring rats combined (Sprague-Dawley)/, adults**	**LogLogistic (high dose dropped)**	**5% ER**	**48.5**	**22.7**	**22.7**	**5.45**
Developmental							
Offspring loss from implantation through PND 4 (Ema et al., 2008)	F2 offspring rats (CRL)/male and female	NCTR/Rai and Van Ryzin	1% ER 5% ER	109 316	54.5 158	54.5 158	54.5 158
			NOAEL = 100 (-2% ER)			100	100
Offspring loss from PND 4 post-culling through PND 21 (Ema et al., 2008)	**F2 offspring rats (CRL)/male and female**	**NLogistic**	**1% ER** 5% ER	**16.9** 88.1	**9.03** 47.1	**9.03** 47.1	**9.03** 47.1
			NOAEL = 19.6 (-7% ER)			19.6	19.6
Decreased pup weight (Ema et al., 2008)	**F2 rats (CRL)/male weanlings**	**Exponential (M4)**	**5% RD**	**354**	**89.6**	**89.6**	**89.6**

Endpoint and Reference	Species/ Sex	Model[a]	BMR	BMD (mg/kg-d)	BMDL (mg/kg-d)	POD_{ADJ}[b] (mg/kg-d)	POD_{HED}[c] (mg/kg-d)
Decreased pup weight (Ema et al., 2008)	F2 rats (CRL)/ female weanlings	Linear	5% RD	417	297	297	297

[a] For modeling details, see [Human Health Supplemental Document *(U.S. EPA, 2019e)*].
[b] All studies involved dietary administration. Therefore, no adjustments to estimate the average daily dose were required, and BMDL, NOAEL, or LOAEL values were equivalent to the POD_{ADJ} in all cases.
[c] POD_{HED} values for endpoints measured in adult animals were calculated using $BW^{3/4}$ scaling. POD_{HED} values for endpoints measured in neonatal animals were expressed as administered dose (see Section 2.1.2).
[d] Relative liver weight from both (Ema et al., 2008) and (WIL Research, 2001) is expressed as g/100 g BW.
Note: Both (Ema et al., 2008) and (WIL Research, 2001) scored a High in data evaluation.

Table 3-8 and Table 3-9 are a continuation of Table 3-7. Table 3-8 summarizes the human equivalent PODs and a breakdown of UFs for each relevant endpoint, leading to the derivation of benchmark MOEs for the risk evaluation of acute exposure scenarios. Table 3-9 provides the same information for the risk evaluation of chronic exposure scenarios.

Table 3-8. PODs and Benchmark MOEs for Effects Following Acute Exposure to HBCD

Endpoint and reference	Exposure window	POD_{HED}[a] (mg/kg-d)	POD type	UF_L	UF_S	UF_A	UF_H	Benchmark MOE
Developmental								
F2 Offspring loss (Ema et al., 2008)	Implantation – PND 4	54.5 158 100	$BMDL_{01}$ $BMDL_{05}$ NOAEL	1	1	10	10	100
F2 Offspring loss (Ema et al., 2008)	**PND 4 – PND 21**	**9.03** 47.1 19.6	**$BMDL_{01}$** **$BMDL_{05}$** **NOAEL**	**1**	**1**	**10**	**10**	**100**
Decreased pup weight, F2 rats, male weanlings (Ema et al., 2008)	**GD 0 – PND 21**	**89.6**	**$BMDL_{05}$**	**1**	**1**	**10**	**10**	**100**
Decreased pup weight, F2 rats, female weanlings (Ema et al., 2008)	GD 0 – PND 21	297	$BMDL_{05}$	1	1	10	10	100

Table 3-9. PODs and Benchmark MOEs for Effects Following Chronic Exposure to HBCD

Endpoint and reference	POD_{HED}[a] (mg/kg-d)	POD type	UF_L	UF_S	UF_A	UF_H	Benchmark MOE
Thyroid							
Decreased T4, F0 rats, male adults (Ema et al., 2008)	**1.68**	**$BMDL_{10}$**	**1**	**10**	**3**	**10**	**300**

Endpoint and reference	POD_{HED}[a] (mg/kg-d)	POD type	UF_L	UF_S	UF_A	UF_H	Benchmark MOE
Decreased T4, F0 rats, male adults (Ema et al., 2008)	7.08	$BMDL_{1SD}$	1	10	3	10	300
Decreased T4, F0 rats, female adults (Ema et al., 2008)	22.5	$BMDL_{10}$	1	10	3	10	300
Decreased T4, F1 rats, female adults (Ema et al., 2008)	30.5	$BMDL_{10}$	1	1	3	10	30
Liver							
Relative liver weight, F1 rats, male weanlings, PND 26 (Ema et al., 2008)	109	$BMDL_{10}$	1	1	10	10	100
Relative liver weight, F1 rats, female weanlings, PND 26 (Ema et al., 2008)	115	$BMDL_{10}$	1	1	10	10	100
Relative liver weight, F1 rats, male adults (Ema et al., 2008)	138	$BMDL_{10}$	1	1	3	10	30
Relative liver weight, F1 rats, female adults (Ema et al., 2008)	44.2	$BMDL_{10}$	1	1	3	10	30
Relative liver weight, F2 rats, male weanlings (Ema et al., 2008)	116	$BMDL_{10}$	1	1	10	10	100
Relative liver weight, F2 rats, female weanlings (Ema et al., 2008)	166	$BMDL_{10}$	1	1	10	10	100
Relative liver weight and hepatocellular vacuolization, rats, male adults (WIL Research, 2001)	**24**	**LOAEL**	**10**	**3**	**3**	**10**	**1,000**
Relative liver weight and hepatocellular vacuolization, rats, female adults (WIL Research, 2001)	**24**	**LOAEL**	**10**	**3**	**3**	**10**	**1,000**

Endpoint and reference	POD_{HED}[a] (mg/kg-d)	POD type	UF_L	UF_S	UF_A	UF_H	Benchmark MOE
Relative liver weight and hepatocellular vacuolization, rats, female adults (WIL Research, 2001)	**24**	**LOAEL**	**10**	**3**	**3**	**10**	**1,000**
Reproductive							
Primordial follicles, F1 parental rat, female adults (Ema et al., 2008)	**0.689**	**$BMDL_{10}$**	**1**	**1**	**3**	**10**	**30**
Incidence of non-pregnancy, F0 parental and F1 offspring rats combined, female adults (Ema et al., 2008)	**5.45**	**$BMDL_{05}$**	**1**	**1**	**3**	**10**	**30**
Developmental							
F2 Offspring loss (Ema et al., 2008); Implantation – PND 4	54.5 158 100	$BMDL_{01}$ $BMDL_{05}$ NOAEL	1	1	10	10	100
F2 Offspring loss (Ema et al., 2008); PND 4 – PND 21	**9.03** 47.1 19.6	**$BMDL_{01}$** $BMDL_{05}$ NOAEL	**1**	**1**	**10**	**10**	**100**
Decreased pup weight, F2 rats, male weanlings (Ema et al., 2008); GD 0 – PND 21	**89.6**	**$BMDL_{05}$**	**1**	**1**	**10**	**10**	**100**
Decreased pup weight, F2 rats, female weanlings (Ema et al., 2008); GD 0 – PND 21	297	$BMDL_{05}$	1	1	10	10	100

Table 3-10 lists the POD_{HEDs} selected for use in risk estimation by target organ/system and exposure category (i.e., acute vs. chronic). The two studies considered for derivation of PODs both received a High in data quality evaluation and all derived BMDLs were considered similarly reasonable for use in risk estimation. Therefore, EPA selected the lowest resulting POD among BMDL modeling results in order to be health-protective.

Table 3-10. PODs Selected for Risk Estimation for Each Target Organ/System

Toxicity Endpoint		POD_{HED} (mg/kg-d)	Benchmark MOE
Effects following acute exposure			
Developmental	F2 generation offspring loss (Ema et al., 2008)	9.03	100
	Decreased F2 generation pup weight (Ema et al., 2008)	89.6	100
Effects following chronic exposure			
Thyroid	Decreased T4 (Ema et al., 2008)	1.68	300
Liver	Increased relative liver weight and vacuolization (WIL Research, 2001)	24	1000
Female Reproductive	Reduced primordial follicles (Ema et al., 2008)	0.689	30
	Increased incidence of non-pregnancy (Ema et al., 2008)	5.45	30
Developmental	F2 generation offspring loss (Ema et al., 2008)	9.03	100
	Decreased F2 generation pup weight (Ema et al., 2008)	89.6	100

3.2.6 Assumptions and Key Sources of Uncertainties for the Human Health Hazard Assessment

3.2.6.1 Toxicokinetics

In vivo animal studies of the individual isomers have not been conducted. Therefore, it is not possible to predict whether the toxicity of an environmental HBCD mixture would differ from the toxicity of commercial mixtures (i.e., those tested in toxicity studies). It is known, however, that the three major isomers have somewhat different physical/chemical properties (see Section 1.1) and differ toxicokinetically. For example, the α-isomer accumulates to a greater extent in tissues, especially fat, when compared to γ- or β-HBCD; γ- and β-HBCD are more rapidly and extensively metabolized than α-HBCD (see Appendix H). Mechanistic studies provide limited evidence of differences in biological activity of the three. Thus, the composition of HBCD mixtures to which humans are exposed is likely to differ from the commercial mixtures used in toxicity testing. Whether, and to what extent, the toxicity of the environmental mixtures differs from the toxicity of the commercial mixtures used to derive the PODs is not known based on the available health effects literature. Similarly, HBCD toxicokinetics including absorption and bioaccumulation differ greatly among isomers and are greatly affected by the relative fat content of tissues and surrounding media (e.g. water, air, diet, breastmilk). For both consistency and health-protectiveness, these issues were accounted for by utilizing the upper range of absorption estimates across available studies and including a 10X subchronic-to-chronic UF based on assumed increasing bioaccumulation over time. This adjustment was not included for developmental endpoints or for effects observed following multi-generational exposure, which should already encompass chronic bioaccumulation. EPA believes that the use of this 10X uncertainty factor is likely to be protective of risk from bioaccumulation in human tissues, however there is insufficient available data to confirm this presumption.

EPA utilized data exclusively from oral studies in developing PODs. While it is assumed that any inhaled particulates will be either absorbed through the lung or swallowed and absorbed in the GI, there could be potentially significant differences metabolic outcomes between these routes. Similarly, oral data was extrapolated for evaluating dermal exposure. The absence of a usable PBPK model to quantitatively account for differences between routes represents an important uncertainty when considering the application of oral PODs to other exposure routes.

EPA assumed an upper-end dermal absorption estimate of 6.5% based on a steady-state value from *in vitro* data following 24hr HBCD exposure as a thin, evenly distributed layer on skin. The actual percentage of HBCD absorbed dermally is variable based on multiple factors including the relative percentage of each isomer in the mixture and the relative ratio of sweat to sebum on skin. This value likely overestimates average dermal absorption when accounting for other factors such as washing or wiping skin clean and uneven distribution along the skin surface area.

3.2.6.2 Human Health Endpoints

PODs were derived from two studies, (Ema et al., 2008) and (WIL Research, 2001). These studies were selected because they both scored High in data evaluation, followed OECD guidance and Good Laboratory Practice, and were of longer duration with effects observed more consistently than other high-quality studies that we evaluated. PODs were derived from these studies using BMD modeling when possible in order to obtain more precise values. BMD modeling results always contain some level of uncertainty, and various factors such as model fit and BMR selection may have a large effect on the final POD value.

Endpoints for Acute Exposures

EPA considered the two developmental toxicity endpoints to be applicable to acute exposures. There is uncertainty surrounding this consideration because the precise critical exposure window is unknown and it is unknown how well the two generational rodent study predicts acute effects in humans. Additionally, published studies that evaluated the use of repeated-dose developmental toxicity data for acute limit setting focused on fetal and not postnatal effects. EPA determined that the sustained persistence of HBCD in human tissue suggests that a single exposure could have sustained effects. Therefore, despite the uncertainties, neonatal mortality and body weight reduction were considered relevant to acute exposures. Offspring loss represents the most severe endpoint representing the developmental toxicity hazard and is also the lowest available POD relevant to acute exposures, thus making EPA's approach health protective.

Endpoints for Chronic Exposures

The available information on weight of evidence and HBCD mode of action suggests that most if not all HBCD human health hazard endpoints are downstream of dysregulation of the hypothalamic-pituitary-thyroid axis as indicated by decreased T4 levels. Therefore, in addition to representing the lowest available POD, changes in T4 thyroid hormone levels was identified as the most important endpoint relevant to chronic exposures. There is some uncertainty over the use of rodent thyroid hormone data for quantitative human health risk assessment, however the complexity of the system makes it difficult to determine whether rodents would in fact be more sensitive to the specific effects of HBCD. Direct extrapolation of rodent thyroid hormone effects to humans is health-protective and may potentially overestimate risk to humans.

The POD from (WIL Research, 2001) could not be fit into any BMD model and therefore a LOAEL value was used, introducing additional uncertainty in the form of a large cumulative uncertainty factor

and benchmark MOE. This is likely to overestimate risk for that endpoint due to the large default values used for various uncertainty factors. Nonetheless, EPA believes that the selected PODs best represent the hazards associated with HBCD for quantitative risk estimation. The liver POD from (WIL Research, 2001) is still less protective than the thyroid effects POD from (Ema et al., 2008), so its inclusion does not significantly impact the risk determination.

Additionally, EPA determined that there was evidence to support potential nervous system effects following HBCD exposure, however limitations in the available data precluded use of any particular study for dose-response analysis of the hazard. Nonetheless, other more sensitive endpoints such as thyroid hormone changes are expected to be protective of neurotoxicity and any other qualitative health effects. Overall, there is medium confidence in all endpoints applicable to chronic exposure, including the most sensitive endpoint of thyroid effects.

4 RISK CHARACTERIZATION

4.1 Environmental Risk

The environmental risk characterization of HBCD was conducted to evaluate whether the potential releases of HBCD from the various conditions of use (COUs) may result in surface water, sediment and soil concentrations of HBCD that exceed the HBCD concentrations observed to result in hazardous effects due to either acute or chronic exposures. In regard to evaluating the environmental hazard of HBCD, a weight of evidence approach was used to select hazard effect concentrations for the derivation of risk quotients for both aquatic and terrestrial organisms. The selected hazard effect concentrations reflect studies with high data quality evaluation scores (as determined by the Systematic Review Metrics for Environmental Toxicological Studies), where measured discrete exposure concentrations resulted in observed effects due to acute and chronic exposures. The only acute toxicity study (Walsh et al., 1987) with measured observed hazardous effect (*i.e.,* growth), where the exposure concentration was below the water solubility of HBCD, was a 72-hr exposure using a marine algae species (*Skeletonema costatum*). As described in Sections 2.1.2.6 and 2.1.2.7, the ubiquitous presence of HBCD in the tissues of marine organisms indicates the exposure of HBCD to marine organisms, despite a lack of information regarding the source of HBCD. The data availability for freshwater pelagic organisms chronically exposed to HBCD was more expansive, and similar to the rationale used to select the study that was the basis for the acute COC (data quality, measured hazard effects concentrations below the water solubility limits of HBCD), the MATC of 0.0042 mg/L derived from a 21-d study using the aquatic invertebrate, *D. magna*, was used to calculate the chronic COC (Drottar and Krueger, 1998). The chronic COC to represent benthic organisms (*L. variegatus*) was also based on the same requirements mentioned above (Oetken et al., 2001). In regard to terrestrial organisms, the effect concentration levels as provided in Table 4-2 similarly represent three trophic levels, and the rationale for selecting these studies are based on high data evaluation quality scores, and the pertinence of the tested exposure and effect measured. The hazard effects concentrations cover a range of observed effects (*i.e.,* growth, reproductive success, oxidative stress), and the potential for organisms to be exposed to such concentrations was evaluated by using both environmental monitoring (*i.e*., surface water, sediment, and soil) and modeled surface water and sediment HBCD concentrations to calculate risk estimates. All risk estimates based on both environmental monitoring and measured data are provided in Appendix J.

For the most part, EPA assessed releases of HBCD to the environment or to disposal based on the production volume of HBCD, emission factors , and number days of release per year. In a few cases, EPA used TRI release data in lieu of the production volume of HBCD and emission factors. A two tiered modeling approach was used to predict both surface water and sediment HBCD concentrations using two models, E-FAST (surface water) and the PSC (surface water and sediment). Briefly, E-FAST was used for all conditions of use where water releases were likely to occur. If the E-FAST predicted 7Q10 SWCs were greater than the chronic or acute COCs, the PSC model was then used to confirm whether the predicted SWC exceeds the chronic or acute COC. While both E-FAST and PSC consider dilution and variability in flow, the PSC model can further estimate a time-varying surface water concentration, partitioning to suspended and settled sediment, and degradation within compartments of the water column.

As explained in Section 2.3.2, the surface water HBCD predictions are based on 7Q10 flow rates (lowest expected weekly flow over a ten-year period). When modeling using E-FAST and PSC, EPA used Standard Industrial Classification (SIC) codes to determine industry-specific dilution factors and stream flows. In lieu of having site-specific release information for HBCD, EPA used SIC code information to

determine 10th and 50th percentile flow rates to crosswalk with specific COUs. Surface water releases for each COU were utilized to estimate surface water concentration using flow values (7Q10 and mean flows, noted in Table 2-51), from both the 10th and 50th percentile facility for the SIC code. The 10th percentile flow values are approximately a factor of ten lower than the 50th percentile flows for the SIC codes chosen (lower flow volume will result in higher predicted concentrations of HBCD in the surface water and sediment). The predicted HBCD concentrations for surface water and sediment are based on the 7Q10 flow values from the 10th percentile facility, and can be found in Appendix J. While the 10th and 50th percentile facilities were estimated in the risk evaluation to account for the variability in receiving stream flows (all risk estimates are provided in Appendix J), only predicted HBCD surface water and sediment concentrations based on 50th percentile facility flow values are used to represent the mean flow from COU-related facilities.

In addition to modeling, environmental monitoring and biomonitoring data was reviewed, and screened to assess wildlife exposure to HBCD. The key studies that were reviewed and used for the environmental exposure assessment are summarized in Section 2.3.1. Environmental monitoring data summarized below in Table 4-3 and Table 4-4 demonstrate that the predicted surface water and sediment HBCD concentrations using both E-FAST and the PSC support measured HBCD concentrations near industrial facilities in most modeled COUs, except for COU 12 (Use of Flux or Solder Pastes). For COU 12, all predicted releases of HBCD are below the concentrations of HBCD that have been measured in surface water and sediment near industrial facilities, yet some surface water concentrations based on the 7Q10 50th percentile predictions are greater than the measured surface water concentrations of HBCD found near general populations (Venier et al., 2014). EPA does expect that the modeling results for some COUs may be overestimates based on the assumptions used in the assessment.

Incorporating both environmental monitoring and predicted environmental concentrations of HBCD provides information that can be used to evaluate each COU. Specifically, environmental monitoring data cannot provide HBCD release information that can be attributed to a specific COU or COU-specific parameter, nor can it be used to determine HBCD releases from a specific time period. Modeled HBCD surface water and sediment concentrations were obtained by using information that is specific to a COU or that pertains to an industrial or commercial sector that is related to a COU (e.g., polymer processing, use of spray polyurethane foam.) Modeled HBCD surface water and sediment concentrations however can only be attributed to the assessed releases in the case of each COU. Although HBCD is expected to partition out of the water column quickly, thereby reducing exposure for pelagic organisms, modeled HBCD surface water and sediment concentrations also do not account for the bioavailability of HBCD to pelagic organisms due to the presence of suspended solids (*i.e.,* resuspension of sediment, presence of natural organic matter).

As stated in Section 2.2.14, EPA performed a sensitivity analyses for three conditions of use using the per site process volumes of 50,000 lbs/yr and 25,000 lbs/yr to examine the effect of process volume on modelled environmental exposures. Due to HBCD declining use, EPA did not identify a current import volume for HBCD, and conservatively used the CDR reporting threshold for small firms of 100,000 lbs/yr as explained in Section 1.2.3. If import is occurring at all, the current import volume could be lower than the threshold volume of 100,000 lbs/yr. For select conditions of use, EPA assessed the most recently identified import volume in 2017 of ~50,000 lbs/yr (see Table 1-4) and to account for the declining use of HBCD, EPA also considered 25,000 lbs/yr. The selected conditions of use (Repackaging of Import Containers, Manufacturing of XPS foam from XPS masterbatch, and

Manufacturing of EPS foam from EPS resin) considered in the sensitivity analysis represent conditions of use that are expected to result in high surface water and sediment concentrations.

In addition, EPA chose to perform additional sensitivity analyses by incorporating a higher onsite (direct release) wastewater removal efficiency when the removal rates were unknown. For Scenario 1 (Repackaging of Import Containers), based on information provided in Section 2.2.2, EPA applied 90% removal for releases to water. As mentioned in Section 2.3.2, when information regarding pretreatment for direct releases to surface was uncertain, EPA chose to apply a removal rate of 0%, likely leading to overestimates of sediment concentrations. In the sensitivity analysis presented below in Table 4-7, a tiered approach was used to assess these releases using both 0% removal and a higher removal rate. Little information was found on the type or efficiency of onsite treatment used by direct discharging facilities using HBCD. Due to its low water solubility (66 µg/L), high log Kow (5.6) and physical state (solid), HBCD is likely to partition to the organic phase, including organic particulates in wastewater. It is expected to behave as a particulate in aqueous wastewater and be removed with other solids by gravity settling during the wastewater clarification process. As mentioned above, HBCD removal may occur due to sorption to total suspended solids (TSS), and the TSS removal of HBCD from thirty-nine observations as reported by the EPA Development Document for Effluent Limitations, Guidelines and Standards for Organic Chemicals, Plastics and Synthetic Fibers Point Source Category (U.S. EPA, 1987) were used as a surrogate to represent HBCD removal from the direct release of HBCD from specific COUs (3 and 5) for the sensitivity analysis .

KABAM (v1) predictions of HBCD bioavailability through diet and water are also used to categorize exposure and predicts body burdens and the contribution to body burden due to both diet and media exposure. Predicted bioaccumulation, bioconcentration and biomagnification factors can also be predicted for representative organisms within each trophic level. American kestrel and Sprague Dawley rats are used as proxy organisms for terrestrial avian and mammalian wildlife organisms that may be exposed to HBCD through trophic transfer and various media exposure. Specifically for this model, based on the assumption that the modeled organisms have the same effect or response to the same effect concentration as those of the proxy organisms, hazard data on the proxy organisms are also input parameters for KABAM. Both the predicted hazard effect concentrations and exposure to HBCD through diet and media exposures are used to calculate risk estimates for mammal and avian species within multiple trophic levels.

There are many potential sources of uncertainty in all of the parameters involved in environmental exposure estimates. As presented in Table 2-110, the greatest influence on exposure estimates given the associated uncertainty and sensitivity (effect on the final values) stems from the selection of emission factor and days of release. Production volume is highly uncertain but not very sensitive, while other factors such as physical-chemical properties, BAF, HBCD half-lives, and exposure model parameters were all estimated to contain low uncertainty. In order to account for these uncertainties and variability among release estimates and exposure considerations including wastewater treatment, EPA provided risk estimates based on a range of exposure sub-scenarios. EPA believes that these sub-scenarios sufficiently capture the range of risk estimates for all reasonably expected environmental exposures, with minimal remaining unaccounted-for uncertainty. Therefore, EPA has high confidence in the range of risk estimates for the highly exposed aquatic and terrestrial organisms.

4.1.1 Risk Estimation

The environmental risk of HBCD is characterized by calculating risk quotients (RQs) (U.S. EPA,

1998; Barnthouse et al., 1982). The concentrations of concern (COCs) derived from hazard data will be used to calculate RQs for aquatic organisms. The hazard effects concentrations will be used to calculate RQs for terrestrial organisms (COC calculation methodologies, specified below, were not originally meant for terrestrial organisms). The environmental concentration for each compartment (i.e., wastewater, surface water, sediment, soil) will be based on measured and/or modeled concentrations of HBCD.

4.1.1.1 Environmental Effect Levels of HBCD

The methods for calculating the environmental concentrations of concern (COCs) are based on published EPA methods (U.S. EPA, 2013a, 2012d).

The acute COC will be based on the 72-hour EC_{50} marine algae value of 0.01 mg/L. The environmental hazard evaluation that is summarized in Section 3.1 of this evaluation is based on high quality studies. Based on the environmental hazard evaluation of HBCD, there were no acute lethal effects reported on aquatic organisms. The only acute toxicity study that reported effects of HBCD below the solubility limit was a 72-hour marine algae study (Walsh et al., 1987). Walsh stated that in his study that *S. costatum* was chosen because of the potential of brominated flame retardants hazardous effects on marine algae due to releases from industrial sites. Other studies also show that HBCD can enter the marine and estuarine environments from industrial waste, leaching from micro-plastics or long-range transport.

The chronic COC will be based on the 21-day daphnia study of 0.004 mg/L. As stated above, the environmental hazard evaluation used the studies with the highest quality values to characterize the hazard of HBCD. For surface water, most of these organisms did not show effects after chronic exposure to HBCD at the chemical's solubility limit. The aquatic invertebrate study (Drottar and Krueger, 1998) is of high quality and reports the effects of HBCD to *D. magna*'s ability to grow and reproduce.

The chronic COC for sediment-dwelling organisms will be based on the 28-day black-worm of 3.1 mg/kg dwt. Section 3.1 and table 3-7 summarizes the effect of HBCD to organisms in sediment compartment. *Lumbriculus variegatus* show that HBCD reduced survivability at 15.7 mg/kg dwt. This is the highest quality study that resulted in survival reduction of the organism after 28-day exposure to HBCD.

As described above, the selection of hazard effect concentrations were based on a weight of evidence approach that takes into consideration: data evaluation quality scores, relevancy of exposure and effect measured, and the availability of supporting studies.

4.1.2 Risk Estimation for Environmental Toxicity

4.1.2.1 Acute and Chronic Concentrations of Concern

The COC's for acute toxicity were determined by dividing the acute effect level (i.e., Marine algae endpoint) by an uncertainty factor of 4; the chronic COC's were calculated using a chronic effect level (i.e., Water flea endpoint) uncertainty factor of 10. Further details on the calculations used to derive COCs are described above in Section 3.1.5.

Table 4-1. Concentrations of Concern (COCs) Derived to Evaluate Toxicity to Aquatic Organisms for HBCD

Environmental Toxicity	Concentration of Concern (COC)	Species	Effect	Reference	Data Evaluation Score
Acute toxicity to aquatic organism	2.5 µg/L	Marine Algae (*S. costatum*)	Growth Rate	(Walsh et al., 1987)	High
Chronic toxicity to aquatic organisms	0.417 µg/L	Water flea (*D. magna*)	Reduced length of surviving young	(Drottar and Krueger, 1998)	High
Chronic toxicity to sediment-dwelling organisms	1.57 mg/kg/dwt.	California blackworm (*Lumbriculus variegatus*)	Reduction in worm number	(Oetken et al., 2001)	High

The methodology used to derive concentrations of concern as presented in Table 4-1 are described above in Sections 3.1.6 and 3.1.7.

Table 4-2. Terrestrial Effect Concentrations (Hazard) used to Evaluate Toxicity to Terrestrial Organisms

Environmental Toxicity	Effect concentration	Effect	Reference	Data Evaluation Score
Maize 4-d LOAEL	2 µg/L	Growth (root and shoot)	(Wu et al., 2016b)	High
Earthworm 14-d LOAEL	200 mg/kg	Oxidative stress	(Shi et al., 2018)	High
American Kestrel 21-d LOAEL	3.27 ng/g ww	Reproduction (clutch size, egg production timing)	(Fernie et al., 2009)	High
Rat 2-generation NOAEL	10 mg/kg bw	Thyroid hormones	(Ema et al., 2008)	High

Studies where terrestrial organisms were exposed to HBCD were evaluated and those with high data evaluation scores (using either environmental or human health Systematic Review metrics) and relevant environmental exposure pathways were used to assess risk to terrestrial organisms. The studies identified in Table 4-2 provide a summary of reported lowest observed adverse effect levels where chronic exposures to HBCD were conducted with terrestrial organisms. The organisms identified in the abovementioned studies were chosen to represent their respective taxa classifications (*i.e.,* vegetation, invertebrate, vertebrate). Out of the four terrestrial vegetation studies (all rated with high data evaluation scores), (Wu et al., 2016b) represents the most highly relevant study because the exposure is not diastereomer-specific and has a discrete effect concentration; maize exposed to HBCD through spiked water resulted in significant reductions in root and shoot growth. Risk estimates were not calculated for maize because it is unlikely that terrestrial plants will be exposed to HBCD through precipitation (as

done in the study). Despite the sparse amount of available terrestrial invertebrate toxicity data, Shi et al., 2015 was the only study with a high data evaluation score that demonstrated potential toxicity due to chronic exposure to HBCD; although growth was not significantly reduced, an upregulation of superoxide dismutase (SOD) and heat shock protein (Hsp70) gene expression suggests that a longer exposure to HBCD may result in organism-level toxicological effects. In the ten highly evaluated studies, three avian species (Chicken, Japanese Quail and American Kestrel) were mainly used to study reproductive effects resulting from HBCD exposure, where there were observations of reduced hatching time, smaller egg production, and the presence of HBCD in eggs where parents were chronically exposed to HBCD.

4.1.3 Calculation of Risk Quotient (RQ) Values for HBCD

Environmental risk was characterized by calculating risk quotients or RQs (U.S. EPA, 1998; Barnthouse et al., 1982); the RQ is defined as:

RQ = Environmental Concentration / Effect Level

For aquatic organisms, the "effect level" is a derived COC based on a hazard effects concentration. For terrestrial organisms, the "effect level" is the hazards effects concentration identified in Table 4-2. COC calculation methodologies were not originally meant for terrestrial organisms. An RQ equal to 1 indicates that the exposures are the same as the concentration that causes effects. If the RQ is above 1, the exposure is greater than the effect concentration. If the RQ is below 1, the exposure is less than the effect concentration. The Concentrations of Concern (COCs) for aquatic and benthic organisms shown in Table 4-1 and the environmental concentrations in Section 2.3 were used to calculate RQs summarized in Table 4-3through Table 4-4. The effect levels for aquatic and terrestrial organisms shown in Table 4-1 and Table 4-2 were used to calculate RQs summarized in Table 4-5. The environmental concentration was determined based on modeled concentrations of HBCD using E-FAST and PSC.

4.1.4 Risk Estimation Approach

The concentrations of concern (COC) used to calculate risk quotients (RQ) for aquatic organisms were derived from hazard values resulting from acute and chronic exposures to HBCD. RQs for terrestrial organisms were derived from the raw hazard values resulting from acute and chronic exposures to HBCD (no COCs were calculated). The calculated RQs based on estimated water and sediment HBCD concentrations are presented below in Appendix J; ranges of the calculated RQs are presented below in Section 4.1.4.1. Environmental monitoring data (*i.e.,* surface water and sediment concentrations of HBCD) are also evaluated below, in the context of the same hazard and COC values as those used for the modeled surface water and sediment HBCD concentrations predicted by E-FAST and PSC. The background of the various sources of monitored data is discussed above in Sections 2.3.2 and 2.3.3. RQ calculations using environmental monitoring data are provided below in Table 4-3 through Table 4-5. Surface water and sediment HBCD concentrations were not predicted for the following conditions of uses: "Use: Installation of Automotive Replacement Parts", "Demolition and Disposal of XPS/EPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures", and "Processing: Formulation of Flux/Solder Pastes", because water releases were not predicted to occur (as explained in Sections 2.2.8, 2.2.10, and 2.2.12, respectively).

Further explanations regarding model parameters used for the different scenario labels in Table 2-50, and can be found in Section 2.3.2. Briefly, E-FAST was used for all conditions of use where water

releases were likely to occur. If the EFAST predicted 7Q10 SWCs were greater than the chronic or acute COCs, the PSC model was then used to affirm whether the predicted SWC exceeds the chronic or acute COC using different parameters. EFAST considers dilution and variability in flow for days exceeded estimates. The PSC also considers dilution but can further estimate a time-varying surface water concentration, partitioning to suspended and settled sediment, and degradation within compartments of the water column within a river segment.

The sensitivity analysis on how production volume and percentage of HBCD removal from the direct release of HBCD into surface water was conducted to reflect declining production volumes and the likelihood that the HBCD will partition to TSS. The surface water and sediment concentrations were predicted for three production volumes (100,000, 50,000 and 25,000 lbs/yr) due to the declining use of HBCD and lack of information regarding the current import volume of HBCD to account for the current processing and use associated with HBCD. Furthermore, the selected COUs (Repackaging of Import Containers, Manufacturing of XPS foam from XPS masterbatch, and Manufacturing of EPS foam from EPS resin) were considered in the sensitivity analysis using the three production volumes because they were expected to result in high surface water and sediment concentrations. The estimated emissions from the three COUs cover emission data from process-specific industry data and OECD ESDs.

4.1.4.1 Risk Estimation Based on HBCD Surface Water and Sediment Concentrations using Environmental Monitoring Data and Modeling Results

The COCs used to calculate RQs below are summarized above in Section 4.1.2.1, with the respective toxicity data.

4.1.4.1.1 Risk Estimation Based on Surface Water and Sediment Monitoring Data

Table 4-3. Calculated Risk Quotients based on HBCD Surface Water (µg/L) Concentrations as Reported in Environmental Monitoring Studies

Site Characterization	Surface Water Concentrations (µg/L)	Reference	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)
Near Industrial Facility (Point Source)	1.52 - 2.1	(Chokwe et al., 2015; Oh et al., 2014; EC, 2008)	0.84	**5.03**
Near General Population (Non-Point Source)	1.2×10^{-6}	(Venier et al., 2014)	4.8×10^{-7}	2.9×10^{-6}

Values in **bold text** denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. Although ranges for SWCs are provided, the more conservative SWC (highest) value was used to calculate respective acute and chronic RQs.

Table 4-4. Calculated Risk Quotients based on HBCD Sediment Concentrations (µg/kg) as Reported in Environmental Monitoring Studies

Site Characterization	Sediment Concentration (µg/kg)	Reference	Chronic RQ (COC: 1,570 µg/kg)
Near Industrial Facility (Point Source)	514 – 2,430	(Guerra et al., 2009)	**1.55**
Downstream of Industrial Facility (27-30 km downstream from point source)	90 - 866		0.55

Values in **bold text** denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. Although ranges for sediment concentrations are provided below, the more conservative sediment concentration (highest) values was used to calculate respective chronic RQs.

4.1.4.1.2 Risk Estimation Based on Surface Water and Sediment Modeling Data

Table 4-5. Range of Risk Quotients for Modeled Surface Water and Sediment HBCD Concentrations for Each Condition of Use Using a Production Volume of 100,000 lbs/yr (0% removal for direct release)

Condition of Use	Surface Water [a]		Sediment [a]	
	Acute: 50th percentile flow	Chronic: 50th percentile flow	11-d half-life: 50th percentile flow	128-d half-life: 50th percentile flow
1. Import and Re-packaging/ Processing: Repackaging of Import Containers	0.01-3.87	0.07-2.26	0.02-0.56	0.05-1.26
2. Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	0-0.33	0.01-0.10	0-0.02	0-0.04
3. Processing: Manufacturing of XPS Foam using XPS Masterbatch	0-1.17	0-0.34	0-0.06	0-0.08
4. Processing: Manufacturing of XPS Foam using HBCD Powder	0-0.46	0-0.13	0-0.02	0-0.03
5. Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	**0.35-42**	**0.71-12.01**	**0.21-3.52**	**0.48-7.77**
6. Processing: Manufacturing of Structural Insulated Panels (SIPs) and Automotive Replacement Parts from XPS/EPS Foam	0-0.63	0-0.18	0-0.05	0-0.12
8. Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures	0-0.14	0-0.04	0-0.01	0-0.01
10. Processing: Recycling of EPS Foam and Reuse of XPS Foam	0-0.78	0-0.22	0-0.04	0-0.06
12. Use of Flux/Solder Pastes	0-0.02	0-0.01	0	0

Notes:

RQs are calculated using aquatic acute and chronic COCs of 2.5 and 0.417 µg/L, respectively.

If the predicted surface water or sediment concentration was 0,or if the calculated RQ was< 0.005, the RQ was rounded to 0.

[a] Values in **bold text** denote COUs where at least half of the model sub-scenarios have risk (RQ≥1) to the aquatic or benthic environment where the surface water concentration (SWC) or sediment concentration, respectively, exceeds the concentration of concern (COC) for acute or chronic environmental hazard.

4.1.4.2 Risk Estimation based on HBCD Soil Concentrations using Models and Environmental Monitoring Data

Table 4-6. Calculated Risk Quotients based on HBCD Soil Concentrations (µg/kg) as Reported in Environmental Monitoring Studies

Data Source	HBCD Source	Site Characterization	Soil Concentrations (µg/kg)	Reference	Chronic RQ (Hazard effect concentration: 200,000 µg /kg)
Environmental Monitoring	Air Deposition	Near Industrial Facility (Point Source)	0.3 – 249	(Wu et al., 2016	0.001
		Near General Population (Non-Point Source)	ND - 46	(Tang et al. (2014b))	0.0002
Model	Biosolid Application	Agriculture (Point Source)	300	(EC/HC, 2011)	0.002
	Air Deposition, Biosolid Application, and Background Levels	N/A	311	EPA methodology outlined in Section 2.3.3	0.002

The shaded values in red denote a risk (RQ≥1) to the terrestrial environment where the soil HBCD concentration exceeds the hazard effects concentration due to chronic exposure using earthworms (presented in Table 4-2). Although ranges for soil concentrations are provided below, the more conservative sediment concentration (highest) values was used to calculate respective chronic RQs. HBCD when undetected in soil samples is denoted as ND.

4.1.4.3 Targeted Sensitivity Analysis

Table 4-7. Range of Risk Quotients for Modeled Surface Water and Sediment HBCD Concentrations for Three Conditions of Use Scenarios Using a Production Volume of 100,000, 50,000, and 25,000 lbs/yr

SCENARIO NAME	Production Volume (lbs / year)	% WWTP Removal for Direct Releases [a]	Surface Water		Sediment	
			Acute: 50th percentile	Chronic: 50th percentile	11-d half-life: 50th percentile	128-d half-life: 50th percentile
Scenario 1.	100,000	---	0.01-3.87	0.07-2.26	0.02-0.56	0.05-1.26
	50,000	---	0.01-3.74	0.04-1.21	0.01-0.34	0.03-0.79
	25,000	---	0.01-4.0	0.02-1.16	0.01-0.21	0.01-0.4
Scenario 3.	100,000	0%	0-1.17	0-0.34	0-0.06	0-0.08
		75%	0-0.59	0-0.17	0-0.03	0-0.04
	50,000	0%	0-0.60	0-0.17	0-0.03	0-0.04
		75%	0-0.30	0-0.09	0-0.01	0-0.02
	25,000	0%	0-0.30	0-0.08	0-0.1	0-0.02
		75%	0-0.15	0-0.04	0-0.1	0-0.1
Scenario 5.	100,000	0%	**0.35-42**	**0.70-12**	**0.21-3.52**	**0.48-7.77**
		75%	**0.35-21**	**0.70-6.2**	0.21-1.78	**0.48-3.97**
	50,000	0%	**0.18-42**	**0.35-12**	0.11-2.23	**0.24-4.39**
		75%	**0.18-21**	**0.35-6.1**	0.11-1.10	0.24-2.13
	25,000	0%	**0.09-42**	**0.18-12**	0.05-2.03	**0.12-3.13**
		75%	0.09-21	0.18-6.1	0.05-1.03	0.12-1.59

a Note, there are no predicted direct releases for Scenario 1. The values in bold denote when half or more of the sub-scenario risk quotients (RQ) modeled for each Condition of Use (COU) scenario are ≥1. If the predicted surface water or sediment concentration was 0,or if the calculated RQ was< 0.005, the RQ was rounded to 0.

4.1.5 Environmental Risk Results

The risk of HBCD to aquatic and terrestrial ecosystems are summarized in Tables 4-3 through 4-7. Specifically, Table 4-3, Table 4-4, Table 4-5 and Table 4-6 include risk quotients (RQ) based on reported environmental monitoring data for HBCD concentrations in sampled surface water, sediment and soil samples. Tables 4-5 and 4-7 include RQs based on predicted surface water and sediment concentrations categorized by the different modeling scenarios for each condition of use (further details provided in Section 2.3). The presented RQs are based on predicted surface water and sediment concentrations using the 50th percentile flow, however additional information on predictions using the 10th percentile flow are available in Appendix J.

Table 4-5 and 4-7 include predictions of surface water and sediment concentrations using the Variable Volume Waterbody Model (VVWM) - Point Source Calculator (PSC) to estimate the risk of HBCD to the aquatic environment that occurs through a condition of use. Risk to the aquatic environment is characterized by evaluating both surface water and sediment concentrations of HBCD, by using both environmental monitoring and predicted surface water and sediment concentrations. Risk to the terrestrial environment was also characterized by using predicted surface water and sediment concentrations using the PSC by using KABAM (v1).

The red shaded values in these tables denote a risk (RQ≥ 1) where the modeled or measured water, sediment or soil concentration of HBCD exceeds the COC derived from effect concentrations or hazards effect concentration (terrestrial organisms only), resulting from acute or chronic exposures.

4.1.5.1 Risk Characterization for Terrestrial Ecosystems based on Environmental Monitoring Data

When evaluating risk to terrestrial organisms, a qualitative approach was used because the exposure scenarios used in studies that characterize the toxicity of HBCD are not represented by the available exposure information. For all conditions of use, except for HBCD in the "Use of Flux/Solder Pastes", there are modeled surface water concentrations (10th percentile) that exceed the 14-day LOAEL of 2 µg/L for maize (reduction in root and shoot growth). Additionally, surface water concentrations of HBCD near industrial facilities also conservatively exceed 2 µg/L. Using maize as the representative organism for terrestrial vegetation, HBCD exposure is expected near industrial facilities where the conditions of use are expected to occur. As depicted in Table 4-6. Calculated Risk Quotients based on HBCD Soil Concentrations (µg/kg) as Reported in Environmental Monitoring Studies, there are no chronic risk estimates greater than one for soil-dwelling organisms (based on the chronic earthworm COC of 23,500 µg/kg).

As stated in Section 4.1.3, the goal of environmental risk characterization is to determine whether there are risks to the aquatic or terrestrial environments from measured levels of HBCD found in surface water, sediment or soil. The risk quotients (RQ) method (U.S. EPA, 1998; Barnthouse et al., 1982) was used to determine whether the exposures of HBCD exceed either the concentrations of concern (COC) or hazard effects concentrations for aquatic or terrestrial organisms, respectively. Regarding terrestrial organisms, the risk is not as easily characterized because the available hazard and exposure data are not completely compatible (*i.e.,* the exposure media and corresponding units do not always match those used in predictive models or reporting methods for biomonitoring data). Specifically, the terrestrial plants with data (regarding HBCD exposure) are all agricultural crops and were exposed to HBCD using exposure solutions with dissolved HBCD; the most relevant exposure pathway for HBCD to agricultural

crops would be via the application of biosolids. Therefore, a RQ cannot be calculated to determine whether the exposure concentration is above the threshold where toxicological effects are observed due to biosolid application. Using all soil biomonitoring data as presented in Table 4-6 the risk of HBCD to soil invertebrates can be evaluated by using the earthworm hazard effect concentration (14-d LOAEL of 200,000 µg/kg). There are no RQs greater than one using the highest soil concentrations across the data sources presented, suggesting that it is unlikely that terrestrial invertebrates will be exposed to HBCD concentrations that exceed the exposure concentrations where toxicological effects were observed. As presented in Table 4-6, using EPA methodology outlined in Section 2.3.3, a soil concentration of 311 µg/kg was calculated, with biosolid application contributing more to HBCD soil concentration, than air deposition (as model parameters). As a PBT chemical, considering the potential for chronic exposures to HBCD due to all sources (*i.e.,* air deposition, biosolid application and background levels) is imperative because evaluating air deposition alone may imply that there isn't risk to terrestrial organisms that do not inhabit areas near industrial facilities (accounting for multiple conditions of uses). In comparison to the environmental monitoring data, 300 or 311 µg/kg is close to the most conservative soil HBCD concentration due to air deposition near an industrial facility (249 µg/kg), suggesting that terrestrial ecosystems within proximity to either type of point source may result in a similar exposure to HBCD.

Similarly, publicly available toxicity information on terrestrial organisms (i.e., mammals and birds) suggest that exposure primarily results from dietary pathways (i.e., spiked food, oil). For comparison purposes, it was not possible to derive a RQ using the available terrestrial hazard data and biomonitoring data (*i.e.,* HBCD tissue concentrations), due to the methodological differences in measuring hazard and tissue concentrations. Specifically, the toxicity effects concentrations for the American kestrel and rat, as reported in Table 4-2, were normalized to body weight, and the environmental biomonitoring data available on American kestrel and rat HBCD tissue concentrations were normalized to lipid weight (Zhu et al., 2017; Yu et al., 2013).

As presented in Section 3.1.3, the trophic transfer potential of HBCD is evaluated for a representative terrestrial and aquatic predator; the potential risk to terrestrial and aquatic organisms can be qualitatively evaluated using this methodology. Specifically in regard to American kestrel, reproductive toxicity was observed in female kestrel exposed to 3.27 ng/g ww. Using the exposure factor for American kestrel body weight in Table 3-2, female American kestrel would need to be chronically exposed to 451 ng HBCD to result in reproductive toxicity. Table 3-2 suggests that American kestrel are exposed to 64.4 ng HBCD per day through the consumption of small mammals (*i.e.* mice), however mice only comprise of approximately a third of American kestrel diet; it is likely that these calculations vastly underestimate HBCD uptake through diet.

Although risk quotients could not be calculated for terrestrial mammals and birds given the availability of hazard and biomonitoring data, and the RQ<1 for earthworms, the potential for both dietary and environmental exposure to HBCD is likely; exposure to HBCD is prolonged given the PBT characteristics of HBCD.

4.1.5.2 Risk Characterization for Aquatic and Terrestrial Ecosystems based on Modeled Surface Water and Sediment Concentrations

To evaluate the risk for organisms in aquatic ecosystems due to of HBCD exposure, both environmental monitoring and predicted surface water and sediment concentrations were compared to acute and chronic concentrations of concern (COC). In regard to surface water and sediment concentrations of HBCD *Exposure* from environmental monitoring data, there is chronic risk for pelagic and benthic organisms that inhabit areas within close proximity to industrial facilities. On the other hand, HBCD

may not be bioavailable for even benthic organisms downstream of industrial facilities. HBCD is expected to have higher binding affinity for sediment and organic matter and will partition out of the water column quickly. HBCD was undetectable in sediment samples 60 km downstream of industrial facilities (Guerra et al., 2009), suggesting that it is unlikely for aquatic organisms that do not inhabit areas within close proximity to industrial facilities to be at risk for HBCD exposure.

Water and sediment exposure to HBCD was further characterized using predicted exposure concentrations from modeled scenarios for each condition of use. The below risk characterization for aquatic organisms is based on risk quotients derived from predicted surface water and sediment concentrations for production volumes of 100,000 lbs/yr and 0% removal of HBCD from directly released HBCD into surface water. Additional production volumes and percentages of HBCD removal from directly released HBCD into surface water are further evaluated in the below sensitivity analyses.

Using the predicted surface water and pore water HBCD concentrations from the PSC, and proxy organism hazard data (*i.e.,* Rats and Japanese Quail) as input parameters for KABAM (v1), risk estimates for multiple mammalian wildlife species can be estimated (assuming that the effect concentrations are the same as those as the proxy organism by scaling of body weight). The risk quotients are available in Appendix J.1.4., based on both the 10th and 50th percentile surface water and pore water concentrations of HBCD, however only those corresponding to the 50th percentile predictions will be addressed in the targeted sensitivity analysis below.

Processing: Repackaging of Import Containers
Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for repackaging of import containers. This process can result in direct releases of HBCD into surface water, or release through POTWs.

For each release medium, EPA assessed a range of daily release rates based on data pertaining to emission factors and number of days of release per year. The emission factors were obtained from the OECD ESD on Plastics Additives (OECD, 2009). The number of days of release per year are estimated values that are applicable to the basic chemical industry in general (ECB, 2003). There is some uncertainty regarding the extent to which these emission factors and number of days of release per year are applicable to the repackaging of import containers that would occur in the U.S.

Releases of HBCD to the aquatic environment are due to the activity of repackaging of import containers. Based on the 7Q10 50th percentile predictions, there is one acute and two chronic risk estimates that are greater than one, based on the acute and chronic COCs of 2.5 and 0.417 µg/L, respectively. For RQs regarding sediment exposures, a chronic COC of 1,570 µg/kg was used (based on growth reduction observed in a California blackworm chronic HBCD exposure). In evaluating the 50th percentile predictions to calculate risk estimates for benthic organisms, there are only two chronic risk estimates greater than one using the 128-day HBCD half-life.

Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch
Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for compounding polystyrene resin to produce XPS Masterbatch. This process can result in direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment.

For each release medium, EPA assessed a range of daily release rates based on data pertaining to emission factors and number of days of release per year. The emission factors pertain to sites in Europe

at which XPS Masterbatch was compounded (ECHA, 2008b). The data pertaining to the number of release days per year are estimated values that are applicable to the polymer formulation industry in general (ECB, 2003). There is some uncertainty regarding the extent to which these emission factors and number of days of release per year are applicable to the compounding of XPS Masterbatch that would occur in the U.S.

Releases of HBCD to the aquatic environment are due to the activity of compounding polystyrene resin to produce masterbatches of XPS. There were no SWCs that exceeded acute or chronic COCs using the 7Q10 50th percentile predictions. All risk estimates are less than one when using the 50th percentile predictions for SWCs or sediment concentrations of HBCD.

Processing: Manufacturing of XPS Foam using XPS Masterbatch
Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for manufacturing of XPS foam using XPS Masterbatch. This process can result in direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment.

For each release medium, EPA assessed a range of daily release rates based on data pertaining to emission factors and number of days of release per year. These emission factors and number of days of release per year pertain to sites in Europe at which XPS Foam was manufactured (ECHA, 2008b). There is some uncertainty regarding the extent to which these emission factors and number of days of release per year are applicable to the manufacture of XPS from Masterbatch that would occur in the U.S.

Releases of HBCD to the aquatic environment are due to the activity of manufacturing of XPS foam using XPS Masterbatch. There is only one acute RQ that is greater than one using the 7Q10 50th percentile predictions.

Based on the 50th percentile predictions for sediment HBCD concentrations, there were no risk estimates greater than one using either the 11- or 128-d half-lives of HBCD.

Processing: Manufacturing of XPS Foam using HBCD Powder
Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for manufacturing of XPS foam using XPS powder. This process can result in direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment.

For each release medium, EPA assessed a range of daily release rates based on TRI data and data pertaining to emission factors and number of days of release per year. These emission factors in general and number of days of release per year in the case of releases to water pertain to sites in Europe at which XPS Foam was manufactured (ECHA, 2008b). In the case of releases to air, the data pertaining to the number of release days are estimated values that are applicable to the industrial use of polymers in general (ECB, 2003).

There is some uncertainty regarding the extent to which these emission factors and number of days of release per year are applicable to the manufacture of XPS from HBCD that would occur in the U.S.

Releases of HBCD to the aquatic environment are due to the activity of manufacturing XPS foam using HBCD powder. All risk estimates are less than one when using the 50th percentile predictions for SWCs or sediment concentrations of HBCD.

Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads

Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for manufacturing of EPS foam imported EPS Resin Beads. This process can result in direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment.

For each release medium, EPA assessed a range of daily release rates based on data pertaining to emission factors and number of days of release per year. The emission factors were obtained from the OECD ESD on Plastics Additives(OECD, 2009) or an EPA/OPPT screening-level model. The number of days of release per year is an estimated value that is applicable to the industrial use of polymers in general or is a value that pertains to the manufacture of EPS foam at a site in Australia(NICNAS, 2012b). There is some uncertainty regarding the extent to which these emission factors and number of days of release per year are applicable to the manufacture of EPS foam that would occur in the U.S. Furthermore, EPA's assessment of releases may be conservative based on a comparison of sources of release and emission factors as assessed by EPA and as reported in EURAR and NICNAS (NICNAS, 2012b; ECHA, 2008b) for this condition of use.

Releases of HBCD to the aquatic environment are due to the activity of the processing of EPS foam from imported EPS resin beads. Predicted SWCs for this condition of use were all determined using PSC calculations. Based on the 7Q10 50th percentile predictions, there are ten acute and nine chronic risk model sub-scenarios that have acute and chronic risk estimates greater than one, respectively.

The 50th percentile sediment HBCD concentration predictions resulted in eight acute and chronic RQs greater than one.

Processing: Manufacturing of Structural Insulated Panels (SIPs) and Automotive Replacement Parts from XPS/EPS Foam

Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for manufacturing of structural insulated panels and automotive replacement parts from XPS/EPS foam. This process can result in direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment.

EPA assessed a range of daily release rates based on data pertaining to particle generation from the cutting or sawing of XPS/EPS foam reported in the EURAR (ECHA, 2008b) and disposal of trimming waste given in the Spray Polyurethane Foam Generic Scenario (U.S. EPA, 2018c). The data pertaining to the number of release days are estimated values that are applicable to the polymer use industry in general (ECB, 2003). There is some uncertainty regarding the extent to which the emission factor data reported in the EURAR and the data on the number of release days are applicable to these specific condition of use activities that would occur in the U.S.

Releases of HBCD to the aquatic environment are due to the activity of manufacturing of structural insulated panels and automotive replacement parts from XPS/EPS foam. All risk estimates are less than one when using the 50th percentile predictions for SWCs or sediment concentrations of HBCD.

Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures

Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for the installation of XPS/EPS foam insulation in residential, public, and commercial buildings (and other

structures). This process can result in direct releases of HBCD into surface water, or release through POTWs.

EPA assessed a range of daily release rates based on an estimated HBCD throughput at residential and commercial buildings, emission data pertaining to particle generation from the cutting or sawing of XPS/EPS foam reported in the EURAR (ECHA, 2008b) and disposal of trimming waste given in the Spray Polyurethane Foam Generic Scenario (U.S. EPA, 2018c). The data pertaining to the number of release days are estimated values given in the Spray Polyurethane Foam (SPF) Generic Scenario for operating days at construction sites. There is some uncertainty regarding the extent to which the emission factor data reported in the EURAR and installation days for SPF are applicable to this specific condition of use that would occur in the U.S.

Releases of HBCD to the aquatic environment are due to the activity of installation of XPS/EPS foam insulation in residential, public and commercial buildings (and other structures). All risk estimates are less than one when using the 50th percentile predictions for SWCs or sediment concentrations of HBCD.

Processing: Recycling of EPS Foam and Reuse of XPS Foam
Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for the recycling of EPS foam and reuse of XPS foam. This process can result in direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment.

EPA assessed a range of daily release rates based on the emission data similar to the Manufacturing of EPS foam from EPS resins as stated earlier in this section with the exclusion of releases from trimming waste. There is some uncertainty regarding the extent to which the emission factor data and the data on number of release days are applicable to this specific condition of use.

Releases of HBCD to the aquatic environment are due to the activity of the recycling of EPS foam and reuse of XPS foam. All risk estimates are less than one when using the 50th percentile predictions for SWCs or sediment concentrations of HBCD.

Use of Solder/Flux Pastes
Section 2.2 of this document describes how HBCD is processed at industrial sites specifically for the use of solder or flux pastes. This process can result in the release of HBCD through POTWs and onsite wastewater treatment.

EPA assessed a range of daily release rates based on estimated emissions from the use of solder paste reported in the OECD ESD on Chemicals Used in the Electronics Industry (OECD, 2010a). The data pertaining to the number of release days are estimated values that are applicable to the electronics industry in general (ECB, 2003). There is some uncertainty regarding the extent to which the emission factor data reported in general for solder paste use in the ESD and the data on number of release days are applicable to the current use of HBCD-containing flux/solder paste.

Releases of HBCD to the aquatic environment are due to the activity of the use of solder or flux pastes. All risk estimates are less than one when using the 50th percentile predictions for SWCs or sediment concentrations of HBCD.

4.1.5.3 Targeted Sensitivity Analysis

Section 2.2.14 describes the context behind conducting a targeted sensitivity analysis based on production volume. Briefly, due to the uncertainty with the imported volume and resulted estimates of environmental releases and exposures to the general population and the environment, a targeted sensitivity analysis on the impact of import volumes on environmental risk estimates is conducted in this section. The conditions of use (COU) considered in the sensitivity analysis represent the COUs that resulted in the highest estimates of releases on a daily basis and include scenarios that rely on both industry data and OECD ESDs. Specifically, those COUs are listed below with their respective discussions on risk estimates for surface water and sediment concentrations of HBCD. Risk estimates based on the 10th percentile surface water, pore water, and sediment concentrations are provided in Appendix J, however only the risk estimates based on the 50th percentile predictions are discussed below.

Originally as presented above in Section 4.1.5.2, all nine COUs with estimated water releases containing HBCD were predicted to have production volumes up to 100,000 lbs/yr. The purpose of the sensitivity analysis is to evaluate how the model parameters of production volume and percent of HBCD removed in COUs with direct releases into surface water may impact the predicted surface water and sediment HBCD concentrations. In addition to deriving risk quotients by using predicted surface water and sediment HBCD concentrations based on a production volume of 100,000 lbs/yr, risk quotients were also derived using the production volumes of 50,000 and 25,000 lbs/yr for the three processing COUs: COU #1: *Repackaging of import containers*, COU #2: *Manufacturing of XPS Foam using XPS Masterbatch*, and COU #3: *Manufacturing of EPS Foam from Imported EPS Resin Beads*. COU #1, *Repackaging of Import Containers,* does not have direct releases into surface water, and is thus only evaluated in the sensitivity analysis in regard to potential changes in surface water and sediment concentrations due to production volume differences. The other two processing COUs (Manufacturing of XPS Foam using XPS Masterbatch, and Manufacturing of EPS Foam from Imported EPS Resin Beads) have direct water releases, and with a lack of specific information, were predicted to have 0% removal of HBCD. Due to the physical chemical properties of HBCD, a sensitivity analysis was also conducted to determine whether a greater percentage of HBCD removal (75% removal) during the direct release of HBCD into surface water, would impact predicted surface water and sediment HBCD concentrations for these two COUs. As stated above, the same sources of information regarding the range of daily release rates, emission factors, number of release days per year, and surrounding uncertainties outlined for each COU apply to the same COUs (1, 3, and 5) below.

For two processing COUs (Manufacturing of XPS Foam using XPS Masterbatch, and Manufacturing of EPS Foam from Imported EPS Resin Beads), risk quotients were also calculated based on predicted surface and pore water HBCD concentrations for terrestrial avian and mammalian wildlife. Specifically, two model sub-scenarios for these COUs (3.3 and 5.7) were selected because despite both having predicted direct releases of HBCD into surface water, the water releases vary greatly, with model sub-scenario 5.7 having greater HBCD surface water, pore water and sediment concentrations than 3.3. These sub-scenarios were selected to provide a range in risk estimates that reflect lower and higher water releases of HBCD. The purpose of using KABAM was to estimate HBCD risk to terrestrial organisms that prey on aquatic wildlife.

Processing: Repackaging of Import Containers

Surface Water:
Based on the 7Q10 50th percentile surface water concentration predictions, there was one acute risk estimate that was greater than one (model sub-scenario 1.7) for all three production volumes. In regard to the chronic risk estimates, for production volumes of 100,000 and 50,000 lbs/yr, there are two chronic risk estimates greater than one (model sub-scenario 1.7 and 1.8). Reducing the production volume to 25,000 lbs/yr decreased surface water concentrations of HBCD for model sub-scenario 1.8, resulting in risk estimates less than one for this sub-scenario, however the chronic risk estimate for model sub-scenario 1.7 remained above one for this production volume.

For this COU, reducing the production volume by 75% only resulted in the net loss of one chronic risk estimate (using the 7Q10 50th percentile surface water concentrations).

Sediment:
Corresponding with the higher surface water HBCD concentrations for model sub-scenarios 1.7 and 1.8, for the production volume of 100,000 lbs/yr, the chronic risk estimates based on the 50th percentile sediment HBCD concentrations are also greater than one. All risk estimates are less than one when using the 50th percentile predictions for sediment concentrations of HBCD, based on both the 11- and 128-d half-lives of HBCD, for production volumes of 50,000 and 25,000 lbs/yr.

For this COU, reducing the production volume resulted in removing the two risk estimates that were greater than one, based on the 50th percentile predictions for sediment concentrations of HBCD.

Processing: Manufacturing of XPS Foam using XPS Masterbatch

For this COU, there are predicted releases of water containing HBCD through direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment. In regard to evaluating how production volumes for this COU may change predicted surface water and sediment concentrations of HBCD, the production volumes of 100,000, 50,000 and 25,000 lbs/yr were used. The initial evaluation based on production volume will specifically target all model sub-scenarios within this COU, and for those with direct releases of HBCD into surface water, only the surface water and sediment HBCD concentration predictions based on a 0% removal of HBCD will be discussed (Sensitivity Analysis Based on Production Volume). Model sub-scenarios with direct releases based on 75% removal of HBCD will be discussed in respect to risk estimates based on 0% removal of HBCD further below (Sensitivity Analysis Based on Percent Removal of HBCD from Direct Releases into Surface Water).

Sensitivity Analysis Based on Production Volume:

Surface Water:
Based on the 7Q10 50th percentile surface water concentration predictions for production volumes 50,000 and 25,000 lbs/yr, there are no acute risk estimates that are greater than one, whereas there is one model sub-scenario (3.3) that has an acute risk estimate greater than one based on a production volume of 100,000 lbs/yr. In regard to chronic risk estimates, there are not any model sub-scenarios where the surface water concentrations of HBCD exceeds the chronic COC of 0.417 µg/L (risk estimate is greater than one), for any of the three production volumes. Reducing the production volumes by 50% removed the one acute risk estimate that is greater than one.

Sediment:
All risk estimates are less than one when using the 50th percentile predictions for sediment concentrations of HBCD for all three production volumes based on either the 11- and 128-d half-lives of HBCD.

Sensitivity Analysis Based on Percent Removal of HBCD from Direct Releases into Surface Water:

The four model sub-scenarios with direct releases of HBCD into surface water (3.1-3.4) underwent another level of sensitivity analysis to evaluate how percent removal of HBCD (0 and 75% removal) from the direct release into surface water may change predicted surface water and sediment concentrations of HBCD. Only these model sub-scenarios will be discussed below in regard to how percent removal of HBCD from the direct release of HBCD to surface water will affect risk estimates for organisms primarily inhabiting either surface water or benthic ecosystems.

Surface Water:
In regard to using the 7Q10 50th percentile surface water concentrations of HBCD for a production volume of 100,000 lbs/yr, there was only one acute risk estimate greater than one based on the 0% of HBCD removed from direct releases for model sub-scenario 3.3; there are no acute risk estimates greater than one for either lower production volumes of 50,000 or 25,000 lbs/yr based on 0 or 75% HBCD removal from direct releases.

Sediment:
There are no risk estimates greater than one based on the 7Q10 50th percentile sediment concentrations of HBCD, using either HBCD half-lives for any of the model sub-scenarios with either a 0 or 75% removal of HBCD from direct releases.

Risk Estimates for Terrestrial Organisms:

For all three production volumes, based on the 50th percentile surface water and sediment concentrations, there are no risk estimates greater than one for small and large mink and small river otters. See Appendix J.2.2.

Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads

For this COU, there are predicted releases of water containing HBCD through direct releases of HBCD into surface water, or release through POTWs and onsite wastewater treatment. In regard to evaluating how production volumes for this COU may change predicted surface water and sediment concentrations of HBCD, the production volumes of 100,000, 50,000 and 25,000 lbs/yr were used. The initial evaluation based on production volume will specifically target all model sub-scenarios within this COU, and for those with direct releases of HBCD into surface water, only the surface water and sediment HBCD concentration predictions based on a 0% removal of HBCD will be discussed (Sensitivity Analysis Based on Production Volume). Model sub-scenarios with direct releases based on 75% removal of HBCD will be discussed in respect to risk estimates based on 0% removal of HBCD further below (Sensitivity Analysis Based on Percent Removal of HBCD from Direct Releases into Surface Water).

Sensitivity Analysis Based on Production Volume:

Surface Water:

Based on the 7Q10 50th percentile surface water concentrations of HBCD, there are ten (all model sub-scenarios except 5.5 and 5.11) acute and nine chronic (all model sub-scenarios except for 5.2, 5.5, and 5.11) risk estimates greater than one for the production volume of 100,000 lbs/yr. For the production volume of 50,000 lbs/yr, there are eight (all model sub-scenarios except for 5.5, 5.6, 5.11, and 5.12) acute and nine chronic (all model sub-scenarios except for 5.2, 5.5, and 5.11) risk estimates greater than one. For the production volume of 25,000 lbs/yr, there are six (all model sub-scenarios except for 5.4, 5.5, 5.6, 5.8, 5.11, and 5.12) acute and seven chronic (all model sub-scenarios except for 5.2, 5.5, 5.6, 5.8, and 5.11) risk estimates greater than one. Although reducing the production volume by 50% only reduced the number of acute risk estimates greater than one, reducing the production volume by 75% did result in an overall decrease by four and two acute and chronic risk estimates greater one, respectively.

Model sub-scenario 5.7 has the greatest acute and chronic risk estimates whether the 7Q10 10th or 50th percentile surface water concentrations were used, across all three production volumes. Based on the 7Q10 50th percentile surface water concentrations, the acute and chronic risk estimates were 42 and 12, respectively; despite a 50% or 75% reduction in production volume from 100,000 lbs/yr, the risk estimates for model sub-scenario 5.7 did not change.

Sediment:

Based on the 7Q10 50th percentile sediment concentrations of HBCD, there are eight model sub-scenarios (out of twelve) with risk estimates greater than one (all model sub-scenarios except for 5.2, 5.5, 5.8, and 5.11), for the production volume of 100,000 lbs/yr, using either the 11- or 128-d half-lives of HBCD. For the production volume of 50,000 lbs/yr, the number of risk estimates greater than one based on the 128-d half-life of HBCD is the same for the same model sub-scenarios as those for the production volume of 100,000 lbs/yr, however the number of model sub-scenarios with risk estimates greater than one based on the 11-d half-life of HBCD was reduced by five (all model sub-scenarios except for 5.2,5.3, 5.5, 5.6, 5.8, 5.11, and 5.12). For the production volume of 25,000 lbs/yr, there are three (model sub-scenarios 5.1, 5.7, and 5.9) and six (5.1, 5.3, 5.4, 5.7, 5.9, and 5.10) risk estimates greater than one based on the 11- and 128-d HBCD half-lives, respectively. Reducing the production volume by 50% only resulted in a reduction in risk estimates greater than one based on the 11-d HBCD half-life, and a 75% reduction in production volume reduced the number of risk estimates greater than one by five and two risk estimates based on the 11- and 128-d HBCD half-lives, respectively.

Sensitivity Analysis Based on Percent Removal of HBCD from Direct Releases into Surface Water:

The four model sub-scenarios with direct releases of HBCD into surface water (5.1, 5.4, 5.7, and 5.10) underwent another level of sensitivity analysis to evaluate how percent removal of HBCD (0 and 75% removal) from the direct release into surface water may change predicted surface water and sediment concentrations of HBCD. Only these model sub-scenarios will be discussed below in regard to how percent removal of HBCD from the direct release of HBCD to surface water will affect risk estimates for organisms primarily inhabiting either surface water or benthic ecosystems.

Surface Water:

Based on the 50th percentile surface water HBCD concentration predictions, all four model sub-scenarios with direct releases of HBCD to surface water, have both acute and chronic risk estimates

greater than one using both 0 and 75% removal, except for sub-scenario 5.4, which does not have an acute risk estimate greater than one based on 75% removal. There is a similar trend with a production volumes of 50,000 and 25,000 lbs/yr, where sub-scenarios 5.1 and 5.7 still have acute and chronic risk estimates greater than one using both 0 and 75% removal, however both sub-scenarios 5.4 and 5.10 do not have acute risk estimates greater than one based on 75% removal. Reducing the production volume does not significantly impact the number of risk estimates greater than one, however reducing HBCD surface water concentrations by increasing HBCD removal only impacted acute risk estimates for two sub-scenarios.

Sediment:
Based on the 50th percentile sediment HBCD concentration predictions, for all four model sub-scenarios with direct releases of HBCD to surface water, there are risk estimates greater than one based on both 0 and 75% removal of HBCD for the production volume of 100,000 lbs/yr, using either the 11- or 128-d HBCD half-lives. Likewise, for all four model sub-scenarios, there are only risk estimates greater than one based on 75% removal of HBCD for the production volume of 100,000 lbs/yr using the 128-d HBCD half-life. In regard to the production volume of 50,000 lbs/yr, only model sub-scenario 5.7 has a risk estimate greater than one based on 75% removal of HBCD, using the 128-d half-life. For the production volume of 25,000 lbs/yr, only model sub-scenarios 5.1 and 5.7 have risk estimates greater than one (using both half-lives) and sub-scenarios 5.4 and 5.10 only have risk estimates greater than one (using the 128-d half-life) based on 0% removal; there are no risk estimates greater than one for any of the model sub-scenarios for this COU based on 75% removal. Increasing the amount of HBCD removed from direct releases into surface water does reduce the amount of risk estimates greater than one within each production volume, but it isn't until the production volume is reduced by 75% that there not any risk estimates greater than one using a 75% removal of HBCD.

Risk Estimates for Terrestrial Organisms:
For all three production volumes, based on the 50th percentile surface water and sediment concentrations, there are risk estimates greater than one for small and large mink, and small river otters (9 out of 15 risk estimates). See Appendix J.2.3.

4.2 Human Health Risk

4.2.1 Risk Estimation Approach

The use scenarios, populations of interest and toxicological endpoints used for acute and chronic exposures are presented in Table 4-8.

Table 4-8. Use Scenarios, Populations of Interest and Toxicological Endpoints Used for Acute and Chronic Exposures

Population of Interest and Exposure Scenario	***Workers:*** Acute- Adult worker (>21 years old) and female workers of reproductive age (>16 year to less than 50 years old) exposed to HBCD for a single 8-hr exposure Chronic- Adult worker (>21 years old) and female workers of reproductive age (>16 year to less than 50 years old) exposed to HBCD for the entire 8-hr workday for 260 days per year for 40 working years ***Occupational Non-User:*** Acute or Chronic- Adult worker (>21 years old) and female workers of reproductive age (>16 year to less than 50 years old) exposed to HBCD indirectly by being in the same work area of the building ***General Population (Background Exposure):*** Acute or Chronic- Infant, Young Toddler, Toddler, Small Child, Child, Teen, Adult ***Highly Exposed Population (Near-Facility):*** Acute or Chronic- Infant, Young Toddler, Toddler, Small Child, Child, Teen, Adult
Health Effects, Concentration and Time Duration	***Units for Non-Cancer Point of Departures (POD)*:** mg/kg-day ***Non-Cancer Health Effects:*** [2] Acute- Developmental effects (pup body weight and offspring loss) Chronic- Thyroid hormone effects, liver effects, reproductive effects (increased incidence of non-pregnancy and decreased primordial follicles), developmental effects (reduced pup body weight and increased offspring loss)
Uncertainty Factors (UF) used in Non-Cancer Margin of Exposure (MOE) calculations	***Benchmark MOEs:*** Vary by endpoint ***Benchmark MOE*** [3] = (UF_S) x (UF_A) x (UF_H) x (UF_L)

[1]Adult workers (>21 years old) include both female and male workers.
[2] Female workers of reproductive age (>16 to less than 50 years old) are the population of interest for reproductive and developmental effects. For other health effects (e.g., liver, kidney, etc.), female or male workers were assumed to be the population of interest. Estimation of the risk was calculated for each group based on differences in body weight as described in the Exposure Factors Handbook (U.S. EPA, 2011b).
[3] UF_S=subchronic to chronic UF; UF_A=interspecies UF; UF_H=intraspecies UF; UF_L=LOAEL to NOAEL UF

The EPA uses a Margin of Exposure (MOE) approach to assessing non-cancer risk. The MOE is the ratio of the point of departure (POD) dose divided by the human exposure dose. The MOE is compared to the benchmark MOE. The MOE estimate was interpreted as human health risk if the MOE estimate was less than the benchmark MOE (i.e., the total UF). On the other hand, the MOE estimate indicated negligible concerns for adverse human health risks if the MOE estimate exceeded the benchmark MOE.

Acute or chronic MOEs (MOE_{acute} or $MOE_{chronic}$) were used in this assessment to estimate non- cancer risks using Equation 4-1.

Equation 4-1 Equation to Calculate Non-Cancer Risks Following Acute or Chronic Exposures Using Margin of Exposures

$$MOE_{acute\ or\ chronic} = \frac{Non-cancer\ Hazard\ value\ (POD)}{Human\ Exposure}$$

Where:

MOE	= Margin of exposure (unitless)
Hazard Value (POD)	= HED (mg/kg)
Human Exposure	= Exposure estimate (in mg/kg) from occupational exposure assessment = Exposure estimate (in mg/kg) from general population and highly exposed population exposure assessment

Acute Absorbed Dose rates (AADs) were used to calculate occupational non-cancer risks following acute exposure and Chronic Absorbed Doses (CADs) were used for occupational non-cancer risks following chronic exposure (see Section 2.4.1 for description). Acute Dose Rates (ADRs) were used to calculate non-cancer risks to the general population following acute exposure (see Section 2.4.2 for description and equations by media type).

EPA used margin of exposures (MOEs)[16] to estimate acute or chronic risks for non-cancer based on the following:

1. the lowest HEDs within each non-cancer health effects domain reported in the literature;
2. the endpoint/study-specific UFs applied to the HEDs per the EPA Guidance (U.S. EPA, 2002a); and
3. the exposure estimates calculated for HBCD uses examined in this risk assessment (see *Section 3 Exposures*).

MOEs allow for the presentation of a range of non-cancer risk estimates. The occupational exposure scenarios considered both acute and chronic exposures. For general population (background) risks only chronic exposure scenarios were considered, while for highly exposed population (living near a facility) both acute and chronic exposures were considered. Risks to the highly exposed population were associated with specific COUs and exposure scenarios, while general population exposures represented baseline steady-state exposures from persistent HBCD in environmental media. Different adverse endpoints were used based on the expected exposure durations. For non-cancer effects, risks for developmental effects were evaluated for acute (short-term) exposures, whereas risks for other adverse effects (toxicity to the thyroid, liver, developmental effects, and the female reproductive system) were evaluated for repeated (chronic) exposures to HBCD. For occupational exposure calculations, mg/kg values were used to calculate MOEs for risk estimates following acute and chronic exposures.

The total UF for each non-cancer POD was the benchmark MOE used to interpret the MOE risk estimates for each use scenario. The MOE estimate was interpreted as a potential human health risk if the MOE estimate was less than the benchmark MOE (i.e. the total UF). On the other hand, the MOE estimate indicated negligible concerns for adverse human health effects if the MOE estimate exceeded

[16] Margin of Exposure (MOE) = (Non-cancer hazard value, POD) ÷ (Human Exposure). Equation 4-1. The benchmark MOE is used to interpret the MOEs and consists of the total UF as described in Section 3.2.5.3.

the benchmark MOE. Typically, the larger the MOE, the more unlikely it is that a non-cancer adverse effect would occur.

Risk estimates in the form of MOE values were calculated for all of the studies per health effects domain that EPA considered suitable for the risk evaluation of acute and chronic exposure scenarios in the risk evaluation for HBCD. The studies selected for dose-response assessment and derivation of PODs examined oral administration of HBCD. These PODs are directly applicable to risks from oral exposures such as via soil, drinking water, and diet. For inhalation exposure, EPA considered the quantification of incidental ingestion of particulates that would result from exposure to HBCD dust in occupational, environmental, or residential settings. It is assumed that any inhaled particulate would either be absorbed through the lungs or swallowed and subsequently absorbed in the GI tract. Based on available toxicokinetic data, EPA conservatively assumes 100% absorption through the lungs and GI tract. EPA is not estimating risks for any respiratory-specific hazards associated with HBCD exposure. Since all HBCD hazards evaluated through dose-response analysis involve systemic toxicity, it is irrelevant for the purposes of this assessment whether HBCD is absorbed through the lungs or GI tract. Therefore, EPA used total inhalation exposure values (as opposed to only respirable) for risk estimation.

For dermal exposure, EPA performed route-to-route extrapolation from oral toxicity based on similar principles to those described in the EPA Guidance Document *Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment)* (U.S. EPA, 2004). All risk calculations for dermal exposure incorporate an adjustment for 6.5% absorption, based on available toxicokinetic data (see Section 3.2.2).

Risk estimates are shown for the representative POD of each health domain following acute or chronic exposure, as shown below. As described above in Section 3.2.5.2.1, developmental toxicity outcomes may result from a single acute exposure during a critical window of development. Given this, the most relevant lifestage in the human population would be women of child-bearing age. However, due to uncertainty in the mode of action for HBCD developmental toxicity (e.g. are outcomes only due to effects on the unborn fetus in utero or could they result from permanent damage to eggs) and the possibility of a bioaccumulative effect following a future acute exposure, risks for developmental toxicity were characterized for all lifestages.

4.2.2 Risk Estimation for Workers

The tables and narratives below describe the conclusions of the risk estimation via inhalation or dermal exposure for each use scenario following acute or chronic exposures. Risks were calculated for average adult workers as well as for women of reproductive age. Results presented below are for average adult workers. MOEs are approximately 10% lower for women of reproductive age compared to average adult workers, and differences in risk conclusions are identified in the tables and risk characterization narratives when applicable. MOEs are provided for scenarios in which risk conclusions differ between average adult workers and women of reproductive age. For a complete list of all evaluated risk estimations, see [*Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental File: Occupational Exposure and Environmental Releases Calculations. (U.S. EPA, 2019a)*]. EPA notes that OSHA recommends employers apply the hierarchy of controls as discussed in Section 2.4.1.1 which first prioritizes elimination, substitution, engineering and administrative controls, and then if not feasible to address the hazard, the implementation of a respiratory protection program. Adjusted MOEs were not calculated based on glove protection because EPA does not expect any level of dermal exposure to HBCD following proper use of gloves impervious to HBCD. As discussed in Section 2.4.1.1, impervious gloves, if worn on clean hands and replaced when contaminated or compromised, are expected to provide employees with protection from HBCD. HBCD is a solid particulate and would not

be expected to permeate through gloves (unlike certain solvents). Some examples of impervious gloves are nitrile, butyl rubber, polyvinyl chloride, and polychloroprene. EPA did not identify any data or applicable model that can be used to estimate inhalation exposure to particulates for ONUs. EPA expects the exposures to ONUs to be lower than those for workers.

4.2.2.1 Risk Estimation for Non-Cancer Effects Following Acute Inhalation Exposures – Occupational Scenarios

Risks to workers were estimated for non-cancer effects following acute inhalation exposures. Table 4-9 displays MOE values for all occupational scenarios and human health hazards associated with acute exposure, including results assuming either respiratory protection of APF = 5 or APF = 10. Risks were not identified for any scenario assuming respiratory protection of APF = 5 or greater.

Table 4-9. Risk Estimation for Non-Cancer Effects Following Acute Inhalation Exposures, Occupational Scenarios (bold indicates calculated MOE < benchmark MOE)

Occupational Scenario – Inhalation Exposure	Margin of Exposure (MOE) [Benchmark MOE = 100]											
	POD_{HED} (mg/kg) = 9.03 Developmental Toxicity F2 offspring loss (Ema et al., 2008)						**POD_{HED} (mg/kg) = 89.6 Developmental Toxicity** Decreased F2 neonatal weight (Ema et al., 2008)					
	High End Exposure			**Central Tendency Exposure**			**High End Exposure**			**Central Tendency Exposure**		
	No Protection	**APF = 5**	**APF = 10**	**No Protection**	**APF = 5**	**APF = 10**	**No Protection**	**APF = 5**	**APF = 10**	**No Protection**	**APF = 5**	**APF = 10**
Processing: Repackaging of Import Containers	**38**	191	382	**81**	406	812	379	1896	3793	805	4027	8054
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	**29**	144	289	**58**	289	578	287	1434	2867	573	2867	5734
Processing: Manufacturing of XPS Foam Using XPS Masterbatch	328	1642	3284	903	4515	9030	3258	16291	32582	8960	44800	89600
Processing: Manufacturing of XPS Foam Using HBCD Powder	**29**	144	289	**58**	289	578	287	1434	2867	573	2867	5724
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads	328	1642	3284	903	4515	9030	3258	16291	32582	8960	44800	89600
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam	328	1642	3284	903	4515	9030	3258	16291	32582	8960	44800	89600
Use: Installation of Automobile Replacement Parts	--	--	--	--	--	--	--	--	--	--	--	--
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	328	1642	3284	903	4515	9030	3258	16291	32582	8960	44800	89600
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	241	1204	2408	688	3440	6880	2389	11947	23893	6827	34133	68267
Processing: Recycling of EPS Foam	328	1642	3284	903	4515	9030	3258	16291	32582	8960	44800	89600
Processing: Formulation of Flux / Solder Paste	**29**	144	289	**58**	289	578	287	1434	2867	573	2867	5724
Use of Flux / Solder Paste	**--**	--	--	--	--	--	--	--	--	--	--	--

Note: As discussed in Section 2.4.1.1 EPA expects potential inhalation exposure of an Occupational Non-User (ONU) in the case of some of the conditions of use but EPA did not assess these exposures due to lack of data. EPA expects these exposures to be lower than the exposures of the corresponding workers.
Note: Bold text indicates MOE is less than the benchmark MOE. Non-bold text indicates the MOE is greater than the benchmark MOE . -- indicates that exposures are not expected during this COU.

Estimation of the risk is below the benchmark MOE without respiratory protection at both HE and CT exposure levels for four COUs: *Repackaging of Import Containers, Compounding of Polystyrene Resin to Produce XPS Masterbatch, Manufacturing of XPS Foam using HBCD Powder, and Formulation of Flux/Solder Paste*. Estimation of the risk for all other COUs is above the benchmark MOE for any exposure level or endpoint.

4.2.2.2 Risk Estimation for Non-Cancer Effects Following Chronic Inhalation Exposures – Occupational Scenarios

Risks to workers were calculated for non-cancer effects following chronic inhalation exposures. Table 4-10 displays MOE values for all occupational scenarios and human health hazards associated with chronic exposure, including results assuming either respiratory protection of APF =10 and APF = 50. Risks were not identified for any scenario assuming respiratory protection of APF =50 or greater.

Table 4-10. Risk Estimation for Non-Cancer Effects Following Chronic Inhalation Exposures in Occupational Scenarios (bold indicates calculated MOE> benchmark MOE)

Occupational Scenario – Inhalation Exposure	MARGIN OF EXPOSURE (MOE)																	
	Benchmark MOE = 300			**Benchmark MOE = 1000**			**Benchmark MOE = 30**			**Benchmark MOE = 30**			**Benchmark MOE = 100**			**Benchmark MOE = 100**		
	POD_{HED} (mg/kg) = 1.68 Thyroid Effects Decreased T4 (Ema et al., 2008)			**POD_{HED} (mg/kg) = 24 Liver Toxicity** Increased relative liver weight and vacuolization (WIL Research., 2001)			**POD_{HED} (mg/kg) = 0.689 Female Reproductive Toxicity** Reduced primordial follicles (Ema et al., 2008)			**POD_{HED} (mg/kg) = 5.45 Female Reproductive Toxicity** Increased incidence of non-pregnancy (Ema et al., 2008)			**POD_{HED} (mg/kg) = 9.03 Developmental Toxicity** F2 offspring loss (Ema et al., 2008)			**POD_{HED} (mg/kg) = 89.6 Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)		
	None[1]	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**
Processing: Repackaging of import containers (HE)	**10**	**104**	519	**148**	1483	7416	**4**	43	213	34	337	1684	**56**	558	2790	554	5537	27686
Processing: Repackaging of import containers (CT)	**39**	394	1969	**562**	5624	28122	**16**	161	807	128	1277	6386	212	2116	10581	2100	20998	104989
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch (HE)	**33**	327*	1635	**467**	4672	23360	**13**	134	671	106	1061	5305	176	1758	8789	1744	17442	87211
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch (CT)	**112**	1121	5606	1602	16018	80091	46	460	2299	364	3637	18187	603	6027	30134	5980	59802	299008
Processing: Manufacturing of XPS Foam Using XPS Masterbatch (HE)	1394	13936	69682	19909	199091	995455	572	5716	28578	4521	45210	226051	7491	74908	374540	74327	743273	3716364
Processing: Manufacturing of XPS Foam Using XPS Masterbatch (CT)	6813	68133	340667	97333	973333	4866667	2794	27943	139714	22103	221028	1105139	36622	366217	1831083	363378	3633778	18168889
Processing: Manufacturing of XPS Foam Using HBCD Powder (HE)	**123**	1226	6132	1752	17520	87600	50	503	2515	398	3979	19893	659	6592	32960	6541	65408	327040
Processing: Manufacturing of XPS Foam Using HBCD Powder (CT)	436	4361	21803	6229	62293	311467	179	1788	8942	1415	14146	70729	2344	23438	117189	23256	232562	1162809
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads (HE)	**159**	1593	7964	2275	22753	113766	65	653	3266	517	5167	25834	856	8561	42805	8495	84945	424727

Occupational Scenario – Inhalation Exposure	MARGIN OF EXPOSURE (MOE)																	
	Benchmark MOE = 300			Benchmark MOE = 1000			Benchmark MOE = 30			Benchmark MOE = 30			Benchmark MOE = 100			Benchmark MOE = 100		
	POD_{HED} (mg/kg) = 1.68 **Thyroid Effects** Decreased T4 (Ema et al., 2008)			POD_{HED} (mg/kg) = 24 **Liver Toxicity** Increased relative liver weight and vacuolization (WIL Research., 2001)			POD_{HED} (mg/kg) = 0.689 **Female Reproductive Toxicity** Reduced primordial follicles (Ema et al., 2008)			POD_{HED} (mg/kg) = 5.45 **Female Reproductive Toxicity** Increased incidence of non-pregnancy (Ema et al., 2008)			POD_{HED} (mg/kg) = 9.03 **Developmental Toxicity** F2 offspring loss (Ema et al., 2008)			POD_{HED} (mg/kg) = 89.6 **Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)		
	None[1]	APF = 10	APF = 50	None	APF = 10	APF = 50	None	APF = 10	APF = 50	None	APF = 10	APF = 50	None	APF = 10	APF = 50	None	APF = 10	APF = 50
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads (CT)	786	7862	39308	11231	112308	561538	322	3224	16121	2550	25503	127516	4226	42256	211279	41928	419282	2096410
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam (HE)	**89**	892	4460	1274	12742	63709	37	366	1829	289	2893	14467	856	8561	42805	8495	84945	424727
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam (CT)	461	4611	23053	6586	65865	329323	189	1891	9454	1496	14957	74784	4226	42256	211279	41928	419282	2096410
Use: Installation of Automobile Replacement Parts (HE)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Use: Installation of Automobile Replacement Parts (CT)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures (HE)	**89**	892	4460	1274	12742	63709	37	366	1829	289	2893	14467	479	4794	23971	4757	47569	237847
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures (CT)	487	4867	24333	6952	69524	347619	200	1996	9980	1579	15788	78938	2616	26158	130792	25956	259556	1297778
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures (HE)	**65**	654	3270	**934**	9344	46720	**27**	268	1341	212	2122	10609	352	3516	17578	3488	34884	174421

Occupational Scenario – Inhalation Exposure	MARGIN OF EXPOSURE (MOE)																	
	Benchmark MOE = 300			**Benchmark MOE = 1000**			**Benchmark MOE = 30**			**Benchmark MOE = 30**			**Benchmark MOE = 100**			**Benchmark MOE = 100**		
	POD_{HED} (mg/kg) = 1.68 Thyroid Effects Decreased T4 (Ema et al., 2008)			**POD_{HED} (mg/kg) = 24 Liver Toxicity** Increased relative liver weight and vacuolization (WIL Research., 2001)			**POD_{HED} (mg/kg) = 0.689 Female Reproductive Toxicity** Reduced primordial follicles (Ema et al., 2008)			**POD_{HED} (mg/kg) = 5.45 Female Reproductive Toxicity** Increased incidence of non-pregnancy (Ema et al., 2008)			**POD_{HED} (mg/kg) = 9.03 Developmental Toxicity** F2 offspring loss (Ema et al., 2008)			**POD_{HED} (mg/kg) = 89.6 Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)		
	None[1]	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**	**None**	**APF = 10**	**APF = 50**
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures (CT)	371	3708	18540	5297	52971	264853	152	1521	7603	1203	12029	60144	1993	19930	99651	19776	197757	988783
Processing: Recycling of EPS Foam (HE)	**159**	1593	7964	2275	22753	113766	65	653	3266	517	5167	25834	856	8561	42805	8495	84945	424727
Processing: Recycling of EPS Foam (CT)	864	8637	43183	12338	123380	616901	354	3542	17710	2802	28018	140088	4642	46422	232109	46062	460620	2303099
Processing: Formulation of Flux / Solder Paste (HE)	**8**	**78**	392	**112**	1121	5606	**3**	32	161	**25**	255	1273	**42**	422	2109	419	4186	20931
Processing: Formulation of Flux / Solder Paste (CT)	**31**	307*	1533	**438**	4380	21900	**13**	126	629	99	995	4973	165	1648	8240	1635	16352	81760
Use of Flux / Solder Paste (HE)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Use of Flux / Solder Paste (CT)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Note: As discussed in Section 2.4.1.1 EPA expects potential inhalation exposure of an Occupational Non-User (ONU) in the case of some of the conditions of use but EPA did not assess these exposures due to lack of data. EPA expects these exposures to be lower than the exposures of the corresponding workers.
Note: Bold text indicates MOE is less than the benchmark MOE. Non-bold/non-shaded text indicates the MOE is greater than the benchmark MOE. HE = High End exposure level; CT = Central Tendency exposure level; -- indicates that exposures are not expected during this COU.
"None" refers to respiratory protection.
Note: * indicates that risks are identified for women of reproductive age only. See text below for details.

Estimation of the risk is below the benchmark MOE without respiratory protection (for at least the HE exposure level) for every COU except: *Manufacturing of XPS Foam Using XPS Masterbatch.* Inhalation risks were not estimated for the following COUs because worker inhalation exposures are not expected: *Installation of Automobile Replacement Parts* and *Use of Flux/Solder Paste*.

4.2.2.3 Risk Estimation for Non-Cancer Effects Following Acute Dermal Exposures – Occupational Scenarios

Risks to workers were calculated for non-cancer effects following acute dermal exposures, assuming 6.5% systemic absorption (see Section 3.2.2). Table 4-11 displays MOE values for all occupational scenarios and human health hazards associated with acute exposure. As mentioned above, adjusted MOEs were not calculated based on glove protection because EPA does not expect any level of dermal exposure to HBCD following proper use of impervious gloves.

Table 4-11. Risk Estimation for Non-Cancer Effects Following Acute Dermal Exposures (bold indicates calculated MOE < benchmark MOE)

Occupational Scenario – Dermal Exposure	Margin of Exposure (MOE) [Benchmark MOE = 100]	
	POD_{HED} (mg/kg) = 9.03 **Developmental Toxicity** F2 offspring loss (Ema et al., 2008)	**POD_{HED} (mg/kg) = 89.6** **Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)
	Worker MOE	**Worker MOE**
Processing: Repackaging of import containers	**4**	**36**
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	**4**	**36**
Processing: Manufacturing of XPS Foam Using XPS Masterbatch	**5**	**51**
Processing: Manufacturing of XPS Foam Using HBCD Powder	**4**	**36**
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads	--	--
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam	--	--
Use: Installation of Automobile Replacement Parts	--	--
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	--	--
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	--	--
Processing: Recycling of EPS Foam	--	--
Processing: Formulation of Flux / Solder Paste	**4**	**36**
Use of Flux / Solder Paste	1010	10025

Note: As discussed in Section 2.4.1, there was no data to assess Occupational Non-User (ONU) exposures.
Note: Bold text indicates MOE is less than the benchmark MOE. Non-bold text indicates the MOE is greater than the benchmark MOE . -- Indicates that exposures are not expected during this COU.

Estimation of the risk is below the benchmark MOE without glove protection for every COU with expected dermal exposures except *Use of Flux/Solder Paste*. Dermal risks were not estimated for COUs in which dermal exposures are not expected.

4.2.2.4 Risk Estimation for Non-Cancer Effects Following Chronic Dermal Exposures – Occupational Scenarios

Risks to workers were calculated for non-cancer effects following chronic dermal exposures. Table 4-12 displays MOE values for all occupational scenarios and human health hazards associated with chronic exposure. As mentioned above, adjusted MOEs were not calculated based on glove protection because EPA does not expect any level of dermal exposure to HBCD following proper use of impervious gloves.

Table 4-12. Risk Estimation for Workers - Non-Cancer Effects Following Chronic Dermal Exposures in Occupational Scenarios (bold indicates calculated MOE < benchmark MOE)

Occupational Scenario – Dermal Exposure	MARGIN OF EXPOSURE (MOE)											
	Benchmark MOE = 300		**Benchmark MOE = 1000**		**Benchmark MOE = 30**		**Benchmark MOE = 30**		**Benchmark MOE = 100**		**Benchmark MOE = 100**	
	POD_{HED} (mg/kg) = 1.68 **Thyroid Effects** Decreased T4 (Ema et al., 2008)		**POD_{HED} (mg/kg) = 24** **Liver Toxicity** Increased relative liver weight and vacuolization (WIL Research., 2008)		**POD_{HED} (mg/kg) = 0.689** **Female Reproductive Toxicity** Reduced primordial follicles (Ema et al., 2008)		**POD_{HED} (mg/kg) = 5.45** **Female Reproductive Toxicity** Increased incidence of non-pregnancy (Ema et al., 2008)		**POD_{HED} (mg/kg) = 9.03** **Developmental Toxicity** F2 offspring loss (Ema et al., 2008)		**POD_{HED} (mg/kg) = 89.6** **Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)	
	High End	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**
Processing: Repackaging of import containers	**1 (1.0)**	**2 (1.7)**	**14**	**25**	**0 (0.4)**	**(0.7)**	**3**	**6**	**5**	**9**	**52**	**93**
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	**4**	**7**	**58**	**99**	**2**	**3**	**13**	**23**	**22**	**37**	216	371
Processing: Manufacturing of XPS Foam Using XPS Masterbatch	**22**	**39**	**311**	**552**	**9**	**16**	71	125	117	208	1159	2061
Processing: Manufacturing of XPS Foam Using HBCD Powder	**15**	**27**	**217**	**386**	**6**	**11**	49	88	**82**	145	812	1443
Processing: Manufacturing of EPS Foam Using Imported EPS Resin Beads	--	--	--	--	--	--	--	--	--	--	--	--
Processing: Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam	--	--	--	--	--	--	--	--	--	--	--	--
Use: Installation of Automobile Replacement Parts	--	--	--	--	--	--	--	--	--	--	--	--
Use: Installation of EPS/XPS Foam Insulation in Residential, Public and	--	--	--	--	--	--	--	--	--	--	--	--

Occupational Scenario – Dermal Exposure	MARGIN OF EXPOSURE (MOE)											
	Benchmark MOE = 300		**Benchmark MOE = 1000**		**Benchmark MOE = 30**		**Benchmark MOE = 30**		**Benchmark MOE = 100**		**Benchmark MOE = 100**	
	POD_{HED} (mg/kg) = 1.68 **Thyroid Effects** Decreased T4 (Ema et al., 2008)		**POD_{HED} (mg/kg) = 24** **Liver Toxicity** Increased relative liver weight and vacuolization (WIL Research., 2008)		**POD_{HED} (mg/kg) = 0.689** **Female Reproductive Toxicity** Reduced primordial follicles (Ema et al., 2008)		**POD_{HED} (mg/kg) = 5.45** **Female Reproductive Toxicity** Increased incidence of non-pregnancy (Ema et al., 2008)		**POD_{HED} (mg/kg) = 9.03** **Developmental Toxicity** F2 offspring loss (Ema et al., 2008)		**POD_{HED} (mg/kg) = 89.6** **Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)	
	High End	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**	**High End**	**Central Tendency**
Commercial Buildings, and Other Structures												
Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	--	--	--	--	--	--	--	--	--	--	--	--
Processing: Recycling of EPS Foam	--	--	--	--	--	--	--	--	--	--	--	--
Processing: Formulation of Flux / Solder Paste	**1 (1.0)**	**2 (1.9)**	**14**	**27**	**0 (0.4)**	**1 (0.8)**	**3**	**6**	**5**	**10**	**52**	101*
Use of Flux / Solder Paste	**274**	540	3921	7718	113	222	890	1753	1475	2904	14637	28813

Note: As discussed in Section 2.4.1, there was no data to assess Occupational Non-User (ONU) exposures.
Note: Bold text indicates MOE is less than the benchmark MOE. Non-bold indicates the MOE is greater than the benchmark MOE .
Note: -- indicates that exposures are not expected during this use scenario.
Note: * indicates that risks are identified for women of reproductive age only. See text below for details.

Estimation of the risk is below the benchmark MOE without glove protection for every COU with expected dermal exposures at both HE and CT exposure levels except *Use of Flux/Solder Paste*. For that COU, estimation of the risk is below the benchmark MOE only at HE exposure levels. Dermal risks were not estimated for COUs in which dermal exposures are not expected.

4.2.3 Risk Estimation for General Population and Highly Exposed Population

4.2.3.1 Risk Estimation for Non-Cancer Effects – General Population (Background Exposure)

Risks were estimated for the general population, representing steady-state chronic risks from sustained background exposure in the environment due to HBCD persistence. In this assessment, general population is considered to be individuals who are not expected to live close to point sources and are not expected to have HBCD articles in their home. HBCD exposures to the general population are highly variable and are influenced by both sources into the environment and degradation and removal from the environment. Estimates of general population exposures based on environmental monitoring and biomonitoring data represent the conditions present at the time the data was collected. It is unknown which combination of potential sources associated with conditions of use as described in this risk assessment contribute to the monitoring data presented here. However, given the wide range of exposures shown within and across the monitoring data, there is a plausible contribution from some of the sources/conditions of use described within this document. These exposure estimates serve as a baseline onto which any COU-specific modeled releases will be added.

General population risk estimates are not specific to a particular use scenario, as they account for steady-state background exposure in the environment independent of any specific release. Therefore, only risks for chronic exposures are applicable. The MOE tables below represent risks to aggregate steady-state HBCD exposure, combining dust, soil, indoor air, diet, and dermal pathways. See Section 2.4.2 for a more detailed explanation of these exposure pathways. Table 4-13 presents the MOEs for general population risks at both central tendency and high end exposure levels.

Table 4-13. Risk Estimation for Non-Cancer Effects – General Population

Aggregate Pathway Exposure – Central Tendency AGE GROUP	Benchmark MOE = 300 POD_{HED} (mg/kg) = 1.68 **Thyroid Effects** Decreased T4 (Ema et al., 2008)		Benchmark MOE = 1000 POD_{HED} (mg/kg) = 24 **Liver Toxicity** Increased relative liver weight and vacuolization (WIL Research, 2001)		Benchmark MOE = 30 POD_{HED} (mg/kg) = 0.689 **Female Reproductive Toxicity** Reduced primordial follicles (Ema et al., 2008)		Benchmark MOE = 30 POD_{HED} (mg/kg) = 5.45 **Female Reproductive Toxicity** Increased incidence of non-pregnancy (Ema et al., 2008)		Benchmark MOE = 100 POD_{HED} (mg/kg) = 9.03 **Developmental Toxicity** F2 offspring loss (Ema et al., 2008)		Benchmark MOE = 100 POD_{HED} (mg/kg) = 89.6 **Developmental Toxicity** Decreased F2 pup weight (Ema et al., 2008)	
	CT	HE	CT	HE	CT	HE	CT	HE	CT	HE	CT	HE
Infant (<1 year)	51752	3939	739312	56272	21224	1615	167885	12779	278166	21172	2760098	210084
Young Toddler (1-<2 years)	44767	4950	639534	70708	18360	2030	145227	16057	240625	26604	2387592	263976
Toddler (2-<3 years)	78041	6001	1114871	85731	32006	2461	253169	19468	419470	32256	4162186	320061
Small Child (3-<6 years)	106318	8111	1518829	115873	43603	3327	344901	26313	571459	43597	5670295	432593
Child (6-<11 years)	174088	12893	2486975	184192	71397	5288	564751	41827	935724	69302	9284707	687649
Teen (11-<16 years)	385668	26213	5509544	374465	158170	10750	1251126	85035	2072966	140892	20568965	1398001
Adult (16-<70 years)	530649	35356	7580705	505089	217629	14500	1721452	114697	2852240	190040	28301298	1885665

Note: Exposures = dust + soil + indoor air + diet + dermal; CT = central tendency exposure, HE = high end exposure
Note: Non bold/ non shaded text indicates the MOE is greater than the benchmark MOE.

Estimation of the risk is above the benchmark MOE for any hazard across all age groups for the general population, assuming both central tendency and high end exposure estimates. MOEs were not within 10x of the benchmark MOE for any health endpoint and therefore HBCD is not expected to present risk to the general population not living near (within 100 meters) from any point source of HBCD release.

4.2.3.2 Risk Estimation for Non-Cancer Effects – Highly Exposed Populations (Near-Facility)

Risks were calculated for the highly exposed general population, representing populations living near a point source of HBCD release (at the fenceline, estimated as 100 meters from the point source). For simplicity, the tables below present risks considering acute or chronic exposure via fish ingestion, inhalation, and additional exposure pathways using the most sensitive POD for either acute or chronic exposure scenarios. MOEs for all other hazards would be higher than the presented values. Exposure via fish ingestion is the primary driver for any risks identified to the highly exposed general population, except for infants whom are not anticipated to ingest fish in their diet. Infants would be uniquely exposed through breast milk, with the received dose dependent on the body burden of the mother.

As discussed in Section 3.2.5.2.1, both reduced pup body weight and offspring loss were considered as relevant hazard for evaluating risks following acute exposure. There is substantial uncertainty whether a single exposure can produce a permanent adverse effect on postnatal mortality or body weight. EPA determined that the sustained persistence of HBCD in human tissue suggests that a single exposure could have sustained effects. EPA evaluated risks for offspring loss for all lifestages, including those below reproductive age. While developmental effects would not be expected to present in younger lifestages, the bioaccumulation and persistence of HBCD in tissues suggests that initial exposure at an earlier age could result in effects later in life. Additionally, it is unknown whether developmental effects on neonates could also present in young exposed children. Therefore despite the uncertainties, neonatal mortality and body weight reduction were considered potentially applicable to acute exposures at all lifestages, however developmental toxicity to teenagers and adults would be of highest concern.

The MOE tables for fish ingestion and inhalation incorporate summed exposures from representative fish ingestion or air inhalation exposure and aggregate central tendency general population exposure (representing background exposure). Background exposure estimates were adjusted from the overall general population exposure values to remove the route of interest (e.g. fish ingestion or air inhalation). EPA evaluated exposures for each condition of use (COU) assuming several differing release scenarios (see Table 2-49 and Table 2-50). MOE tables in Section 4.2.3.2 present risks for two exposure sub-scenarios under each COU, including both the scenario resulting in the highest exposure and a representative moderate exposure level.

EPA is unable to model estimations of breast milk ingestion for infants associated with a condition of use, so exposures are based on monitoring data. Dietary risk estimation for highly exposed infants was therefore based on high-end general population exposure values (applicable to chronic exposures only). EPA additionally estimated risk for two scenarios from exposure to HBCD via consumer articles. MOE tables for these scenarios incorporated the sum of cumulative dust and air exposure and background general population exposure (with general population dust and air values removed). Risk estimates are also provided for chronic exposure to HBCD via mouthing of plastic articles containing HBCD.

EPA assessed risks to the highly exposed population following acute or chronic exposures independently, however these do not necessarily represent independent populations. An individual living near a facility would have both acute and chronic exposures to HBCD over time. Only short term residents or visitors would experience acute but not chronic exposures.

4.2.3.2.1 Risk Estimation for Non-Cancer Effects Following Acute Exposures – Highly Exposed Populations

Risks to the highly exposed population were calculated for non-cancer effects following acute exposures based on fish ingestion and inhalation.

Risks via Fish Ingestion / Dietary Exposure

Risks were not estimated for the following COUs via dietary exposure because releases were not identified, or associated exposures were not quantified:

- *Installation of Automobile Replacement Parts*
- *Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures*
- *Formulation of Flux / Solder Paste*

A description of all subscenarios for fish ingestion exposure can be found in Table 2-49.

Highly Exposed Population

Infants

Infants are not expected to ingest fish in their diet (U.S. EPA, 2011b) (as discussed in Section 2.4.2.1). Therefore, dietary risks to highly exposed infants were estimated based on high end general population exposure values, which incorporates breast milk in its dietary component as well as high-end estimates of dust, dermal, air, and soil exposure. Infant risks are based on steady-state exposures estimated via biomonitoring and are not associated with a particular condition of use. Similar to the risk estimation for general population, the risk estimation for highly exposed infants is therefore only relevant to chronic exposures. Therefore, risks were not estimated for highly exposed infants following acute exposures.

Other lifestages

EPA estimated risks to the highly exposed general population following acute exposure via fish ingestion. EPA selected high-end fish ingestion rates for calculation of ADR values in order to represent high-end acute exposures. This exposure scenario contains large uncertainty and may overestimate exposures because bioaccumulation is a chronic and not acute process, however fish ingestion ADRs incorporate BAF estimates that are based on chronic exposure durations. Nonetheless EPA decided to calculate risk estimates for this exposure scenario in order to provide conservative bounds for risk estimates in all potential exposure scenarios.

Table 4-14 displays risk estimates for each condition of use and life stage following acute HBCD exposure (as the sum of acute fish ingestion dose (ADR) and central tendency non-fish pathway dose) based on the most sensitive relevant hazard endpoint of offspring loss. Scenario-specific discussions of risk are below.

Table 4-14. Risk Estimation for Non-Cancer Effects Following Acute Exposure to Highly Exposed Population - Fish Ingestion

Developmental Toxicity - F2 Offspring Loss POD_{HED} (mg/kg) = 9.03; Benchmark MOE = 100						
SCENARIO NAME	Young Toddler (1- <2 years)	Toddler (2- <3 years)	Small Child (3- <6 years)	Child (6 - <11 years)	Teen (11- <18 years)	Adult (18- <78 years)
1.5 Repackaging of Import Containers (Moderate Exposure)	1675	2032	3021	2864	4749	2500
1.7 Repackaging of Import Containers (Highest Exposure)	336	407	445	573	949	499
2.11 Compounding of Polystyrene Resin to Produce XPS Masterbatch (Moderate Exposure)	14826	18291	20152	26149	43638	23241
2.3 Compounding of Polystyrene Resin to Produce XPS Masterbatch (Highest Exposure)	1760	2136	2335	3010	4992	2628
3.4 Manufacturing of XPS Foam using XPS Masterbatch (Moderate Exposure)	7140	8722	9565	12363	20554	10871
3.3 Manufacturing of XPS Foam using XPS Masterbatch (Highest Exposure)	509	617	674	868	1439	757
4.2 Manufacturing of XPS Foam using HBCD Powder (Moderate Exposure)	14347	17690	19484	25276	42171	22450
4.1 Manufacturing of XPS Foam using HBCD Powder (Highest Exposure)	1306	1584	1731	2231	3699	1946
5.8 Manufacturing of EPS Foam using Imported EPS Resin beads (Moderate Exposure)	139	168	184	323	392	206
5.7 Manufacturing of EPS Foam using Imported EPS Resin beads (Highest Exposure)	**14**	**17**	**18**	**24**	**39**	**21**
6.4 Manufacturing of SIPs and Automotive Replacement Parts (Moderate Exposure)	4218	5133	5620	7253	12042	6353
6.7 Manufacturing of SIPs and Automotive Replacement Parts (Highest Exposure)	921	1117	1220	1572	2606	1371
8.1 Installation of Insulation in Buildings (Moderate Exposure)	215019	358065	470747	735701	1520242	1463047
8.3 Installation of Insulation in Buildings (Highest Exposure)	15845	19574	21579	28016	46776	24936
10.3 Recycling of EPS Foam (Moderate Exposure)	7881	9636	10573	13670	22736	12033
10.7 Recycling of EPS Foam (Highest Exposure)	763	925	1011	1302	2158	1135
12.2 Use of Flux/Solder Paste (Moderate Exposure)	113882	161167	190541	264200	471320	288316
12.6 Use of Flux/Solder Paste (Highest Exposure)	74674	99865	114476	154015	266251	152040

Note: MOEs represent risk from aggregate exposure values from fish ingestion ADR and background general population exposure.
Note: Bold text indicates MOE is less than the benchmark MOE. Non-bold text indicates the MOE is greater than the benchmark MOE .

Estimated risks are above the benchmark MOE for the highly exposed general population for all conditions of use except for Manufacturing of EPS Foam from Imported EPS Resin Beads.

Manufacturing of EPS Foam from Imported EPS Resin Beads
Estimation of the risk is below the benchmark MOE for all lifestages from the highest exposure sub-scenario (5.7) but not under the representative moderate exposure scenario (5.8). MOEs for sub-scenario 5.7 ranged from 14 - 39, benchmark MOE = 100. Quantitative risk estimates are only provided for sub-scenarios 5.7 and 5.8 as representative exposure levels; however EPA has determined that estimated risks are below the benchmark MOE for at least the most sensitive lifestage (young toddlers) under 4 of the 12 evaluated sub-scenarios.

Risks via inhalation

Risks were not assessed for the following COUs via dietary exposure because releases were not identified or associated exposures were not quantified:

- *Installation of Automobile Replacement Parts*
- *Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures*

A description of all subscenarios for outdoor air inhalation exposure can be found in Table 2-50. Table 4-15 displays risk estimates for each occupational scenario and life stage following acute HBCD exposure (as the sum of acute air inhalation dose (ADR) and central tendency non-air pathway dose) based on the most sensitive hazard endpoint of offspring loss. Estimation of the risk is above the benchmark MOE for the highly exposed population at all lifestages for all COUs (including the highest exposure sub-scenarios) following acute exposures.

Table 4-15. Risk Estimate for Non-Cancer Effects Following Acute Exposure to Highly Exposed Population - Inhalation

POD_{HED} (mg/kg) = 9.03 Developmental Toxicity - F2 Offspring Loss; Benchmark MOE = 100							
SCENARIO NAME	Infants (<1 years)	Young Toddler (1- <2 years)	Toddler (2- <3 years)	Small Child (3- <6 years)	Child (6 - <11 years)	Teen (11- <16 years)	Adult (16- <70 years)
1.5 Repackaging of Import Containers (Moderate Exposure)	38319	38609	46356	62468	91159	126743	170648
1.3 Repackaging of Import Containers (Highest Exposure)	1292	1335	1516	2041	2940	3934	5290
2.5 Compounding of Polystyrene Resin to Produce XPS Masterbatch (Moderate Exposure)	249469	219531	365482	497256	799985	1617626	2214316
2.3 Compounding of Polystyrene Resin to Produce XPS Masterbatch (Highest Exposure)	141582	133209	187232	253377	385480	615839	833657
3.3 Manufacturing of XPS Foam using XPS Masterbatch (Moderate Exposure)	20129	20537	23990	32307	46843	63881	85950
3.1 Manufacturing of XPS Foam using XPS Masterbatch (Highest Exposure)	2714	2803	3189	4292	6187	8291	11149
4.7 Manufacturing of XPS Foam using HBCD Powder (Moderate Exposure)	40232	40483	48747	65695	95934	133664	179979
4.9 Manufacturing of XPS Foam using HBCD Powder (Highest Exposure)	2594	2680	3049	4103	5914	7924	10655
5.3 Manufacturing of EPS Foam using Imported EPS Resin beads (Moderate Exposure)	4663	4810	5489	7388	10655	14307	19239
5.7 Manufacturing of EPS Foam using Imported EPS Resin beads (Highest Exposure)	671	694	788	1060	1527	2042	2746
6.5 Manufacturing of SIPs and Automotive Replacement Parts (Moderate Exposure)	174789	161023	238284	322960	499080	845997	1148143
6.3 Manufacturing of SIPs and Automotive Replacement Parts (Highest Exposure)	14195	14544	16837	22670	32803	44463	59812
8.4 Installation of Insulation in Buildings (Moderate Exposure)	224274	200387	320499	435464	690520	1304729	1779770
8.2 Installation of Insulation in Buildings (Highest Exposure)	209822	189138	295678	401441	631578	1152664	1569678
10.7 Recycling of EPS Foam (Moderate Exposure)	156825	146122	210281	284767	436286	715415	969520
10.3 Recycling of EPS Foam (Highest Exposure)	38976	39253	47176	63575	92796	129112	173842
11.1 Formulation of Flux/Solder (Moderate Exposure)	130269	123460	170530	230660	349151	547724	740891
11.3 Formulation of Flux/Solder (High Exposure)	39856	40115	48276	65060	94994	132299	178138
12.3 Use of Flux/Solder (Moderate Exposure)	267938	233201	399922	544679	886182	1896722	2604496
12.1 Use of Flux/Solder (Highest Exposure)	266659	232264	397496	541334	880040	1875758	2575104

Note: MOEs represent risk from aggregate exposure values from fish ingestion ADR and background general population exposure.
Note: Bold text/red shading indicates MOE is less than the benchmark MOE. Non-bold/non-shaded text indicates the MOE is greater than the benchmark MOE .

Consumer Articles

Risks were also estimated for consumer articles. These use scenarios are specific to the highly exposed general population and involve exposure to HBCD dust and indoor air. See Section 2.4.2.6 for a more detail on these exposure scenarios. Scenario A3 corresponds to COUs #8 and #9, *Installation/Demolition of EPS/XPS foam insulation in residential, public and commercial buildings, and other structures*, and scenario A4 corresponds to COU #7, *Installation of automobile replacement parts*.

MOEs were calculated incorporating the summation of these exposures and background general population non-dust, non-air exposures. Results are presented in Table 4-16.

Table 4-16. Risk Estimate for Non-Cancer Effects Following Acute Exposure to Highly Exposed Populations - Consumer Articles

POD_{HED} (mg/kg) = 9.03 Developmental Toxicity - F2 Offspring Loss Benchmark MOE = 100							
SCENARIO NAME	Infant (<1 year)	Young Toddler (1- <2 years)	Toddler (2- <3 years)	Small Child (3- <6 years)	Child (6 - <11 years)	Teen (11- <16 years)	Adult (16- <70 years)
A3 - EPS/XPS Insulation in residences	81554	84557	97120	130442	189153	271503	386947
A4 - HBCD contained in automobile components	85445	88584	101837	136804	198649	286305	407937
Note: MOEs represent risk from aggregate exposure values from combined dust and indoor air ADR along with background general population exposure. **Note:** Non bold/ non shaded text indicates the MOE is greater than the benchmark MOE.							

Estimation of the risk is multiple orders of magnitude above the benchmark MOE for the highly exposed general population from either EPS/XPS insulation in residences or HBCD contained in automobile components for all lifestages following acute exposure.

Additionally, EPA estimated risks to the most sensitive lifestage of young toddlers based on *Mouthing of Plastic Articles Containing HBCD* (see Appendix F for exposure values). For the highest modeled acute exposure dose of 7.7E-5 mg/kg-day, when summed with central tendency aggregate background exposure the total exposure is 1.11E-4 mg/kg-day, and the estimation of the risk is multiple orders of magnitude above the benchmark MOE (MOE = 78522, benchmark MOE = 100).

4.2.3.2.2 Risk Estimation for Non-Cancer Effects Following Chronic Exposures – Highly Exposed Populations

Risks to the highly exposed population were calculated for non-cancer effects following chronic exposures based on fish ingestion and inhalation. In addition to calculating risks for individual lifestages, risks were calculated for an individual living near a facility across multiple lifestages. The upper-end estimate of residential mobility of 33 years was selected for a high-end exposure duration (U.S. EPA, 2011c). A central tendency value of 13 years was also selected (U.S. EPA, 2011c), with risks calculated both from birth through 13 years of age. The calculated MOEs based on integrated exposure across lifestages for these durations represent estimations of the risk based on a weighted average of lifestage-specific exposures across the stated period of time. As an example, for residency from birth to 13 years old, integrated exposure is calculated as: (1/13 * infant exposure [high end general

population value] + 1/13 * young toddler exposure + 1/13 * toddler exposure + 3/13 * small child exposure + 5/13 * child exposure + 2/13 * teen exposure).

Risks via Fish Ingestion / Dietary Exposure

Risks were not estimated for the following COUs via dietary exposure because releases were not identified or associated exposures were not quantified:

- *Installation of Automobile Replacement Parts*
- *Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures*
- *Formulation of Flux / Solder Paste*

A description of all subscenarios for fish ingestion exposure can be found in Table 2-49.

Highly Exposed Population

Infants

Infants are not expected to ingest fish in their diet (U.S. EPA, 2011b) (as discussed in Section 2.4.2.1). Therefore, dietary risks to highly exposed infants were estimated based on high end aggregate general population exposure values, which incorporates breast milk in its dietary component as well as high-end estimates of dust, dermal, air, and soil exposure. Infant risks are based on steady-state exposures estimated via biomonitoring and are not associated with a particular condition of use. Estimation of the risk is more than 10-fold above the benchmark MOE for infants (MOE 3,939; Benchmark MOE = 300) based on 95th percentile aggregate exposures (4.26E-4 mg/kg-day).

EPA also modeled infant exposures up to and exceeding the 99.5th percentile and compared those with available biomonitoring data (see Section 2.4.2.9.1). Estimation of the risk is above the benchmark MOE even for the highest-end exposures (MOE = 468, benchmark MOE = 300), where the maximum modeled HBCD dose is combined with the lower (90th) assumed percentile of the underlying distribution of environmental data. In this circumstance, the maximum estimated dose is 3.59E-3 mg/kg-day.

Other lifestages

Table 4-17 provides risk estimates for each occupational scenario and life stage following acute HBCD exposure (as the sum of chronic fish ingestion dose (ADD) and central tendency non-fish pathway dose) based on the most sensitive hazard endpoint of thyroid effects. ADD values representing chronic exposure utilized central-tendency fish ingestion rates, which are expected to be more representative of the most populations over a sustained period. Integrated exposure across lifestages incorporated the high-end (95th percentile) aggregate exposure value for infants and high-end adult ADD. Scenario-specific discussions of risk are below.

Table 4-17. Risk Estimate for Non-Cancer Effects Following Chronic Exposure to Highly Exposed Population - - Fish Ingestion

Thyroid Effects - Decreased T4 Levels POD_{HED} (mg/kg) = 1.68; Benchmark MOE = 300									
SCENARIO NAME	Young Toddler (1- <2 years)	Toddler (2- <3 years)	Small Child (3- <6 years)	Child (6 - <11 years)	Teen (11- <18 years)	Adult CT residency (18- <78 years)	Adult HE residency (18- <78 years)	**Integrated Exposure** Residency across lifestages	
								Birth-13	Birth-33
1.5 Repackaging of Import Containers (Moderate Exposure)	12642	16749	20003	23229	42592	60070	25397	16158	21817
1.7 Repackaging of Import Containers (Highest Exposure)	3260	4036	4700	5191	9325	13179	5270	4954	5494
2.11 Compounding of Polystyrene Resin to Produce XPS Masterbatch (Moderate Exposure)	35152	55988	72598	102461	206567	288453	169034	32526	64374
2.3 Compounding of Polystyrene Resin to Produce XPS Masterbatch (Highest Exposure)	28037	41972	52806	68941	133373	187070	93586	28422	50369
3.4 Manufacturing of XPS Foam using XPS Masterbatch (Moderate Exposure)	39209	64810	85690	127789	266093	370248	251773	34560	72603
3.3 Manufacturing of XPS Foam using XPS Masterbatch (Highest Exposure)	14387	19312	23183	27213	50126	70663	30267	17860	24939
4.2 Manufacturing of XPS Foam using HBCD Powder (Moderate Exposure)	41889	71013	95207	148079	316678	439298	345521	35801	78140
4.1 Manufacturing of XPS Foam using HBCD Powder (Highest Exposure)	24547	35696	44320	56061	106797	150036	71252	26108	43693
5.8 Manufacturing of EPS Foam using Imported EPS Resin beads (Moderate Exposure)	5236	6573	7692	8577	15468	21852	8828	7652	8868
5.7 Manufacturing of EPS Foam using Imported EPS Resin beads (Highest Exposure)	585	711	823	898	1605	2269	896	940	980
6.4 Manufacturing of SIPs and Automotive Replacement Parts (Moderate Exposure)	35989	57755	75179	107238	217501	303522	182512	32962	66056
6.7 Manufacturing of SIPs and Automotive Replacement Parts (Highest Exposure)	20972	29629	36325	44639	83900	118033	53700	23489	36980
8.1 Installation of Insulation in Buildings (Moderate Exposure)	44713	77906	106100	173553	384198	530814	526889	37030	84067
8.3 Installation of Insulation in Buildings (Highest Exposure)	37804	61680	80985	118365	243493	339262	217484	33877	69732
10.3 Recycling of EPS Foam (Moderate Exposure)	29116	43989	55582	73337	142632	199945	101921	29094	52460
10.7 Recycling of EPS Foam (Highest Exposure)	18568	25740	31306	37794	70471	99221	44053	21567	32537
12.2 Use of Flux/Solder Paste (Moderate Exposure)	43893	75865	102839	165654	362761	501839	459972	36681	82336
12.6 Use of Flux/Solder Paste (Highest Exposure)	43037	73770	99523	157868	342075	473807	404316	36310	80539

Note: MOEs represent risk from aggregate exposure values from fish ingestion ADR and background general population exposure.
Note: Non bold/ non shaded text indicates the MOE is greater than the benchmark MOE.

Estimation of the risk is above the benchmark for all lifestages among the highly exposed population for any condition of use following chronic exposure via fish ingestion. Scenario 5.7 resulted in the lowest MOEs, but estimation of the risk for that sub-scenario even for the most sensitive lifestage was almost double the benchmark MOE. Estimation of the risk is also above the benchmark MOE for residency across lifestages from either birth to 13 years of age or birth to 33 years of age.

Risks via Inhalation

Risks were not assessed for the following COUs via dietary exposure because releases were not identified or associated exposures were not quantified:

- *Installation of Automobile Replacement Parts*
- *Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures*

A description of all subscenarios for outdoor air inhalation exposure can be found in Table 2-50. Estimated chronic exposures (ADD) for all subscenarios and lifestages were below 1E-5 mg/kg, which corresponds to an MOE of 168,000 for the most sensitive chronic endpoint of thyroid effects. Therefore, estimation of the risk is multiple orders of magnitude above the benchmark MOE for all lifestages of the highly exposed population via inhalation following chronic exposures from any COU.

Consumer Articles

Risks were also calculated for consumer articles. These use scenarios are specific to the highly exposed general population and involve exposure to HBCD dust and indoor air. See Section 2.4.2.6 for a more detail on these exposure scenarios. Scenario A3 corresponds to COUs #8 and #9, *Installation/Demolition of EPS/XPS foam insulation in residential, public and commercial buildings, and other structures*, and scenario A4 corresponds to COU #7, *Installation of automobile replacement parts*.

MOEs were calculated incorporating these exposures and background general population non-dust, non-air exposures. Results are presented in Table 4-18.

Table 4-18. Risk Estimate for Non-Cancer Effects Following Chronic Exposure to Highly Exposed Populations - Consumer Articles

POD_{HED} (mg/kg) = 1.68 Thyroid Effects - Decreased T4 Levels Benchmark MOE = 300							
SCENARIO NAME	Infant (<1 year)	Young Toddler (1- <2 years)	Toddler (2- <3 years)	Small Child (3- <6 years)	Child (6 - <11 years)	Teen (11- <16 years)	Adult (16- <70 years)
A3 - EPS/XPS Insulation in residences	52020	48691	56935	70657	103592	154935	209924
A4 - HBCD contained in automobile components	41905	37661	54732	70493	108491	187754	255716
Note: MOEs represent risk from aggregate exposure values from combined dust and indoor air ADR along with background general population exposure. **Note:** Non bold/ non shaded text indicates the MOE is greater than the benchmark MOE (risk not identified).							

Estimation of the risk is multiple orders of magnitude above the benchmark for the highly exposed general population from either EPS/XPS insulation in residences or HBCD contained in automobile components for any lifestage following chronic exposure. Risks were not calculated for extended periods of residency because risks were not identified for any individual lifestage.

Additionally, EPA estimated risks to the most sensitive lifestage of young toddlers based on *Mouthing of Plastic Articles Containing HBCD* (see Appendix F for exposure values). For the highest modeled acute exposure dose of 5.28E-5 mg/kg-day, when summed with central tendency aggregate background exposure the total exposure is 9.08E-5 mg/kg-day, and the estimation of the risk is multiple orders of magnitude above the benchmark MOE (MOE = 18502, benchmark MOE = 300).

4.2.3.3 Targeted Sensitivity Analysis

Section 2.2.14 describes the context behind conducting a targeted sensitivity analysis based on production volume. Briefly, due to the uncertainty with the imported volume and resulting estimates of environmental releases and exposures to the general population and the environment, a targeted sensitivity analysis on the impact of import volumes on environmental risk estimates was conducted. The conditions of use (COU) considered in the sensitivity analysis represent the COUs that resulted in the highest estimates of releases on a daily basis and include scenarios that rely on both industry data and OECD ESDs. Originally as presented above in Section 4.1.5.2, all nine COUs with estimated water releases containing HBCD were predicted to have production volumes up to 100,000 lbs/yr. The purpose

of the sensitivity analysis is to evaluate how the model parameters of production volume and percent of HBCD removed in in COUs with direct releases into surface water may impact the predicted fish ingestion exposure values. In addition to the risk estimates described throughout Section 4.2.3 based on a production volume of 100,000 lbs/yr, risk estimates were also derived using the production volumes of 50,000 and 25,000 lbs/yr for the following three processing COUs: COU #1: *Repackaging of import containers*, COU #2: *Manufacturing of XPS Foam using XPS Masterbatch*, and COU #3: *Manufacturing of EPS Foam from Imported EPS Resin Beads*.

EPA also performed a sensitivity analysis based on estimated wastewater treatment (WWT) removal of HBCD from direct discharging facilities. Risk estimates for fish ingestion in Section 4.2.3 assumed 0% removal for those exposure sub-scenarios with direct discharge to water. COU #1, *Repackaging of Import Containers,* does not have direct releases into surface water, and is thus only evaluated in the sensitivity analysis in regard to potential changes in surface water and sediment concentrations due to production volume differences. The other two processing COUs (*Manufacturing of XPS Foam using XPS Masterbatch*, and *Manufacturing of EPS Foam from Imported EPS Resin Beads*) have direct water releases, and with a lack of specific information, were predicted to have 0% removal of HBCD. Based on the EPA Development Document for Effluent Limitations, Guidelines and Standards for Organic Chemicals, Plastics and Synthetic Fibers Point Source Category, 75% removal was selected as a reasonable removal estimate.

Estimation of the risk to highly exposed general population via fish ingestion was below the benchmark MOE only for the higher sub-scenario of COU #5, *Manufacturing of EPS Foam from Imported EPS Resin Beads*. The highest exposure sub-scenario for that COU, 5.7, did assume direct discharge and 0% WWT removal. Therefore, a sensitivity analysis based on both production volume and WWT removal was performed only for that sub-scenario. Results are provided in Appendix K. Table Apx_K-1.

Manufacturing of EPS Foam from Imported EPS Resin beads
Estimation of the risk is below the benchmark MOE for all lifestages only following acute exposure from the highest exposure sub-scenario (5.7) assuming 100,000 lbs PV and 0% WWT removal. Estimation of the risk remains below the benchmark MOE for all lifestages except teenagers when assuming 75% WWT removal and both lower PVs. Reduced PV alone has essentially no effect on acute exposures and associated risk estimates.

4.3 Assumptions and Key Sources of Uncertainty for the Risk Characterization

4.3.1 Assumptions and Key Sources of Uncertainties for the Environmental Risk Characterization

In characterizing the environmental risk of HBCD, the same uncertainties mentioned above regarding environmental hazard characterization also apply. Specifically, the uncertainty regarding the diastereomer composition of HBCD will differ based on commercial and consumer products used, and the changes of such proportions that may incur following environmental release.

For evaluating the potential trophic transfer of HBCD in the environment, many assumptions and uncertainties were taken into consideration due to the complexity of food web dynamics. In general, there is an inherent uncertainty when using proxy organisms to represent all terrestrial and aquatic prey and predators; the selection was based on data availability, thus making it difficult to represent more than three levels of prey-predator relationships. Organism selection for this evaluation was exclusively from the available exposure factors in the U.S. EPA Wildlife Exposure Factors Handbook (also incorporated in the U.S. EPA Final Water Quality Guidance for Great Lakes System). Variations in diet categories due to life stage, gender, and seasonal differences are not addressed in this evaluation because the specificity of each exposure factor differed based on the methodologies used in their respective original references. Further, the inability to account for complete diets and the potential variations in diet may have resulted in the under- or overestimation of HBCD uptake. Further underestimations of HBCD uptake by terrestrial predators, as compared to aquatic predators in this assessment (*i.e.,* calculated by evaluating Kestrel ingestion of mice) may also be due to the use of fruit and grasshopper HBCD biomonitoring data as the original source of HBCD for Kestrel, as opposed to smaller mammals with a higher body fat composition. The limited data regarding HBCD in terrestrial organisms contributes to the uncertainty regarding HBCD trophic transfer in terrestrial food webs. Underestimates of HBCD uptake may have resulted from the inability to account for a majority of diet compositions for various predators due to an overall lack of information on such species-specific preferences, and an inability to account for varying sources of physiological differences amongst organisms. The evaluation of trophic transfer may also overestimate uptake of HBCD from a specific prey type because HBCD metabolism and elimination were not accounted for.

EPA assessed releases of HBCD to the environment or to disposal based on the production volume of HBCD, emission factors, and number days of release per year. In a few cases, EPA used TRI release data in lieu of the production volume of HBCD and emission factors. The emission factors were obtained from the EURAR, OECD ESDs, an EPA GSs, or a scientific journal article and the number of days of release per year were obtained from the EURAR, EU TGD, the NICNAS RAR, an OECD ESD, or an EPA GS as discussed in detail in Section 2.2. These data do not specifically pertain to the sites that are the subject of this risk evaluation. Therefore, in the case of each COU, EPA estimated a range of emission factors and a range of number of days of release per year and calculated a range of daily release rate from these estimated ranges to account for uncertainty about the values of the emission factor and number of days of release. Also, in the case of some releases, there is uncertainty about medium of release and therefore EPA assessed various media of release to account for this uncertainty. The emission factors and numbers of days of release per year that are the basis of the assessment pertain to HBCD processing or use that occur at sites that are not located in the U.S. or pertain to an industrial or commercial sector that is related to a COU (e.g., polymer processing, use of spray polyurethane foam.) There is some uncertainty regarding the extent to which this data is applicable to processing or

use of HBCD in the U.S. To account for the uncertainties and variability among release estimates and exposure considerations including wastewater treatment, EPA provided risk estimates based on a range of exposure sub-scenarios. EPA believes this sufficiently captures the range of risk estimates for all reasonably expected environmental exposures. In regard to the calculation of risk estimates using predicted surface water or sediment concentrations of HBCD based on E-FAST or the PSC, all risk estimates can be associated with a specific condition of use.
Water dilution models can be used to determine the concentration of a chemical in the surface water after a source emits the chemical into a water body. Since the E-FAST model incorporates defaults that encompass either a combination of upper percentile and mean exposure parametric values, or all upper percentile parametric values, the resulting model predictions represent high-end exposures estimates. Simple dilution models, such as EFAST provide exposure estimates that are derived from a simple mass balance approach, and does not account for partitioning between compartments within a surface water body or degradation over time in different media, parameters which are relevant to HBCD, therefore EPA utilized a two tier approach by complementing the EFAST modeling with more refined estimate from the PSC model to further describe environmental exposures. However, these predicted surface water and sediment concentrations will likely underestimate HBCD concentrations because they do not take into consideration background HBCD concentrations (only what may be in these matrices due to water releases containing HBCD from a specific condition of use).

Monitoring data on measured water, sediment, and soil concentrations of HBCD take into consideration real time HBCD concentrations in these matrices, however they cannot be associated with a specific condition of use. Some monitoring studies will associate measurements to a specific sector, however this categorization is still too broad for one to associate with a condition of use. Furthermore, although risk estimates can be condition of use- or sector-specific, the sole use of surface water, sediment, and soil concentrations of HBCD will not account for dietary-associated sources of HBCD and will underestimate the risk to both terrestrial and aquatic organisms.

4.3.2 Assumptions and Key Sources of Uncertainties for the Human Health Risk Characterization

4.3.2.1 Physical-Chemical Properties and Toxicokinetics

HBCD toxicokinetics including absorption and bioaccumulation differ greatly among the three HBCD isomers (α-, β-, and γ-HBCD) and are greatly affected by the relative fat content of tissues and surrounding media (e.g. water, air, diet, breastmilk). Reasonably available information on human health hazard and exposure does not typically differentiate among the three isomers of HBCD, and it is unknown whether a particular COU or exposure pathway may bias toward one isomer over another. In the absence of reasonably available information, this risk evaluation only assessed HBCD as a variable mixture and it cannot be determined whether how the risk estimates would compare to a more refined isomer-specific assessment.

EPA estimated dermal risks assuming consistent 6.5% dermal absorption based on the highest-end estimate from available *ex vivo* and *in vitro* data in order to be health-protective. The actual percentage of HBCD absorbed dermally is variable based on multiple factors including the relative percentage of each isomer in the mixture and the relative ratio of sweat to sebum on skin. Absorption in occupational settings may be substantially lower than this value based on frequent hand washing or uneven distribution across skin. The true percentage of any dermally delivered dose that would be systemically absorbed is likely to vary between COUs and over time. Additionally, for many COUs HBCD is expected to be entrenched within granules or pellets for which absorption is not expected. This will significantly reduce the amount of HBCD absorbed from within these materials. However, for most

COUs the estimate of the risk was more than 10-fold below the benchmark MOE, so refinements in dermal absorption are unlikely to result in a different risk conclusion.

4.3.2.2 Applicability of Human Health Hazards

To derive the benchmark MOEs, the UF approach (U.S. EPA, 2000; U.S. EPA, 1994) was applied to a POD_{HED} based on changes in thyroid hormone levels (T4) in male rats exposed to HBCD. UFs were applied to the POD_{HED} to account for extrapolating from an animal bioassay to human exposure, the likely existence of a diverse population of varying susceptibilities, and subchronic to chronic duration (chronic exposures only). For the most part, these extrapolations are carried out with default approaches given the lack of data to inform individual steps. EPA presumes that in general these uncertainty factors are health-protective and are unlikely to underestimate risk relative to more data-driven refinement of uncertainty factors.

As discussed in Section 3.2.5.2.1, both reduced pup body weight and offspring loss were considered as relevant hazard for evaluating risks following acute exposure. There is substantial uncertainty whether a single exposure can produce a permanent adverse effect on postnatal mortality or body weight. EPA determined that the sustained persistence of HBCD in human tissue suggests that a single exposure could have sustained effects. Additionally, acute and short-term exposure has been associated with thyroid hormone disruption, which would be expected to have downstream effects on development. Therefore, despite the uncertainties, neonatal mortality and body weight reduction were considered relevant to acute exposures. EPA evaluated risks for offspring loss for all lifestages, including those below reproductive age. While developmental effects would not be expected to present in younger lifestages, the bioaccumulation and persistence of HBCD in tissues suggests that initial exposure at an earlier age could result in effects later in life. Additionally, it is unknown whether developmental effects on neonates could also present in young exposed children. This is a health protective approach that will overestimate risks to the general population following acute exposures, especially for those lifestages below reproductive age. There is substantially less uncertainty for risk estimations of teenagers and adults.

For risks following chronic exposure, there is medium confidence in the risk estimates for most sensitive endpoint of thyroid effects for all populations and lifestages. There is uncertainty over the use of rodent thyroid hormone data for quantitative human health risk assessment, as the complexity of the system makes it difficult to determine whether rodents would in fact be more sensitive to the specific effects of HBCD. Direct extrapolation of rodent thyroid hormone effects to humans is health-protective and may potentially overestimate risk to humans.

4.3.2.3 PBT and General Population Exposure Considerations

EPA evaluated risk to the general population for individual lifestages for both acute and chronic exposure scenarios. For chronic exposure, EPA also evaluated risk for an individual living near a facility throughout their lifetime using integrated exposure values across lifestages, representing a weighted average across a lifetime. Although some simplistic toxicokinetic models for HBCD exist (empirical two-compartment open kinetic model; and a simple first-order elimination model to estimate the steady-state lipid concentration); these models introduce significant uncertainties that reduce the value of their use. Therefore, EPA was unable to model the potential effects of bioaccumulation in human tissues over time. For both consistency and health-protectiveness, these issues were accounted for by utilizing the upper range of absorption estimates across available studies and including a 10X subchronic-to-chronic UF based on assumed increasing bioaccumulation over time. This adjustment was not included for developmental endpoints or for effects observed following multi-generational exposure, which should already encompass chronic bioaccumulation. EPA believes that the use of this 10X uncertainty factor is

likely to be protective of risk from bioaccumulation in human tissues, however there is insufficient available data to confirm this presumption.

Estimated risks to the highly exposed populations are driven by fish ingestion exposure. Therefore, these estimated risks are highly dependent on the selected BAF value. EPA chose a BAF value at the low-end of the reported range. This was done because the modeled dissolved surface water estimates are generally larger than values reported in the literature. Pairing a higher BAF value with higher surface water values could result in unreasonably high estimated fish-tissue concentrations. EPA compared the range of reported fish-tissue concentrations from monitoring data and found the modeled fish tissue concentrations (range of modeled dissolved surface water and low-end BAF) to be of a similar order of magnitude. Therefore, while selection of a different BAF value would have a significant effect on fish ingestion risk estimates, the values for BAF and resulting fish ingestion exposure are well-supported by the data.

For estimating fish ingestion exposures to the highly exposed general population, EPA selected high-end fish ingestion rates for calculation of ADR values in order to represent high-end acute exposures. ADD values representing chronic exposure utilized central-tendency fish ingestion rates, which are expected to be more representative of the most populations over a sustained period. While these assumptions are expected to protect the majority of populations, there is potential for higher risk among subpopulations with consistently elevated fish consumption rates. Risk estimates for chronic exposure scenarios may therefore underestimate risk to these subpopulations, however it is uncertain whether any of these subpopulations with significantly elevated fish ingestion rates actually live nearby a HBCD facility.

Estimated days of release for a given COU are assumed to be evenly distributed throughout the year. Additionally, days of release for certain sub-scenarios may be as low as a single day per year. There is not available toxicological data comparing intermittent and continuous exposures for relative chronic health outcomes, but the effects of these uncertainties are minimized due to the sustained environmental persistence and elevated bioaccumulation of HBCD in tissues. For acute exposures, fish ingestion exposure estimates based on chronic bioaccumulation data likely overestimate the risk. The incongruency between chronic BAF values and acute release/exposure scenarios must be considered when evaluating the relevance of risk estimates for acute fish ingestion exposures.

There are many potential sources of uncertainty in all of the parameters involved in general population exposure estimates. As presented in Table 2-110, the greatest influence on exposure estimates given the associated uncertainty and sensitivity (effect on the final values) stems from the selection of emission factor and days of release. Production volume is highly uncertain but not very sensitive, while other factors such as physical-chemical properties, BAF, HBCD half-lives, and exposure model parameters were all estimated to contain low uncertainty. In order to account for these uncertainties and variability among release estimates and exposure considerations including wastewater treatment, EPA provided risk estimates based on a range of exposure sub-scenarios. EPA believes that these sub-scenarios sufficiently capture the range of risk estimates for all reasonably expected general population exposures, with minimal remaining unaccounted-for uncertainty. Consumer article modeling defaults are believed to be highly uncertain and highly sensitive, however estimation of the risk for consumer articles were orders of magnitude above the benchmark MOE. Therefore, EPA has high confidence in the range of risk estimates for the highly exposed general population.

Overall, acute exposures via fish ingestion likely represent a potentially significant overestimation of risk. Therefore, when accounting for exposure considerations there is higher confidence in risk estimates

from fish ingestion for chronic exposures and lower confidence for acute exposures. There is high confidence in risk estimates for inhalation exposure and low-medium confidence for consumer articles.

4.3.2.1 Occupational Exposure Considerations

There is high confidence in the most sensitive human health endpoints for chronic and acute exposures, and all endpoints are relevant to workers whom are all likely to be of reproductive age. Occupational inhalation exposure estimates (see Section 2.4.1.15) were assigned Medium or Medium-High confidence based on inhalation monitoring data for all COUs except for *Demolition and Disposal of EPS/XPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structure,* which was based on OSHA regulatory limits for particulates not otherwise regulated (PNOR). Estimated exposures for that COU may not be representative of likely exposure levels; however, EPA is confident that they represent an upper bound exposure estimate. Therefore, estimated risks for occupational exposures are overall of medium confidence for that COU and of high confidence for all other COUs.

In the absence of data, the dermal exposures to workers for relevant COUs were estimated using a dermal exposure model routinely used in the new chemicals program, "EPA/OPPT Direct 2-Hand Dermal Contact With Solids". The dermal exposure levels were estimated using conservative assumptions including: ,high-end quantity of solids on skin. These assumptions likely result in conservative estimates of dermal exposures to workers for the various COUs. When also considering the variability in expected dermal absorption (see above), it is likely that dermal risk estimates are overestimated for the majority of occupational scenarios.

For the purposes of this evaluation, inhalation and dermal routes of exposure were not combined to evaluate occupational risks to HBCD. Dermal and inhalation exposure were considered independently. Combining exposure routes would entail too much uncertainty given the lack of a usable PBPK model.

4.3.2.2 PPE Considerations

Non-cancer risk estimates (MOEs) for occupational exposure scenarios are presented in Section 4.2.2. These tables also present the minimum respirator requirement needed to mitigate risk for all health domains. The MOEs for these respirator scenarios assume workers are properly trained and fitted on respirator use, and that they wear respirators for the entire duration of the work activity. The MOEs for respirator scenarios following chronic exposure also assume that workers and occupational non-users wear respirators for the entire duration of the work activity throughout their career. Such regular use of respirators in chronic scenarios may not always be feasible. Additionally, potential inhalation exposure is expected for occupational non-users (ONUs), however EPA did not identify any data or applicable model that can be used to estimate inhalation exposure to particulates for ONUs. EPA expects the exposures to ONUs to be lower than those for workers. Depending on companies' procedures, the ONUs may be required to wear PPE similar to the worker handling HBCD, which would mitigate any risk to this population. Similar assumptions apply to the use of gloves and their expected elimination of any dermal exposure.

4.4 Other Risk Related Considerations

4.4.1 Potentially Exposed or Susceptible Subpopulations

TSCA requires that a risk evaluation "determine whether a chemical substance presents an unreasonable risk of injury to health or the environment, without consideration of cost or other non-risk factors, including an unreasonable risk to a *potentially exposed or susceptible subpopulation* (PESS) identified as relevant to the risk evaluation by the Administrator, under the conditions of use." TSCA § 3(12) states that "the term 'potentially exposed or susceptible subpopulation' means a group of individuals within the general population identified by the Administrator who, due to either greater susceptibility or greater exposure, may be at greater risk than the general population of adverse health effects from exposure to a chemical substance or mixture, such as infants, children, pregnant women, workers, or the elderly."

4.4.1.1 Exposure Considerations

In developing the exposure assessment for HBCD, EPA analyzed the reasonably available information to ascertain whether some human receptor groups may have greater exposure or susceptibility than the general population to the hazard posed by HBCD. Exposures of HBCD would be expected to be higher amongst groups living near industrial facilities, groups with HBCD containing products in their homes, workers who use HBCD as part of typical processes, and groups who have higher age and route specific intake rates compared to the general population.

EPA identified potentially exposed and susceptible subpopulations for further analysis during the development and refinement of the life cycle, conceptual models, exposure scenarios, and analysis plan. In Section 2.4, EPA addressed the potentially exposed or susceptible subpopulations identified as relevant based on greater exposure. EPA addresses the subpopulations identified as relevant based on greater susceptibility in Section 4.4.1.2.

Of the human receptors identified in the previous sections, EPA identifies the following as potentially exposed or susceptible subpopulations due to their *greater exposure* and considered them in the risk evaluation:

- Workers and occupational non-users. EPA reviewed monitoring data found in published literature including both personal exposure monitoring data (direct exposure) and area monitoring data (indirect exposures) and identified data sources that contain measured monitoring data and or/estimated data for the various conditions of use (including import and processing of HBCD). Exposure estimates were developed for users (males and females workers of reproductive age) exposed to HBCD as well as non-users or workers exposed to HBCD indirectly by being in the same work area of the building (Table 2-68 and Table 2-69). Also, adolescents and female workers of reproductive age (>16 to less than 50 years old) were also considered as a potentially exposed or susceptible subpopulation as specified in Section 2.4.1.1.
- Consumer users and bystanders associated with consumer use. HBCD has been identified as being used in products available to consumers; however, only some individuals within the general population may use these products. Therefore, those who do use these products are a potentially exposed or susceptible subpopulation due to greater exposure. A description of the exposure assessment for consumers is available in Section 2.4.2.6.

Other groups of individuals within the general population may be more highly exposed due to their proximity to conditions of use identified in Section 1.2 and Section 2.4.2.1 that result in releases to the environment and subsequent exposures (e.g., individuals who live or work near manufacturing, processing, distribution, use or disposal sites). Table 2-71 provides an overview of types of receptors

and exposure descriptors within the general population (central tendency and high-end). EPA estimated age-specific exposures and doses for each overall exposure group (Section 2.4.2.8) and acknowledges that individuals among the highly exposed group (i.e., high-end estimates) and PESS overlap, as some individuals may belong to multiple receptor groups (as described in Table 2-71). Also, EPA estimated ambient air concentrations for highly exposed groups, including toddlers and adults living near facilities. Further characterization about highly-exposed group and associated variability of exposure factors within the highly-exposed group is discussed in the *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment* (U.S. EPA, 2019d).

In developing exposure scenarios, EPA considered age-specific differences (Section 2.4.2.1). For HBCD, exposure scenarios that involve potentially exposed or susceptible subpopulations considered age-specific behaviors, activity patterns, and exposure factors unique to those subpopulations. EPA used the Exposure Factors Handbook (U.S. EPA, 2011c)to inform body weights and intake rates for children and adults also described in the *Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment (U.S. EPA, 2019d)*. Table 2-71 and Table 2-72 provide an overview of exposure pathways considered for the different age groups.

There are some exposure scenarios where greater exposure from multiple sources may occur and individuals who may have greater potential for exposure to HBCD. For example, as part of the Risk Evaluation:

- EPA used the CHAD database to inform how much time children spend in microenvironments (Section 2.4.2) to determine children with elevated dust concentrations (Section 2.4.2.4).
- EPA considered breast milk concentration data and ingestion for breast-fed infants (< 1 year old) in the exposure estimation (Table 2-81 and Table 2-82) .
- EPA used an activity-pattern based method to model hand-to-mouth and object-to-mouth contact and to derive transfer rates of soil and dust to the mouth to estimate ingestion rate (Section 2.4.2.3) for children and/or adults who ingest soil or sediment in environments where HBCD concentrations are elevated (Table 2-83), and for children who may mouth objects containing HBCD (Table 2-91).
- EPA completed an assessment of human dietary exposure from multiple sources for children or adults who consume edible aquatic biota or terrestrial biota containing elevated levels of HBCD. EPA considered available biomonitoring data in wildlife and dietary patterns across trophic levels as part of its exposure assessment. These approaches were considered together to determine HBCD concentrations in surface water, sediment, soil, and targeted wildlife biota. See Section 2.4.2.2 for detailed information.

EPA also considered and analyzed the available data to ascertain whether some human receptor groups may be exposed via exposure pathways that may be distinct to a particular subpopulation or lifestage (e.g., children's crawling, mouthing or hand-to-mouth behaviors, see Appendix F) and whether some human receptor groups may have higher exposure via identified pathways of exposure due to unique characteristics (e.g., activities, duration or location of exposure) when compared with the general population (U.S. EPA, 2006).

4.4.1.2 Hazard Considerations

In developing the hazard assessment, EPA evaluated available data to ascertain whether some human subpopulations may have greater susceptibility than the general population to the chemical's hazard(s).

Early lifestages are potentially susceptible to HBCD exposure. HBCD is widely detected in breast milk and umbilical cord serum, indicating a potential for prenatal and lactational exposure (Fängström et al., 2008; Kakimoto et al., 2008; Meijer et al., 2008; Fangstrom et al., 2005).

In animal studies, HBCD exposure resulted in thyroid alterations. Thyroid hormones play a critical role in coordinating complex developmental processes, and perturbations of thyroid hormone levels in a pregnant woman or neonate can have persistent adverse health effects for the child (Zoeller et al., 2007)), including adverse neurological outcomes (Finken et al., 2013; Julvez et al., 2013a; Román et al., 2013; Henrichs et al., 2010; Haddow et al., 1999). During early gestation, the developing fetus relies solely on thyroid hormones of maternal origin. As the fetus begins to produce thyroid hormones, there is less reliance on maternal thyroid hormones; however, early development remains a sensitive life stage for hormone deficits, largely due to minimal reserve capacity when compared to adults (Gilbert and Zoeller, 2010). Effects on female reproduction parameters are an additional consideration for identifying pregnant and lactating females as a susceptible subpopulation.

Some gender-specific differences in distribution, metabolism, and elimination of HBCD have been noted in animals. A toxicokinetic study in rats administered a single oral dose of [^{14}C]-HBCD found that males had faster elimination rates and lower tissue concentrations when compared to females (Yu and Atallah, 1980). These data are consistent with observations that female rats had higher liver concentrations of HBCD following repeated oral exposure for 28 days (van der Ven et al., 2006) or following gestational, lactational, and dietary exposure (van der Ven et al., 2009). Measures of mechanistic endpoints provide limited evidence of gender-specific responses to HBCD. For example, (Germer et al., 2006) reported significant induction of CYP3A1/3 mRNA and the associated proteins in both sexes of rats exposed to HBCD for 28 days, but the effect was greater and occurred at lower doses in females (doses of ≥3 mg/kg-day in females and ≥30 mg/kg-day in males). In another 28-day study, female rats exposed to HBCD had, overall, a significantly higher number of up- or down-regulated hepatic genes than males (Cantón et al., 2008); however, genes involved in phase I and II metabolism were up-regulated predominantly in males. In vivo toxicity studies, however, do not show a clear pattern of sex-specific toxicity associated with HBCD exposure (for non-reproductive/developmental endpoints). It is therefore unclear whether either males or females are more biologically susceptible to HBCD toxicity on non-reproductive/developmental endpoints.

HBCD is preferentially deposited in adipose tissue, especially the α-HBCD isomer (see Appendix H.1.2). The bioaccumulative nature of HBCD suggests that individuals who consume a high-fat diet may be at increased risk for HBCD toxicity. Additionally, individuals with higher body fat content may also be at greater susceptibility to HBCD. This is corroborated by multiple studies demonstrating increasing liver toxicity in mice administered a high-fat diet (Bernhard et al., 2016; Yanagisawa et al., 2014).

Humans with pre-existing health conditions or genetic predispositions related to any of the affected health domains would also be expected to be especially susceptible to HBCD toxicity, perhaps at significantly lower doses than healthy populations.

4.4.1.3 Risk Considerations

This risk evaluation included risk estimates for adult workers and female workers of reproductive age in order to account for developmental endpoints and for various lifestages of the general population in order to account for differential exposures. Risk estimates for female workers of reproductive age were 10% lower than workers overall, however in most instances the risk conclusions were the same. Risk estimates for consumers and bystanders were developed for specific COUs identified as being used in

products available to consumers. Risk estimates for the general population incorporated aggregate exposure, including background levels of HBCD from dietary sources, dust, soil, ambient air, indoor air, and dermal loading, with age specific exposure factors and activity patterns that included all age-groups. Risk estimates were calculated for the highly exposed general population (representing populations living close to a facility with HBCD releases) using the most sensitive relevant POD for both the highest exposure sub-scenario along with a representative moderate exposure scenario. EPA also estimated risks for all lifestages, including the most susceptible lifestages of infants and young toddlers. For dietary risks to infants (whom are not expected to ingest fish), risks were estimated for the absolute worst-case scenario of breastmilk exposure based on biomonitoring data. EPA additionally evaluated risks to susceptible lifestages from ingestion of house dust or mouthing of plastic articles.

For estimating fish ingestion exposures to the highly exposed general population, EPA selected high-end fish ingestion rates for calculation of ADR values in order to represent high-end acute exposures. ADD values representing chronic exposure utilized central-tendency fish ingestion rates, which are expected to be more representative of the most populations over a sustained period. While these assumptions are expected to protect the majority of populations, there is potential for higher risk among subpopulations with consistently higher fish consumption rates. For some populations, such as Native American tribes, fish consumption rates may differ from that of the general population, including the highly exposed population. Fish consumption rates among multiple tribes have been investigated, and this information is documented in EPA's Exposure Factors Handbook (U.S. EPA, 2011b) and other publications (Burger, 2002; Critfc, 1994). Because ingestion rates vary across tribes, use of a single value for fish consumption rate may over or underestimate exposures. Infants, children and pregnant woman are also groups among Native American tribes and these populations overlap with other potentially exposed or susceptible subpopulations. For populations with higher rates of fish ingestion, this may result in elevated exposure. Additionally, other activities unique to these communities(Gochfeld and Burger, 2011) may lead to additional aggregate exposure pathways which have not been characterized in this risk evaluation.

4.4.2 Aggregate and Sentinel Exposures

Section 2605(b)(4)(F)(ii) of TSCA requires EPA, as a part of the risk evaluation, to describe whether aggregate or sentinel exposures under the conditions of use were considered and the basis for their consideration. EPA has defined aggregate exposure as "the combined exposures to an individual from a single chemical substance across multiple routes and across multiple pathways." A detailed description of the aggregate exposure evaluation is presented in Section 2.4.2.8. The relative contribution of each pathway to the aggregated exposure is shown in Table 2-100 (central tendency) and Table 2-102 (high end). As a result of the widespread occurrence of HBCD coupled with its persistence and bioaccumulation, aggregate exposures were considered for HBCD by evaluating multiple pathways, routes of exposure and age groups. EPA defines sentinel exposure as "the exposure to a single chemical substance that represents the plausible upper bound of exposure relative to all other exposures within a broad category of similar or related exposures."

In terms of this risk evaluation, EPA considered sentinel exposures by considering exposures to populations who may have upper bound exposures due to their exposure factors (e.g., higher intake rates such as elevated fish consumption), who live in close proximity to point sources associated with the conditions of use and spend time in environments with HBCD-containing building materials or automobile replacement parts. EPA characterized high end exposures in evaluating both modeled and monitored exposures; for health, the approach is described in Table 2-71.

5 RISK DETERMINATION

5.1 Unreasonable Risk

5.1.1 Overview

In each risk evaluation under TSCA Section 6(b)[17], EPA determines whether a chemical substance presents an unreasonable risk of injury to health or the environment, under the conditions of use. The determination does not consider costs or other non-risk factors. In making this determination, EPA considers relevant risk-related factors, including, but not limited to: the effects of the chemical substance on health and human exposure to such substance under the conditions of use (including cancer and non-cancer risks); the effects of the chemical substance on the environment and environmental exposure under the conditions of use; the population exposed (including any potentially exposed or susceptible subpopulations); the severity of hazard (including the nature of the hazard, the irreversibility of the hazard); and uncertainties. EPA takes into consideration the Agency's confidence in the data used in the risk estimate. This includes an evaluation of the strengths, limitations and uncertainties associated with the information used to inform the risk estimate and the risk characterization. This approach is in keeping with the Agency's final rule, *Procedures for Chemical Risk Evaluation Under the Amended Toxic Substances Control Act* (82 FR 33726).

Under TSCA, conditions of use are defined as the circumstances, as determined by the Administrator, under which the substance is intended, known, or reasonably foreseen to be manufactured, processed, distributed in commerce, used, or disposed of. TSCA §3(4).

An unreasonable risk may be indicated when health risks under the conditions of use are greater than the risk benchmarks and where the risks to the general population or certain potentially exposed or susceptible subpopulations (PESS), such as consumers. For other PESS, such as workers, an unreasonable risk may be indicated when health risks under the conditions of use are greater than the risk benchmarks and where risks are not adequately addressed through expected use of workplace practices and exposure controls, including engineering controls or use of personal protective equipment (PPE). An unreasonable risk may also be indicated when environmental risks under the conditions of use are greater than environmental risk bench marks. The degree of uncertainty surrounding these indications is a factor in determining whether or not unreasonable risk is present. Where uncertainty is low, and EPA has high confidence in the hazard and exposure characterizations (for example, the basis for the characterizations is measured or monitoring data or a robust model and the hazards identified for risk estimation are relevant for conditions of use), the Agency has a higher degree of confidence in its risk determination. EPA may also consider other risk factors, such as severity of endpoint, reversibility of effect, or exposure-related considerations such as magnitude or number of exposures, in determining that the risks are unreasonable under the conditions of use. Where EPA has made assumptions in the scientific evaluation, whether or not those assumptions are protective, will also be a consideration. Additionally, EPA considers the central tendency and high-end scenarios when determining the unreasonable risk. High-end risk estimates (e.g. 95th percentile) are generally intended to cover the most exposed individuals or sub-populations and central tendency risk estimates are generally estimates of average or typical exposure.

[17] This risk determination is being issued under TSCA section 6(b) and the terms used, such as unreasonable risk, and the risk considerations discussed are specific to TSCA. Other statutes have different authorities and mandates, and may involve risk considerations other than those discussec here.

Conversely, EPA may make a no unreasonable risk determination for conditions of use where the hazard potential of the substance and exposure potential are low, or where the risk-related factors described previously lead EPA to determine that the risks are not unreasonable.

5.1.2 Risks to Human Health

5.1.2.1 Determining Non-Cancer Risks

Margins of exposure (MOEs) are used in EPA's risk evaluations as a starting point to estimate non-cancer risks for acute and chronic exposures. The non-cancer evaluation refers to potential adverse health effects associated with health endpoints other than cancer, including to the body's organ systems, such as reproductive/developmental effects, cardiac and lung effects, and kidney and liver effects. The MOE is the point of departure (an approximation of the no-observed adverse effect level (NOAEL) or benchmark dose level (BMDL)) for a specific health endpoint divided by the exposure concentration for the specific scenario of concern. The benchmark for the MOE that is used accounts for the total uncertainty in a point of departure for the hazard, including, as appropriate: (1) the variation in sensitivity among the members of the human population (i.e., intrahuman/intraspecies variability); (2) the uncertainty in extrapolating animal data to humans (i.e., interspecies variability); (3) the uncertainty in extrapolating from data obtained in a study with less-than-lifetime exposure to lifetime exposure (i.e., extrapolating from subchronic to chronic exposure); and (4) the uncertainty in extrapolating from a lowest observed adverse effect level rather than from a NOAEL. MOEs can provide a non-cancer risk profile by presenting a range of estimates for different non-cancer health effects for different exposure scenarios and are a widely recognized point estimate method for evaluating potential non-cancer health risks from exposure to a chemical.

A calculated MOE value that is under the benchmark MOE indicates the possibility of risk to human health. Whether the EPA determines those risks to be unreasonable will depend upon additional risk-related factors, such as severity of endpoint, reversibility of effect, exposure-related considerations (e.g. duration, magnitude, frequency of exposure, population exposed), and the confidence in the information used to inform the hazard and exposure values. If the calculated MOE is higher than the benchmark MOE, generally the EPA considers that there is no unreasonable risk.

Uncertainty factors also play an important role in the risk estimation approach and in determining unreasonable risk. A lower benchmark MOE (e.g. 30) indicates greater certainty in the data (because fewer of the default uncertainty factors are relevant to a given point of departure). A higher benchmark MOE (e.g. 1000) would indicate more uncertainty in the hazard evaluation.

5.1.2.2 Determining Cancer Risks

HBCD has not been identified as having cancer effects. Therefore, risk estimates for cancer were not included in this risk evaluation

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5.1.3 Environmental Risk

To assess environmental risk, EPA identifies and evaluates environmental hazard data for aquatic, sediment-dwelling, and terrestrial organisms exposed under acute and chronic exposure conditions. The environmental risk includes any risks that exceed benchmarks to the aquatic environment from levels of

the evaluated chemical found in the environmental (e.g., surface water, sediment, soil, biota) based on the fate properties, relatively high potential for release, and the availability of environmental monitoring data and hazard data.

Environmental risks are estimated by calculating a risk quotient (RQ). The RQ is defined as:

RQ = Environmental Concentration / Effect Level

An RQ equal to 1 indicates that the exposures are the same as the concentration that causes effects when considering appropriate uncertainty factors. If the RQ exceeds 1, the exposure is greater than the effect concentration and there is potential for risk presumed. If the RQ does not exceed 1, the exposure is less than the effect concentration and there is no risk presumed. The Concentrations of Concern or hazard value for certain aquatic, sediment-dwelling, or terrestrial organisms are used to calculate RQs for acute and chronic exposures. For environmental risk, EPA is more likely to determine that there is unreasonable risk if the RQ exceeds 1 for the conditions of use being evaluated. Consistent with EPA's human health evaluations, the RQ is not always treated as a bright line and other risk-based factors may be considered (e.g., exposure scenario, uncertainty, severity of effect) for purposes of making a risk determination.

5.2 Risk Determination for HBCD

EPA has determined that HBCD does not present unreasonable risk under the conditions of use. As described below, risks to the general population, highly exposed subpopulations, consumers, workers, occupational non-users and the environment (aquatic and terrestrial species) from HBCD were evaluated and found not to be unreasonable.

Table 5-1. Environment and Health Risk Determination[a]

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
Manufacture	Import	Import	Section 6(b)(4)(A) unreasonable risk determination for HBCD for import repackaging of import containers: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, and the general population) or the environment (aquatic and terrestrial organisms). Environment exposure scenario with highest risk estimate: Chronic toxicity to aquatic organisms Environment risk driver benchmark: RQ > 1 Environment risk estimates: RQ = 5.03 (see Table 4-3 for chronic surface water RQs based on monitoring data) Human health exposure scenario with highest risk estimate: noncancer effects from chronic dermal occupational exposure. Benchmark: MOE = 300 for thyroid effects. Risk estimate: MOE = approximately 1 for workers using no PPE (see Table 4-12). (High end estimate) Note: There is no unreasonable risk when PPE is used. Systematic Review confidence rating (environmental hazard): High Systematic Review confidence rating (environmental exposure): High Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): N/A (risks estimates derived using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model* and the *EPA/OPPT Direct 2-Hand Dermal Contact with Container Surfaces (Solids) Model)*. Risk Considerations: There is no evidence that domestic manufacturing or import of HBCD is occurring. However, since the reporting threshold under the Chemical Data Reporting (CDR) regulations for small businesses is

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			100,000 lbs/yr it is possible, though unlikely, that amounts at or below that threshold are domestically manufactured or imported without being reported through CDR. EPA used a range of values in its environmental risk evaluation to account for this possibility (100,000 lbs., 50,000 lbs. and 25,000 lbs.). Each of the estimates used for volume introduces significant uncertainty that may overestimate exposure and risk. EPA relied upon available monitoring data to estimate risk to aquatic and sediment-dwelling organisms. This monitoring data was corroborated by modeling done for all of the relevant conditions of use. The modeling incorporated several assumptions that could overestimate exposures such as the production volumes and the levels of removal assumed prior to release. An uncertainty related to the use of the monitoring data is that the levels of HBCD found in the environment cannot be attributed to a particular condition of use. Assuming that the monitored concentration values are attributed to each of the conditions of use individually in this evaluation is a conservative approach that does not underestimate risk for any particular condition of use. Another uncertainty introduced by using the monitoring data is that the data was collected between 5-10 years ago at a time when the use of HBCD was significantly more widespread and at much higher volumes that is currently the case. Considering that there is no evidence of current import or domestic manufacture of HBCD, use of the monitoring data is likely an overestimate of actual current levels of exposure. Therefore, while the risk estimate (RQ) is higher than the Agency benchmark, EPA does not believe that this condition of use presents an unreasonable risk to the environment. For human health, all risk estimates for the most highly exposed groups in the general population are not below Agency benchmarks. Therefore, risk is not unreasonable. For worker dermal risk, the models used include several conservative assumptions that likely overestimate exposure. Further, EPA used high-end

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			assumptions for the expected quantity of solids present on the skin. Specifically, the model estimates that there are 3,100 mg of chemical on workers' skin based on handling material that is 100% HBCD. Further, based on available *ex vivo* and *in vitro* data, a higher-end estimate of 6.5% dermal absorption of HBCD is used as a conservative assumption. While risk estimates for all pathways of occupational exposure for this condition of use (including acute and chronic inhalation exposures and acute and chronic dermal exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered (See Table 4-11 and Table 4-12). Quantitative dermal risk estimates that account for the use of gloves were not calculated for HBCD because the substance is in a solid form for this condition of use such that the use of impervious gloves is expected to prevent exposures. EPA expects exposures to ONUs are significantly less than worker exposures. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposure to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical. Estimated exposed worker population:3 workers; 1 ONU.

Processing	Processing - incorporated into formulation, mixture or reaction product	Flame retardants used in custom compounding of resin (e.g., compounding in XPS masterbatch, in solder paste)	Section 6(b)(4)(A) unreasonable risk determination for HBCD for processing-incorporation into formulation, mixture or reaction product; custom compounding of resin: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, and the general population) or the environment (aquatic and terrestrial organisms). Environment exposure scenario with highest risk estimate: Chronic toxicity to aquatic organisms Environment risk driver benchmark: RQ > 1 Environment risk estimates: RQ = 5.03 (see Table 4-3 chronic surface water RQs based on monitoring data) Human health exposure scenario with highest risk estimate: noncancer effects from chronic dermal occupational exposure. Benchmark: MOE = 300 for thyroid effects. Risk estimate: MOE = 4 for workers using no PPE (see Table 4-12). (High end estimate) Note: There is no unreasonable risk when PPE is used. Systematic Review confidence rating (environmental hazard): High Systematic Review confidence rating (environmental exposure): High Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): N/A (risks estimates derived using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids*

			Model and the *EPA/OPPT Direct 2-Hand Dermal Contact with Container Surfaces (Solids) Model)*. Risk Considerations: There is no evidence that domestic manufacturing or import of HBCD is occurring thus it is unknown whether this condition of use is current. However, since the reporting threshold under the Chemical Data Reporting (CDR) regulations for small businesses is 100,000 lbs/yr it is possible, though unlikely, that amounts at or below that threshold are domestically manufactured or imported without being reported through CDR. Using this estimate for volume introduces significant uncertainty that may overestimate exposure and risk. EPA relied upon available monitoring data to estimate risk to aquatic and sediment-dwelling organisms. This monitoring data was corroborated by modeling done for all of the relevant conditions of use. The modeling incorporated several assumptions that could overestimate exposures such as the production volumes and the levels of removal assumed prior to release. The uncertainty related to the use of the monitoring data is that the levels of HBCD found in the environment cannot be attributed to a particular condition of use. Assuming that the monitored concentration values are attributed to each of the conditions of use individually in this evaluation is a conservative approach that does not underestimate risk for any particular condition of use. Another uncertainty introduced by using the monitoring data is that the data was collected between 5-10 years ago at a time when the use of HBCD was significantly more widespread and at much higher volumes that is currently the case. Considering that there is no evidence of current import or domestic manufacture of HBCD, use of the monitoring data is likely an overestimate of actual current levels of exposure. For terrestrial mammals, EPA used a model to estimate potential exposure and subsequent risks to mammals via consumption of contaminated aquatic prey. Using the model, RQs were calculated based on estimated HBCD

			surface water and sediment concentrations and no RQs were greater than 1 based on the 50th percentile surface water and sediment concentrations (Table_Apx J-12 in Appendix J.2.4). EPA believes the 50th percentile is the appropriate level to consider as it balances the uncertainties in the exposure assumptions that may both over and under estimate calculated environmental risks. Overall, while the aquatic organism risk estimate (RQ) is higher than the Agency benchmark, EPA does not believe that this condition of use presents an unreasonable risk to the environment. For human health, all risk estimates for the most highly exposed groups in the general population are not below Agency benchmarks. Therefore, risk is not unreasonable. For worker dermal risk, the models used include several conservative assumptions that likely overestimate exposure. Further, EPA used high-end assumptions for the expected quantity of solids present on the skin. Specifically, the model estimates that there are 3,100 mg of chemical on workers' skin based on handling material that is 100% HBCD. Further, based on available *ex vivo* and *in vitro* data, a higher-end estimate of 6.5% dermal absorption of HBCD is used as a conservative assumption. While risk estimates for all pathways of occupational exposure for this condition of use (including acute and chronic inhalation exposures and acute and chronic dermal exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered (See Table 4-6). Quantitative dermal risk estimates that account for the use of gloves were not calculated for HBCD because the substance is in a solid form for this condition of use such that the use of impervious gloves is expected to prevent exposures.

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			EPA expects exposures to ONUs are significantly less than worker exposure. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposure to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical. Estimated exposed worker population:20 workers; 6 ONUs

	Incorporated into article	Flame retardants used in plastics product manufacturing (manufacture of XPS and EPS foam; manufacture of structural insulated panels (SIPS) and automobile replacement parts from XPS and EPS foam)	Section 6(b)(4)(A) unreasonable risk determination for HBCD for processing-incorporation into articles: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, and the general population) or the environment (aquatic and terrestrial organisms). Environment exposure scenario with highest risk estimate: Chronic toxicity to aquatic organisms Environment risk driver benchmark: RQ > 1 Environment risk estimates: RQ = 5.03 (see Table 4-3) chronic surface water RQs based on monitoring data) Human health exposure scenario with highest risk estimate: noncancer effects from acute dermal occupational exposure. Benchmark: MOE = 100 for developmental effects. Risk estimate: MOE = 4 for workers using no PPE (see Table 4-11). (High end estimate). Note: There is no unreasonable risk when PPE is used. Systematic Review confidence rating (environmental hazard): High Systematic Review confidence rating (environmental exposure): High Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): N/A (risks estimates derived using the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model* and the *EPA/OPPT Direct 2-Hand Dermal Contact with Container Surfaces (Solids) Model)*.

			Risk Considerations: There is no evidence that domestic manufacturing or import of HBCD is occurring thus it is unknown whether this condition of use is current. However, since the reporting threshold under the Chemical Data Reporting (CDR) regulations for small businesses is 100,000 lbs/yr it is possible, though unlikely, that amounts at or below that threshold are domestically manufactured or imported without being reported through CDR. Using this estimate for volume introduces significant uncertainty that may overestimate exposure and risk. EPA relied upon available monitoring data to estimate risk to aquatic and sediment-dwelling organisms. This monitoring data was corroborated by modeling done for all of the relevant conditions of use. The modeling incorporated several assumptions that could overestimate exposures such as the production volumes and the levels of removal assumed prior to release. For this condition of use, the difference between the modeled values and the values found in the monitoring data were more pronounced than for other COUs, specifically for the manufacturing of foam from EPS resin beads. For this modeling EPA relied upon assumptions for environmental releases that likely overestimate potential environmental exposures as data from facilities performing this process was not available. Additional sensitivity analysis was conducted to refine the modeled estimates for this condition of use including assuming a 75% removal rate and lower production volume assumptions in order to better approximate exposures were HBCD still being used. An uncertainty related to the use of the monitoring data is that the levels of HBCD found in the environment cannot be attributed to a particular condition of use. Assuming that the monitored concentration values are attributed to each of the conditions of use individually in this evaluation is a conservative approach that does not underestimate risk for any particular condition of use. The uncertainty introduced by using the monitoring data is that the data was collected between 5-10 years ago at a time when the use of

			HBCD was significantly more widespread and at much higher volumes that is currently the case. Considering that there is no evidence of current import or domestic manufacture of HBCD, use of the monitoring data is likely an overestimate of actual current levels of exposure. For terrestrial mammals, EPA used a model to estimate potential exposure and subsequent risks to mammals via consumption of contaminated aquatic prey. Using the model, RQs were calculated based on estimated HBCD surface water, sediment and fish tissue concentrations and several RQs were slightly greater than 1 (1.8-2.1) based on the 50th percentile surface water and sediment concentrations (Table_Apx J-12 in Appendix J.2.4). EPA believes the 50th percentile is the appropriate level to consider as it balances the uncertainties in exposure assumptions that may both over and under estimate calculated environmental risks. Additional sources of uncertianainty in the model that may lead to over estimation of exposure and calculated risk include using prediticted HBCD concentrations in surface water, sediment and fish tissue, rather and environmental monitoring data for those sources of exposure. Overall, while there are some aquatic and terrestrial organism risk estimates (RQs) higher than the Agency benchmarks, EPA does not believe that this condition of use presents an unreasonable risk to the environment. For human health, all risk estimates for the most highly exposed groups in the general population are not below Agency benchmarks with exception of acute exposures to highly exposed populations living near facilities. For acute exposures, fish ingestion exposure estimates based on acute bioaccumulation data likely overestimate the risk of acute exposures to subsistence fishers near facilities. For worker dermal risk, the models used include several conservative assumptions that likely overestimate exposure. Further, EPA used high-end assumptions for the expected quantity of solids present on the skin.

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			Specifically, the model estimates that there are 2,170 mg of chemical on workers' skin based on handling material that is 70% HBCD. Further, based on available *ex vivo* and *in vitro* data, a higher-end estimate of 6.5% dermal absorption of HBCD is used as a conservative assumption. Several occupational exposure scenarios were used to evaluate this condition of use. Dermal exposure was only considered relevant for a subset of this condition of use (manufacturing XPS foam using masterbatch and powder). Dermal exposure during the incorporation of HBCD into other articles as described in the condition of use sub-category is not expected and was not quantified. While risk estimates for all pathways of occupational exposure for this condition of use (including acute and chronic inhalation exposures and acute and chronic dermal exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered (See Table 4-10). Quantitative dermal risk estimates that account for the use of gloves were not calculated for HBCD because the substance is in a solid form for this condition of use such that the use of impervious gloves is expected to prevent exposures. EPA expects exposures to ONUs are significantly less than worker exposure. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposure to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical. Estimated exposed worker population: 39 workers; 11 ONUs

	Recycling	Recycling of XPS and EPS foam, resin, panels containing HBCD	Section 6(b)(4)(A) unreasonable risk determination for HBCD for processing-recycling: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, and the general population) or the environment (aquatic and terrestrial organisms). Environment exposure scenario with highest risk estimate: Chronic toxicity to aquatic organisms Environment risk driver benchmark: RQ > 1 Environment risk estimates: RQ = 5.03 (see Table 4-3) chronic surface water RQs based on monitoring data) Human health exposure scenario with highest risk estimate: noncancer effects from chronic inhalation occupational exposure. Benchmark: MOE = = 300 for thyroid effects. Risk estimate: MOE = 159 for workers using no PPE (see Table 4-10). (High end estimate). Note: There is no unreasonable risk when PPE is used. Systematic Review confidence rating (environmental hazard): High Systematic Review confidence rating (environmental exposure): High Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): High Risk Considerations: While there is no evidence that domestic manufacturing or import of HBCD is occurring, recycling of materials is

			likely to be occuring and could be expected to continue in the future even with the lack of introduction of new materials into the marketplace. EPA relied upon available monitoring data to estimate risk to aquatic and sediment-dwelling organisms. This monitoring data was corroborated by modeling done for all of the relevant conditions of use. The modeling incorporated several assumptions that could overestimate exposures such as the production volumes and the levels of removal assumed prior to release. An uncertainty related to the use of the monitoring data is that the levels of HBCD found in the environment cannot be attributed to a particular condition of use. Assuming that the monitored concentration values are attributed to each of the conditions of use individually in this evaluation is a conservative approach that does not underestimate risk for any particular condition of use. Another uncertainty introduced by using the monitoring data is that the data was collected between 5-10 years ago at a time when the use of HBCD was significantly more widespread and at much higher volumes that is currently the case. Considering that there is no evidence of current import or domestic manufacture of HBCD, use of the monitoring data is likely an overestimate of actual current levels of exposure. Therefore, while the risk estimate (RQ) is higher than the Agency benchmark, EPA does not believe that this condition of use presents an unreasonable risk to the environment. For human health, all risk estimates for the most highly exposed groups in the general population are not below Agency benchmarks. While risk estimates for some pathways of occupational exposure for this condition of use (chronic inhalation exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered (See Table 4-10). Quantitative dermal risk estimates that account for the use of gloves were not calculated for HBCD because the substance is in a solid form for this condition of use such that the use of impervious gloves is expected to

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			prevent exposures. Dermal exposures are not expected under this condition of use. EPA expects exposures to ONUs are significantly less than worker exposure. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposure to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical. Estimated exposed worker population: 39 workers; 11 ONUs
Distribution	Distribution	Distribution	Section 6(b)(4)(A) unreasonable risk determination for distribution of HBCD: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, general population) or to the environment (aquatic and terrestrial species). Risk Considerations: Activities related to distribution (e.g., loading, unloading) were considered throughout the HBCD life cycle, rather than using a single distribution scenario. Those conditions of use do not present an unreasonable risk therefore distribution also does not.

Use	Building/construction materials	Plastic articles (hard): construction and building materials covering large surface areas (e.g., EPS/XPS foam insulation in residential, public and commercial buildings, and other structures) and solder paste	Section 6(b)(4)(A) unreasonable risk determination for HBCD for use-building/construction materials: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, consumer and the general population) or the environment (aquatic and terrestrial organisms). Environment exposure scenario with highest risk estimate: Chronic toxicity to aquatic organisms Environment risk driver benchmark: RQ > 1 Environment risk estimates: RQ = 5.03 (see Table 4-3) chronic surface water RQs based on monitoring data) Human health exposure scenario with highest risk estimate: noncancer effects from chronic inhalation occupational exposure. Benchmark: MOE = 300 for thyroid effects. Risk estimate: MOE = 89 for workers using no PPE (see Table 4-10). (High end estimate). Note: There is no unreasonable risk when PPE is used. Systematic Review confidence rating (environmental hazard): High Systematic Review confidence rating (environmental exposure): High Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): High Risk Considerations: There is no evidence that domestic manufacturing or import of HBCD is occurring thus it is unknown whether this condition of

			use is current. However, since the reporting threshold under the Chemical Data Reporting (CDR) regulations for small businesses is 100,000 lbs/yr it is possible, though unlikely, that amounts at or below that threshold are domestically manufactured or imported without being reported through CDR. Using this estimate for volume introduces significant uncertainty that may overestimate exposure and risk. EPA relied upon available monitoring data to estimate risk to aquatic and sediment-dwelling organisms. This monitoring data was corroborated by modeling done for all of the relevant conditions of use. The modeling incorporated several assumptions that could overestimate exposures such as the production volumes and the levels of removal assumed prior to release. An uncertainty related to the use of the monitoring data is that the levels of HBCD found in the environment cannot be attributed to a particular condition of use. Assuming that the monitored concentration values are attributed to each of the conditions of use individually in this evaluation is a conservative approach that does not underestimate risk for any particular condition of use. Another uncertainty introduced by using the monitoring data is that the data was collected between 5-10 years ago at a time when the use of HBCD was significantly more widespread and at much higher volumes that is currently the case. Considering that there is no evidence of current import or domestic manufacture of HBCD, use of the monitoring data is likely an overestimate of actual current levels of exposure. Therefore, while the risk estimate (RQ) is higher than the Agency benchmark, EPA does not believe that this condition of use presents an unreasonable risk to the environment. For human health, all risk estimates for the most highly exposed groups in the general population and consumers are not below Agency benchmarks. Therefore, risk is not unreasonable.

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			While risk estimates for pathways of occupational exposure for this condition of use (chronic inhalation exposures and chronic dermal exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered (see Table 4-10). Quantitative dermal risk estimates that account for the use of gloves were not calculated for HBCD because the substance is in a solid form for this condition of use such that the use of impervious gloves is expected to prevent exposures. Dermal exposures are only expected for solder paste use under this for this condition of use. EPA expects exposures to ONUs are significantly less than worker exposure. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposure to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical. Estimated exposed worker population: 310-25,000 workers; 30-2,400 ONUs

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
	Other	Automobile replacement parts	Section 6(b)(4)(A) unreasonable risk determination for use; other automobile replacement parts: - Does not present an unreasonable risk of injury to health (workers, occupational non-users, consumers, general population) or to the environment (aquatic and terrestrial species). Human health exposure scenario with highest risk estimate: noncancer effects from consumer exposure. Benchmark: MOE = 100 for developmental effects. Risk estimate: MOE = 85445 (High end estimate) Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): High EPA does not expect that workers at automotive repair sites further process the replacement parts containing HBCD. Because the automotive replacement parts are received at repair shops as finished articles containing XPS and EPS foam, in which HBCD is incorporated into the foam matrix, inhalation and dermal exposures are not expected. Environmental exposures are also not expected to result from this condition of use. EPA also conducted an assessment for consumer exposures specific to the highly exposed general population and included exposure to HBCD dust and indoor air. MOEs were calculated incorporating the summation of these exposures and background general population non-dust, non-air exposures.

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
		Recycled Plastics	Section 6(b)(4)(A) unreasonable risk determination for use; other recycled plastic articles: - Does not present an unreasonable risk of injury to health (general population) or to the environment (aquatic and terrestrial species). Human health exposure scenario with highest risk estimate: noncancer effects from consumer exposure. Benchmark: MOE = 100 for developmental effects. Risk estimate: MOE = 78522 (High end estimate) Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): High Risk Considerations: This condition of use was not identified during the problem formulation for inclusion in the risk evaluation. However, during the course of conducting this risk evaluation, the Agency determined that it is appropriate to include as a condition of use and estimated risks accordingly. This condition of use is intended to address the presence of HBCD in articles resulting from those articles containing recycled materials that may contain HBCD. Environmental exposures are not expected from this condition of use and were not quantified. Human health exposures assumed mouthing of toys or other children's items which presents the highest possible exposure to HBCD in articles that contain HBCD resulting from use of recycled plastics that could contain HBCD.
Disposal	Disposal	Other land disposal (e.g.	Section 6(b)(4)(A) unreasonable risk determination for HBCD for disposal:

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
		Construction and Demolition Waste)	- Does not present an unreasonable risk of injury to health (workers, occupational non-users, consumers and the general population). Human health exposure scenario with highest risk estimate: noncancer effects from chronic inhalation occupational exposure. Benchmark: MOE = 300 for thyroid effects. Risk estimate: MOE = 65 for workers using no PPE (see Table 4-10). (High end estimate). Note: There is no unreasonable risk when PPE is used. Systematic Review confidence rating (health hazard): High Systematic Review confidence rating (health exposure): High Risk Considerations: There is no evidence that domestic manufacturing or import of HBCD is occurring thus it is unknown whether this condition of use is current. However, since the reporting threshold under the Chemical Data Reporting (CDR) regulations for small businesses is 100,000 lbs/yr it is possible, though unlikely, that amounts at or below that threshold are domestically manufactured or imported without being reported through CDR. Environmental exposures are not expected to result from this condition of use as demolition and disposal of construction waste is not expected to result in releases to water. For human health, all risk estimates for the most highly exposed groups in the general population and for consumers are not below Agency benchmarks. Therefore, risk is not unreasonable.

Life Cycle Stage	Category [b]	Subcategory [c]	Risk Determination
			While risk estimates for pathways of occupational exposure for this condition of use (chronic inhalation exposures) are below the Agency's benchmarks in the absence of PPE, risk estimates for these pathways are above those benchmarks when PPE was considered (see Table 4.X). Dermal exposures are not expected under this for this condition of use. EPA expects exposures to ONUs are significantly less than worker exposure. Risk estimates for inhalation exposure to occupational non-users were not quantified and dermal exposure to this population are not expected. For inhalation, EPA assumes that exposures are significantly less likely for workers not directly handling the chemical. Estimated exposed worker population: 5,300-420,000 workers; 510-40,000 ONUs

[a] This table presents categories and subcategories of conditions of use that are based on the 2016 CDR industrial function category and industrial sector descriptions and the OECD product and article category descriptions for the HBCD uses identified.

[b] These categories of conditions of use appear in the Life Cycle Diagram, reflect CDR codes and broadly represent conditions of use of HBCD in industrial and/or consumer settings.

[c] These subcategories reflect more specific uses of HBCD.

[d] Activities related to distribution (e.g. loading, unloading) were considered throughout the lifecycle, rather than using a single distribution scenario.

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APPENDICES

Appendix A REGULATORY HISTORY

A.1 Federal Laws and Regulations

Table_Apx A-1. Federal Laws and Regulations

Statutes/Regulations	Description of Authority/Regulation	Description of Regulation
Toxic Substances Control Act (TSCA) – Section 5(a)	Once EPA determines that a use of a chemical substance is a significant new use under TSCA section 5(a), persons are required to submit a significant new use notice (SNUN) to EPA at least 90 days before they manufacture (including import) or process the chemical substance for that use.	In September 2015, EPA promulgated a SNUR to designate manufacture or processing of HBCD for use as a flame retardant in consumer textiles (apart from use in motor vehicles) as a significant new use. Manufacturers (which includes importers) and processors are required to notify EPA 90 days before commencing the activity (80 FR 57293, September 23, 2015).
TSCA – Section 6(b)	EPA is directed to identify and begin risk evaluations on 10 chemical substances drawn from the 2014 update of the TSCA Work Plan for Chemical Assessments.	Cyclic Aliphatic Bromide Cluster (HBCD) is on the initial list of chemicals to be evaluated for unreasonable risk under TSCA (81 FR 91927, December 19, 2016).
TSCA – Section 8(a)	The TSCA section 8(a) CDR Rule requires manufacturers (including importers) to give EPA basic exposure-related information on the types, quantities and uses of chemical substances produced domestically and imported into the United States.	HBCD manufacturing (including importing), processing, and use information is reported under the CDR rule (76 FR 50816, August 16, 2011)
TSCA – Section 8(b)	EPA must compile, keep current and publish a list (the TSCA Inventory) of each chemical substance manufactured, processed or imported into the United States.	HBCD (CASRN 25637-99-4 and CASRN 3194-55-6) was on the initial TSCA Inventory and therefore was not subject to EPA's new chemicals

Statutes/Regulations	Description of Authority/Regulation	Description of Regulation
		review process (60 FR 16309; March 29, 1995).
Emergency Planning and Community Right-to-Know Act (EPCRA) – Section 313	Requires annual reporting from facilities in specific industry sectors that employ 10 or more full-time equivalent employees and that manufacture, process or otherwise use a TRI-listed chemical in quantities above threshold levels.	EPA listed HBCD on the TRI under 81 FR 85440 effective November 28, 2016. The first TRI reporting deadline for HBCD is July 1, 2018.
US EPA Policy on Evaluating Risk to Children (1995)	It is EPA's policy to consider the risks to infants and children consistently and explicitly as a part of risk assessments generated during its decision making process, including the setting of standards to protect public health and the environment. To the degree permitted by available data in each case, the Agency will develop a separate assessment of risks to infants and children.	HBCD Draft Risk Evaluation assessed risks to infants and children.
Executive Order 13045 - Protection of Children from Environmental Health Risks and Safety Risks (1997)	Executive Order (EO) 13045 pertains to environmental health or safety risk that EPA has reason to believe may disproportionately affect children. EO 13045 states that each federal agency "(a) shall make it a high priority to identify and assess environmental health risks and safety risks that may disproportionately affect children; and (b) shall ensure that its policies, programs, activities, and standards address disproportionate risks."	HBCD Draft Risk Evaluation assessed environmental health risks and safety risks that may disproportionately affect children and complied with EO 13045 (62 FR 19885; April 23, 1997).

A.2 State Laws and Regulations

Table_Apx A-2. State Laws and Regulations

State Actions	Description of Action
Classification of HBCD as Chemical of Concern to Children; law requiring reporting by manufacturers	Maine classifies HBCD as a chemical of high concern (Maine 38 M.R.S.A. § 1693-A(1)) Maine requires manufacturers or distributers to report the use of deca BDE and/or hexabromocylododecane, when intentionally added to certain children's products which are sold in the State of Maine. The first reporting deadline was August 31, 2017. (Rule Chapter 889) http://www.maine.gov/dep/safechem/
	Minnesota classifies HBCD as a chemical of high concern (Toxic Free Kids Act Minn. Stat. 2010 116.9401-116.9407)

State Actions	Description of Action
	Oregon's Toxic-Free Kids Act requires manufacturers of children's products sold in Oregon to report products containing HBCD or other high priority chemicals of concern for children's health if found at or above specific levels in those products. Ultimately, manufacturers are to remove these chemicals from certain products or seek a waiver. Products that fall under this law are those that are marketed to or intended for children. The first deadline for providing notice was January 2018.
	Washington requires manufacturers of children's products sold in Washington to report if their product contains certain chemicals of high concern to children, including HBCD. The law also bans from manufacture or sale, in the state, children's products or residential upholstered furniture containing >1,000 ppm of five flame retardants, including HBCD (Wash. Admin. Code § 173-334-130)
Other	In California, HBCD is listed as an initial informational candidate under California's Safer Consumer Products regulations, on the state's Proposition 65 list (Cal. Code Regs, tit. 22, § 69502.3, subd. (a))
	California lists HBCD as a designated priority chemical for biomonitoring. However, California has not yet started biomonitoring HBCD. (California SB 1379)
	The Oregon Department of Environmental Quality lists HBCD as a priority persistent pollutant and publishes use, exposure pathways and release data for HBCD (Oregon SB 737)
	In Massachusetts, HBCD will be reportable under the Toxics Use Reduction Act beginning in reporting year 2018. (300 CMR 41.00)

A.3 International Laws and Regulations

Table_Apx A-3. International Laws and Regulations

Country/Organization	Requirements and Restrictions
Canada	In October 2016, the Regulations Amending the Prohibition of Certain Toxic Substances Regulations, 2012 (the Amendments) were published in the Canada Gazette, Part II: Vol. 150, No. 20 - October 5, 2016 and will come into force in December 2016. The Amendments include controls on HBCD that prohibit HBCD and certain products containing the substance. Time-limited exemptions for certain uses are included to allow industry to phase-out their use of HBCD. (Government of Canada)
European Union	HBCD is listed as a substance of very high concern (SVHC) and it is also listed under Annex XIV (Authorisation list) of European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). After August 21, 2015, only persons with approved authorization applications may continue to use the chemical (European Chemicals Agency)

Country/Organization	Requirements and Restrictions
	The Waste Electrical and Electronic Equipment (WEEE) directive in the European Union requires the separation of plastics containing brominated flame retardants prior to recycling (European Commission WEEE).
Japan	HBCD is subject to mandatory reporting requirements in Japan under the Chemical Substances Control Law (CSCL); specifically, Japan requires type III monitoring for all substances that may interfere with the survival and/or growth of flora and fauna (Ministry of Economy, Trade and Industry Japan).
Stockholm Convention on POPs	In May 2013, HBCD was added to the United Nation's Stockholm Convention list of POPs with specific exemptions for production and use in EPS or XPS in buildings. As required by the convention, Parties that use these exemptions must register with the secretariat and the exemptions, unless extended in accordance with the obligations of the Convention, expire five years from after the date of entry into force of the Convention with respect to the particular chemical (SCCH, 2018b).

Appendix B LIST OF SUPPLEMENTAL DOCUMENTS

1. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment. (U.S. EPA, 2019d)*– Provides additional details and information on the exposure assessment and analyses including modeling inputs and outputs, summary of monitoring data and tornado plots.

2. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on Human Health Hazard. (U.S. EPA, 2019e)*.– Provides additional details and information of the human health hazard of HBCD, dose response analysis, dose response modeling.

3. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental File: Occupational Exposure and Environmental Releases Calculations. (U.S. EPA, 2019a)* – Provides the calculation spreadsheet for the occupational exposure and environmental releases estimates.

4. Associated Systematic Review Data Quality Documents – Provides information on data quality criteria used for evaluating individual studies.
    a. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Updates to the Data Quality Criteria for Epidemiological Studies. (U.S. EPA, 2019c)*

5. Associated Systematic Review Data Evaluation Documents – Provides additional detail and information on individual study evaluations including criteria and scoring results.
    a. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Environmental Fate and Transport Studies. (U.S. EPA, 2019l)*
    b. *Draft Risk Evaluation for Cyclic Aliphatic Bromides Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation for Occupational Exposure and Release Data. (U.S. EPA, 2019j)*
    c. *Draft Risk Evaluation for Cyclic Aliphatic Bromides Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation for Occupational Exposure and Release Data for Common Sources. (U.S. EPA, 2019i)*
    d. *Draft Risk Evaluation for Cyclic Aliphatic Bromides Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of General Population and Environmental Exposure Studies . (U.S. EPA, 2019m)*
    e. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Ecological Hazard Studies . (U.S. EPA, 2019k)*
    f. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Quality Evaluation of Human Health Hazard Studies . (U.S. EPA, 2019n)*

6. Associated Systematic Review Data Extraction Documents – Provides data extracted from acceptable studies following evaluation of individual studies.
    a. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables of Environmental Fate and Transport Studies. (U.S. EPA, 2019h)*

b. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables for Human Health Hazard Studies (In Vivo and In Vitro Toxicity Studies). (U.S. EPA, 2019g)*
c. *Draft Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables of Environmental Hazard Studies.*
d. *Draft Risk Evaluation for Cyclic Aliphatic Bromides Cluster (HBCD), Systematic Review Supplemental File: Data Extraction of General Population and Environmental Exposure Studies (U.S. EPA, 2019f)*

Appendix C FATE AND TRANSPORT

C.1 Biodegradation

A closed bottle screening-level test for ready biodegradability (OECD Guideline 301D, EPA OTS 796.3200) was performed using an initial HBCD concentration of 7.7 mg/L and an activated domestic sludge inoculum (Schaefer and Haberlein, 1996 as cited in (ECHA, 2008b); IUCLID, 2005). No biodegradation was observed (0% of the theoretical oxygen demand) over the test period of 28 days under the stringent guideline conditions of this test.

Degradation of HBCD during simulation tests with viable microbes, based on OECD 307 and 308, was approximately 61% in anaerobic freshwater sediment, 44% in aerobic freshwater sediment, and 10% in aerobic soil after 112–113 days (Davis et al., 2006; ECB, 2008). The results from this study correspond to estimated HBCD half-lives of 92 days in anaerobic freshwater sediment, 128, 92, and 72 days for α-, γ-, and β--HBCD, respectively in aerobic freshwater sediment, and >120 days in aerobic soil. An initial total 14C-HBCD concentration of 3.0–4.7 mg/kg dry weight in the sediment and soil systems was used, allowing for quantification of individual isomers, metabolite identification, and mass balance evaluation (Davis et al., 2006; NICNAS, 2012). Although very high spiking rates can be toxic to microorganisms in biodegradation studies and lead to unrealistically long estimated half-lives, the results of this study did not suggest toxicity to microorganisms. Tests with viable microbes demonstrated increased HBCD degradation compared to the biologically inhibited control studies. In combination, these studies suggest that HBCD will degrade slowly in the environment, although faster in sediment than in soil, faster under anaerobic conditions than aerobic conditions, faster with microbial action than without microbial action, and at different rates for individual HBCD diastereomers (slower for α-HBCD than for the γ- and β- stereoisomers. The same researchers previously conducted a water-sediment simulation test for commercial HBCD based on OECD guideline 308 using nominal HBCD concentrations of 0.034–0.089 mg/kg dry weight (Davis et al., 2003b, 2005; IUCLID, 2005; ECB, 2008). Aerobic and anaerobic microcosms were pre-incubated at 20 °C for 49 days and at 23 °C for 43–44 days, respectively. HBCD was then added to 14–37 g dry weight freshwater sediment samples in 250 ml serum bottles (water:sediment ratio of 1.6–2.9) and the microcosms were sealed and incubated in the dark at 20 °C for up to 119 days. For the aerobic microcosms, the headspace oxygen concentration was kept above 10–15%. This study evaluated only γ-HBCD and did not address interconversion of HBCD isomers or α- and β-HBCD degradation. Disappearance half- lives of HBCD with sediment collected from Schuylkill River and Neshaminy creek were 11 and 32 days in viable aerobic sediments, respectively (compared to 190 and 30 days in abiotic aerobic controls, respectively), and 1.5 and 1.1 days in viable anaerobic sediments, respectively (compared to 10 and 9.9 days in abiotic anaerobic controls).Data from these tests suggest that anaerobic degradation is faster than aerobic degradation of HBCD in viable and abiotic sediments and that degradation is faster in viable conditions than abiotic conditions. While these findings are consistent with Davis et al. (2006), the actual degradation rates in this study are much faster. However, results from this study do not provide a reliable indication of HBCD persistence. A mass balance could not be established because only γ-HBCD was used to quantify HBCD concentrations, ^{14}C-radiolabeled HBCD was not used, and degradation products were not identified; therefore, apparent disappearance of HBCD in this study may not reflect biodegradation. In addition, there were concerns that contaminated sediment may have been used, HBCD extraction was incomplete (HBCD recovery varied from 33 to 125 %), and an interfering peak was observed in the LC/MS chromatograms corresponding to γ-HBCD (NICNAS, 2012a; ECHA, 2008b).

Similarly, a soil simulation test was conducted based on OECD guideline 307 for commercial HBCD using 50 g dry weight sandy loam soil samples added to 250 ml serum bottles (Davis et al., 2003a, (Davis et al., 2005)IUCLID, 2005;(ECHA, 2008b). The moisture content was 20% by weight. Aerobic and anaerobic microcosms were pre-incubated at 20 °C for 35 days and at 23 °C for 43 days, respectively. Activated sludge was added to the soil at 5 mg/g, and HBCD was added to the soil to achieve a nominal concentration of 0.025 mg/kg dry weight. The microcosms were then incubated in the dark at 20 °C for up to 120 days. The disappearance half- lives were 63 days in viable aerobic soil (compared to >120 days in abiotic aerobic controls) and 6.9 days in viable anaerobic soil (compared to 82 days in abiotic anaerobic controls). As in the sediment studies, HBCD degradation in soil occurred faster under anaerobic conditions compared to aerobic conditions, and faster in viable conditions than abiotic conditions. The disappearance half-lives in soil were slower than those in sediment.

Biological processes were suggested to be responsible for the increased degradation of HBCD in this study using viable conditions, relative to abiotic conditions; however, degradation was not adequately demonstrated in soil because no degradation products were detected and only γ-HBCD was used to quantify HBCD concentrations, making it impossible to calculate a mass balance. HBCD recoveries on day 0 of the experiment were well below (0.011–0.018 mg/kg dry weight) the nominal test concentrations (0.025 mg/kg dry weight), suggesting rapid adsorption of HBCD to soil and poor extraction methods (NICNAS, 2012a; ECHA, 2008b).

In studies using 0.025–0.089 mg/kg HBCD (Davis et al., 2005), the estimated half-life values were shorter than studies using 3.0–4.7 mg/kg HBCD (Davis et al., 2006) by approximately one order of magnitude for aerobic, viable sediment (11–32 days compared to 72– 128 days) and anaerobic viable sediment (1.1–1.5 days compared to 92 days). The viable aerobic soil half-life using lower concentrations of HBCD (Davis et al., 2005) was less than half of the half-life based on the higher HBCD concentration (63 days compared to >120 days) (Davis et al., 2006). Both Davis et al. ((Davis et al., 2006; Davis et al., 2005) studies suggest that HBCD degrades faster in sediment than in soil, faster under anaerobic conditions than aerobic conditions, and faster with microbial action than without microbial action. HBCD is poorly soluble, and it was suggested that at higher concentrations of HBCD, degradation is limited by mass transfer of HBCD into microbes. However, results from the Davis et al. (2005) study likely overestimate the rate of HBCD biodegradation, for the reasons noted above (primarily, failure to use ^{14}C-radiolabeled HBCD, quantify isomers other than γ-HBCD, identify degradation products, or establish a mass balance, but also procedural problems with contamination of sediment, incomplete HBCD extraction, and occurrence of an interfering peak in the LC/MS chromatograms corresponding to γ-HBCD).

Furthermore, the rapid biodegradation rates from Davis et al. (2005) are not consistent with environmental observations. HBCD has been detected over large areas and in remote locations in environmental monitoring studies. Dated sediment core samples indicate slow environmental degradation rates (NICNAS, 2012a; Marvin et al., 2011; ECHA, 2008b; Davis et al., 2005). For example, HBCD was found at concentrations ranging from 112 to 70,085 µg/kg dry weight in sediment samples collected at locations near a production site in Aycliffe, United Kingdom 2 years after the facility was closed down (ECHA, 2008b). Monitoring data do not provide a complete, quantitative determination of persistence because HBCD emission sources, rates, and quantities are typically unknown, and all environmental compartments are not considered. However, the monitoring data do provide evidence in support of environmental persistence.

Rapid HBCD biodegradation has been demonstrated under laboratory conditions not representative of typical environmental conditions. A study designed to elucidate HBCD degradation mechanisms and

optimize biodegradation capability reported an HBCD degradation half-life of only 0.66 days in anaerobic digested sewage sludge amended with yeast and starch at 37 °C. In this test, α-HBCD had lower susceptibility to degradation than β- or γ-HBCD (Gerecke et al., 2006). The authors noted that these results are specific to the anaerobic conditions established by the experiment, and that the degradation rate constants are expected to vary based on redox conditions of each specific anaerobic environment.

C.2 Bioconcentration/Bioaccumulation

HBCD has been shown in numerous studies to bioaccumulate and biomagnify in aquatic and terrestrial food chains.

Bioisomerization

In general, α-HBCD bioaccumulates in organisms and biomagnifies through food webs to a greater extent than the β- and γ- diastereomers. Uncertainty remains as to the balance of diastereomer accumulation in various species and the extent to which bioisomerization and biotransformation rates for each isomer affect bioaccumulation potential. Some authors (e.g., (Law et al., 2006)) have proposed that γ-HBCD isomerizes to α-HBCD under physiological conditions, rather than uptake being diastereoisomer-specific. To test this theory, Esslinger et al. (Esslinger et al., 2010) exposed mirror carp (*Cyprinus carpio morpha noblis*) to only γ-HBCD and found no evidence of bioisomerization. In contrast, when Du et al. (Du et al., 2012) exposed zebrafish (*Danio rerio*) to only γ-HBCD, they found detectable levels of α-HBCD in fish tissue, suggesting that bioisomerization occurred. Marvin et al. (Marvin et al., 2011) hypothesized that differences in accumulation could also be due in part to a combination of differences in solubility, bioavailability, and uptake and depuration kinetics.

(Zhang et al., 2014a) calculated diastereomer-specific BCFs in algae and cyanobacteria ranging from 174 to 469. For the cyanobacteria (*Spirulina subsalsa*), the BCF for α-HBCD (350) was higher than the BCFs for β-HBCD (270) and γ-HBCD (174). However, for the tested alga (*Scenedesmus obliquus*), the BCF for β-HBCD (469) was higher than that for the other isomers (390 – 407).

Bioconcentration

BCFs for HBCD in fish in the peer-reviewed literature range as high as 18,100, as shown in Appendix C.2 Drottar(Zhang et al., 2014b; 2000; Veith et al., 1979). Drottar and Krueger (2000) provided strong evidence that HBCD bioaccumulates in a bioconcentration test that was conducted according to guidelines OECD Test Guideline (TG) 305 and Office of Prevention, Pesticides and Toxic Substances (OPPTS) 850.1730. In this study, BCFs of 13,085 and 8,974 were reported in rainbow trout (*O. mykiss*) exposed to 0.18 and 1.8 µg/L, respectively. Concentrations of HBCD in tissue reached steady-state at day 14 for fish exposed to 1.8 µg/L and, during the subsequent depuration stage, a 50% reduction of HBCD from edible and non-edible tissue and whole fish was reported on days 19 and 20 post-exposure. In fish exposed to 0.18 µg/L, an apparent steady-state was reached on day 21, but on day 35, the tissue concentration of HBCD in fish increased noticeably; thus, steady-state was not achieved according to study authors, and BCF values (for the exposure concentration of 0.18 µg/L) were calculated based on day 35 tissue concentrations. A kinetic BCF value 14039 for the 0.18 µg/L exposure concentration was calculated to address the possibility that steady state was not reached (ECHA, 2008b). Clearance of 50% HBCD from tissue of 0.18 µg/L exposed fish occurred 30 – 35 days post-exposure.

Veith et al. (Veith et al., 1979) further supports a conclusion that HBCD bioaccumulates in a study conducted prior to the establishment of standardized testing guidelines for bioconcentration studies. The

study reported a BCF of 18,100 following exposure of fathead minnow to 6.2 µg/L; the BCF was identified as a steady-state BCF, but the report does not indicate time when steady- state was reached. A depuration phase was not included in this study. Zhang et al. (Zhang et al., 2014b) calculated BCFs for each diastereomer in mirror carp and found strong evidence that α-HBCD (BCF of 5,570 – 11,500) is much more bioaccumulative than β- and γ-HBCD (BCF of 187 – 642); BCF values that were normalized to lipid content were much higher (30,700 – 45,200 for α-HBCD, 1,030 – 1,900 for β-HBCD, and 950 – 1,730 for γ-HBCD) than non-normalized BCFs.

Bioaccumulation

BAFs, which capture accumulation of HBCD from diet as well as water and sediment, were calculated for freshwater food webs in industrialized areas of Southern China in two separate field studies. He et al. (He et al., 2013) calculated log BAFs of 4.8 – 7.7 (corresponding to BAFs of 63,000 – 50,000,000) for HBCD isomers in carp, tilapia, and catfish, and found higher BAFs for α-HBCD than β- and γ-HBCD. In a pond near an e-waste recycling site, Wu et al. (Wu et al., 2011) calculated log BAFs of 2.85 – 5.98 for ΣHBCD (corresponding to BAFs of 700 – 950,000) in a freshwater food web. Log BAFs for each diastereomer in this study were comparable to one another (see Appendix C.2). La Guardia et al. (La Guardia et al., 2012) calculated log BAFs in bivalves and gastropods collected downstream of a textile manufacturing outfall; these ranged from 4.2 to 5.3 for α- and β-HBCD (BAFs of 16,000 – 200,000), and from 3.2 to 4.8 for γ-HBCD (BAFs of 1,600 – 63,000).

Biota Sediment Accumulation

BSAFs calculated in studies of invertebrates and fish are generally lower than reported BCFs and BAFs. Haukås et al. (Haukås et al., 2010a) reported BSAFs ≤0.006 calculated from lipid-normalized concentrations of HBCD in ragworms and HBCD concentrations normalized to total organic content in sediment, indicating very low bioavailability of HBCD from sediments. Ragworm tissue concentrations were all less than the limit of detection. The pattern of diastereomers in sediments was found to generally resemble the composition of technical HBCD (i.e., predominantly γ-HBCD). This study also found that in ragworms exposed to HBCD through a diet of contaminated mussels (containing diastereomer contributions of 48% α-HBCD, 7% β-HBCD, and 45% g-HBCD), the tissue concentration of α-HBCD was greater than that of β-HBCD or γ-HBCD, suggesting selective bioaccumulation of the α-diastereomer.

Log BSAFs calculated in bivalves and gastropods collected downstream of a textile manufacturing outfall ranged from 0 to 0.9 (for α- and β-HBCD) and from -1.5 to 0 (for γ-HBCD) (La Guardia et al., 2012). These correspond to BSAFs of 1 – 8 for α- and β-HBCD and 0.03 – 1 for γ-HBCD. BSAFs in benthivorous barbell (*Barbus graellsii*) and pelagic bleak (*Alburnus alburnus*) were calculated based on measured concentrations of HBCD reported in Eljarrat et al. (2004, 2005) as cited in (van Beusekom et al., 2006) and ranged from 0.1 to 1.44 and from 0.14 to 1.23, respectively (van Beusekom et al., 2006).

Biomagnification of HBCD was demonstrated by Law et al. (Law et al., 2006), who reported BMFs of 9.2 (α-HBCD), 4.3 (β-HBCD), and 7.2 (γ-HBCD). Uptake of HBCD into muscle from the diet of rainbow trout was exponential for α-HBCD with a doubling time of 8.2 days, exponential for β-HBCD with a doubling time of 17.1 days, and linear for γ-HBCD with a rate constant of 0.006 per day. Depuration was rapid during the first 14 days and slower for the remainder of the experiment for α-HBCD (overall depuration rate was not determined). Depuration rates of 0.44×10^{-2} and 0.48×10^{-2} per day were found for β-HBCD and γ-HBCD, respectively. Steady- state was not reached for any of the diastereomers within the 52-day exposure period.

Biomagnification

Additional studies are available that support the conclusion that HBCD has the potential to biomagnify. Studies of zebrafish by Du et al. (Du et al., 2013; Du et al., 2012) reported diastereo- and enantiomer-specific biomagnification. When BMFs were calculated for diastereomers without accounting for specific enantiomers, after 42 days of exposure and a 21-day depuration period, α-HBCD was shown to biomagnify to a greater extent than β- and γ-HBCD (maximum BMFs of 29.71, 11.63, and 7.76, respectively). Enantiomer-specific BMFs calculated in zebrafish by Du et al. (Du et al., 2013) followed a similar diastereomer pattern, although the BMF values were much lower than those from Du et al. (Du et al., 2012). Additionally, the results of Du et al. (Du et al., 2013) suggest that the (+) enantiomers of β- and γ-HBCD are selectively magnified compared to their (−) enantiomers. This pattern did not hold true for α-HBCD.

Letcher et al. (Letcher et al., 2009) found evidence of biomagnification of HBCD from the ringed seal to the polar bear in an East Greenland food web, reporting a BMF of 1.7. BMFs for α-HBCD in a harbor seal food web varied according to prey fish species, but ranged from 0.54 to 3.0 (Shaw et al., 2012). Shaw et al. (Shaw et al., 2012) calculated higher BMFs from prey fish to the livers of adult male harbor seals than to the blubber of those seals.

BMFs for α-HBCD in gulls and common eiders in a coastal marine food web in Norway provide evidence of biomagnification, ranging from 3.1 to 1,285 when calculated on a wet weight basis and from 2.8 to 26 when calculated on a lipid-weight basis (Haukås et al., 2010b). In terrestrial food webs in China, both Sun et al. (Sun et al., 2012) and Yu et al. (Yu et al., 2013) found evidence of biomagnification (see Appendix C.2), with BMFs up to 30 in passerine birds and up to 16 in owls. Yu et al. (Yu et al., 2013) found more (−) α-HBCD in predator species than (+) α-HBCD, but other studies do not agree, suggesting that enantiomer biomagnification may be species-specific.

Trophic Transfer/Trophic Magnification

Tomy et al.(Tomy et al., 2008) describes the extent of trophic transfer (transfer and accumulation of HBCD between trophic levels) by calculating TMFs of 2.1 and 0.5 for α- and γ-HBCD, respectively, based on the Arctic marine food web. Samples of blubber were taken and analyzed from the beluga whale (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), and walrus (*Odobenus rosmarus*), while whole organisms were analyzed for arctic cod (*Boreogadus saida*), shrimp (*Pandalus borealis* and *Hymenodora glacialis*), clams (*Mya truncate* and *Serripes groenlandica*), deepwater redfish (*Sebastes mentella*), and mixed zooplankton to determine HBCD concentrations in the tissue of animals of different trophic levels in order to establish whether HBCD biomagnifies between trophic levels.

Brandsma et al. (Brandsma et al., 2015) studied trophic magnification of HBCD through benthic and pelagic food webs in the Western Scheldt estuary, The Netherlands, and found similar results: α-HBCD concentrations increased and γ-HBCD concentrations decreased with an increase in trophic level (TMFs of 2.2 and 0.3, respectively). In a freshwater food web studied near an e-waste recycling site in South China, Wu et al. (Wu et al., 2010) calculated enantiomer-specific TMFs for α-HBCD of 2.18 – 2.2, and found evidence that as HBCD migrates up through the food web, α-HBCD increases and γ-HBCD decreases, while β-HBCD comprises a very low proportion of ∑HBCD. This pattern, also demonstrated by data in Haukås et al. (Haukås et al., 2010b), becomes more prominent at upper trophic levels. In marine and freshwater food webs, Zhang et al. (Zhang et al., 2013) calculated TMFs greater than 1 for α-HBCD and ΣHBCD.

In summary, while HBCD has been shown in numerous studies to bioaccumulate and biomagnify in aquatic and terrestrial food chains, diastereomer- and enantiomer-specific mechanisms of accumulation are still unclear.

C.3 Calculation of Lipid Normalized Bioaccumulation Factors for HBCD

The lipid normalized bioaccumulation factors were calculated for:

1) He et al. 2013 using mean concentration for total HBCDs in field collected Nile tilapia and Plecostomus expressed as lipid weight and total HBCD concentrations in the dissolved phase in water.

The lipid normalized BAF calculations are presented below where:

$$BAF = C_B/C_{WD}$$

C_B = chemical concentration in the organism (g/kg LW)
C_{WD} = freely dissolved chemical concentration in the water (g/L)

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Sample	Mean concentration total HBCDs	Conversion	BAF
Nile tilapia	92 ng/g lw	C_B = 9.2e-5 g/kg	2.32E6
Plecostomus	361 ng/g lw	C_B = 0.000361 g/kg	9.09E6
Mud carp	58.3 ng/g lw	C_B = 5.83e-5 g/kg	1.47E6
Water, dissolved phase	39.7 pg/L	C_{WD} = 3.97e-11 g/L	n/a

Underlying data:

Table 1
Concentrations of TBBPA and HBCDs in sediment, sediment cores, water, and fish in the Dongjiang River, South China.

	Sediment (ng/g dw)	Sediment cores (ng/g dw)		Water		Fish (ng/g lw)		
		Core 1	Core 2	Dissolved phase	Particulate phase	Mud carp	Nile tilapia	Plecostomus
	N = 42	*N* = 19	*N* = 19	*N* = 5 (pg/L)	*N* = 5 (ng/g dw)	*N* = 9	*N* = 15	*N* = 10
Lipid (%)						2.7 (1.2–4.7)	3.7 (1.6–9.0)	3.2 (1.8–5.7)
TBBPA	15.2 (nd–82.3)	91.6 (7.9–450)	2.9 (0.2–14)	1750 (1110–2830)	1.3 (nd[a]–1.6)[b]	35.2 (6.5–66)	18.1 (nd–51)	21.2 (nd–53.4)
α-HBCD	0.94 (nd–3.3)	1.8 (0.2–8.2)	0.8 (0.2–2.1)	16.0 (7.5–27.6)	3.9 (nd–3.9)	47.3 (17.5–114)	83.6 (nd–361)	353 (nd–825)
β-HBCD	0.33 (nd–2.2)	0.5 (0.1–2.2)	0.3 (0.1–0.6)	4.3 (nd–7.1)	0.9 (nd–0.9)	3.6 (nd–6.7)	5.6 (nd–19.5)	6.2 (nd–9.2)
γ-HBCD	5.7 (0.06–28.9)	6.2 (0.8–42.8)	4.2 (0.3–20.5)	25.2 (nd–54.6)	6.8 (nd–11.3)	12.6 (nd–33.4)	6.3 (nd–11.4)	6.5 (nd–10.4)
∑HBCD	6.9 (0.07–31.6)	8.5 (0.5–53.1)	5.3 (1.2–22.6)	39.7 (9.5–82.4)	8.0 (nd–11.3)	58.3 (17.5–154)	92 (nd–391)	361 (nd–832)

[a] Non detected.
[b] Mean (range).

2) Wu et al. 2010 using mean concentration for total HBCDs in field collected mud carp and Northern snakehead expressed as lipid weight and total HBCD concentrations in the dissolved phase in water.

Sample	Mean concentration total HBCDs	Conversion	BAF
Mud Carp	868 ng/g lw	C_B = 0.000868 g/kg	1.45E7
Northern Snakehead	187 ng/g lw	C_B = 0.000187 g/kg	3.12E6
Water, dissolved phase	0.06 ng/L	C_{WD} = 6e-11 g/L	n/a

Underlying data:

TABLE 1. Concentrations of HBCDs and Other Non-PBDE Brominated Flame Retardants in the Aquatic Species (ng/g lipid), Dissolved Phase of Water (ng/L), and Sediment (ng/g wet wt) from an E-waste Recycling Site, South China

	Chinese mysterysnail n = 43, [3][a]	prawn n = 7, [3]	mud carp n = 12, [8]	cruciancarp n = 18, [7]	northern snakehead n = 6	water snake n = 2	water n = 6, [3]	sediment n = 6, [3]
lipid (%)	0.59 ± 0.11[b]	2.39 ± 0.32	2.87 ± 0.41	3.63 ± 0.71	1.49 ± 0.31	1.06 ± 0.15		
α-HBCD	7.73 ± 1.83	267 ± 80.9	649 ± 228	102 ± 32.8	168 ± 82.4	494 ± 315	0.05 ± 0.01	61.4 ± 10.2
β-HBCD	0.24 ± 0.24	10.2 ± 2.74	24.5 ± 9.48	5.42 ± 3.39	3.12 ± 1.76	8.76 ± 6.22	bdl[c]	23.5 ± 1.07
γ-HBCD	5.90 ± 1.25	118 ± 29.3	195 ± 66.9	21.1 ± 8.83	16.6 ± 9.06	64.0 ± 42.8	0.01 ± 0.00	84.3 ± 4.22
ΣHBCDs[d]	13.9 ± 2.61	395 ± 94.5	868 ± 280	129 ± 44.3	187 ± 92.7	567 ± 364	0.06 ± 0.01	169 ± 12.1
BTBPE	67.1 ± 36.4	44.7 ± 8.04	518 ± 277	323 ± 315	1.71 ± 1.11	9.22 ± 9.22	0.02 ± 0.01	4554 ± 608
DBDPE	bdl	84.3 ± 84.3	338 ± 171	14.0 ± 14.0	bdl	bdl	bdl	1796 ± 770
HBB	298 ± 51.3	197 ± 53.4	2451 ± 778	680 ± 158	1153 ± 470	3099 ± 2809	0.52 ± 0.04	8672 ± 1053
PBEB	14.3 ± 2.53	6.35 ± 2.52	25.6 ± 11.1	3.98 ± 2.10	17.5 ± 5.53	4.14 ± 4.14	0.06 ± 0.00	132 ± 6.12
PBT	3.60 ± 0.90	1.55 ± 0.64	3.24 ± 1.51	1.59 ± 0.45	1.20 ± 0.57	106 ± 103	0.03 ± 0.01	20.6 ± 2.89
BDE 47[e]	4270 ± 820	4640 ± 1330	20910 ± 3740	5860 ± 1480	25960 ± 4020	51870 ± 29940	10.7 ± 0.14	44130 ± 717

[a] Numer of individual samples collected, figures in brackets indicate analyses number of pooled samples when individuals were pooled. [b] Mean ± SE. [c] Below the detection limit. [d] total HBCDs. [e] Data from ref *30* given for comparison.

The concentration of a chemical in an organism can be expressed based on several different measurements: wet weight (WW), dry weight (DW) or lipid weight (LW). Lipid normalizing is a method of expressing the chemical concentration on a lipid weight basis by dividing the WW chemical concentration by the lipid fraction of the measured sample.

$$BAF_{LW} = \frac{BAF_{WW}}{\text{lipid fraction}}$$

Appendix D RELEASES TO THE ENVIRONMENT

Table_Apx D-1 includes a crosswalk between the subcategories of use listed in the *Problem Formulation Document for Cyclic Aliphatic Bromides Cluster (HBCD)* and the conditions of use assessed in this risk evaluation, with the associated environmental release assessment sections.

Table_Apx D-1. Crosswalk of Subcategories of Use Listed in the Problem Formulation Document to Conditions of Use Assessed in the Risk Evaluation for Environmental Releases

Life Cycle Stage	Category [a]	Subcategory [b]	Assessed Condition of Use
Manufacture	Import	Import	Section 2.2.2 – Processing: Repackaging of Import Containers
Processing	Processing - incorporated into formulation, mixture or reaction product	Flame retardants used in custom compounding of resin (e.g., compounding in XPS masterbatch) and in solder paste	Section 2.2.3 – Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch Section 2.2.12 – Processing: Formulation of Flux/Solder Pastes
	Incorporated into article	Flame retardants used in plastics product manufacturing (manufacture of XPS and EPS foam; manufacture of structural insulated panels (SIPS) and automobile replacement parts from XPS and EPS foam)	Section 2.2.4 – Processing: Manufacturing of XPS Foam using XPS Masterbatch Section 2.2.5 – Processing: Manufacturing of XPS Foam using HBCD Powder Section 2.2.6 – Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads Section 2.2.7 – Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam
	Recycling	Recycling of XPS and EPS foam, resin, panels containing HBCD	Section 2.2.11 – Recycling of EPS Foam and Reuse of XPS Foam
Distribution	Distribution	Distribution	Activities related to distribution (e.g., loading, unloading) are considered throughout the life cycle, rather than using a single distribution scenario.
Commercial/consumer Use	Building/construction materials	Plastic articles (hard): construction and building materials covering large surface areas (e.g., EPS/XPS foam insulation in residential, public and commercial buildings, and other structures) and solder paste	Section 2.2.9 – Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures Section 2.2.13 – Use of Flux/Solder Pastes
	Other	Automobile replacement parts	Section 2.2.8 – Use: Installation of Automobile Replacement Parts

Life Cycle Stage	Category [a]	Subcategory [b]	Assessed Condition of Use
Disposal	Disposal	Other land disposal (e.g. Construction and Demolition Waste)	Section 2.2.10 – Demolition and Disposal of XPS/EPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures

[a] These categories of conditions of use appear in the Life Cycle Diagram, reflect CDR codes, and broadly represent conditions of use of HBCD in industrial and/or commercial settings.
[b] These subcategories reflect more specific uses of HBCD.

D.1 2017 TRI Releases Not Used in this Assessment

Table_Apx D-2. presents 2017 TRI data that was not used in this assessment. These HBCD release data were reported by Flame Control Coatings, LLC for one site that previously used HBCD as a component in flame regarded coatings. These TRI releases were not used in the assessment because Flame Control Coatings, LLC has indicated that they have ceased use of HBCD and the use of coatings is not a condition of use in this risk evaluation, as discussed in the *Uses and Production Volume* section (Section 2.2) of the Risk Evaluation.

Table_Apx D-2. 2017 TRI Data Not Used in this Assessment

Site Identity	Reported NAICS Code -Meaning	Function Inferred from Communication with Company	Annual HBCD Release per Site (kg/site-year)
Flame Control Coatings, LLC, Niagara NY	325510 - Paint and Coating Manufacturing	Flame retardant in architectural coatings	Fugitive air [a]: 0.612 Stack air [b]: 5.505

[a] These fugitive air releases were reported under Section 5.1 of the TRI Form R, which correspond to on-site fugitive or non-point air emissions.
[b] These stack air releases were reported under Section 5.2 of the TRI Form R, which correspond to on-site stack or point air emissions.

D.2 Evaluation of Environmental Release Data Sources

EPA has reviewed acceptable sources for HBCD release data according to the data quality evaluation criteria found in *The Application of Systematic Review in TSCA Risk Evaluations*(U.S. EPA, 2018a). Table_Apx D-3 summarizes the results of this evaluation. The data quality evaluation indicated the release sources included are of medium to high confidence and are used to characterize releases of HBCD.

Table_Apx D-3. Summary of Release Data and Systematic Review Results

Row	Condition of Use	Release Data from Source		Source	Data Identifier from Data Extraction and Evaluation (DEE)	Overall Confidence Rating from DEE	Rationale for Inclusion / Exclusion
		Identifier	Release				
1	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Site 1	Water: 0.12 kg HBCD/yr Air: 2.6 kg HBCD/yr	(ECHA, 2008b)	3970747	High	Included - EPA calculated emission factors from these data and used them to estimate releases in the corresponding condition of use
2	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Site 2	Water: 0.27 kg HBCD/yr Air: 1.2 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
3	Compounding of Polystyrene Resin to Produce XPS Masterbatch	Site 3	Water: 37 kg HBCD/yr Air: 3.3 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
4	Manufacturing of XPS Foam using XPS Masterbatch	Site 1	Water: 2.2 kg HBCD/yr Air: 0.31 kg HBCD/yr	(ECHA, 2008b)	3970747	High	Included - EPA calculated emission factors from these data and used them to estimate releases in the corresponding condition of use
5	Manufacturing of XPS Foam using XPS Masterbatch	Site 2	Water: 0 kg HBCD/yr Air: 18 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
6	Manufacturing of XPS Foam using XPS Masterbatch	Site 3	Water: 1.3 kg HBCD/yr Air: 14 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
7	Manufacturing of XPS Foam using XPS Masterbatch	Site 4	Water: 4.2 kg HBCD/yr Air: 9.3 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
8	Manufacturing of XPS Foam using XPS Masterbatch	Calculated Site Estimate - reported by EURAR as worst-case emission factor derived from site-specific data	Water: 7.9 kg HBCD/yr Air: 17.4 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
9	Manufacturing of XPS Foam using HBCD Powder	Site 1	Water: 4.4 kg HBCD/yr Air: 1.5 kg HBCD/yr	(ECHA, 2008b)	3970747	High	Included - EPA calculated emission factors from these data and used them to estimate releases in the corresponding condition of use
10	Manufacturing of XPS Foam using HBCD Powder	Site 2	Water: 1.2 kg HBCD/yr Air: 1.4 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
11	Manufacturing of XPS Foam using HBCD Powder	Site 3	Water: 0.055 kg HBCD/yr Air: 3.7 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
12	Manufacturing of XPS Foam using HBCD Powder	Site 4	Water: 3.7 kg HBCD/yr Air: 1.5 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
13	Manufacturing of XPS Foam using HBCD Powder	Site 5	Water: 0.0024 kg HBCD/yr Air: 1.1 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
14	Manufacturing of XPS Foam using HBCD Powder	Site 6	Water: 0 kg HBCD/yr Air: 0.73 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
15	Manufacturing of XPS Foam using HBCD Powder	Site 7	Water: 6 kg HBCD/yr Air: 0.54 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
16	Manufacturing of XPS Foam using HBCD Powder	Site 8	Water: 0.0029 kg HBCD/yr Air: 0.7 kg HBCD/yr	(ECHA, 2008b)	3970747	High	

Row	Condition of Use	Release Data from Source		Source	Data Identifier from Data Extraction and Evaluation (DEE)	Overall Confidence Rating from DEE	Rationale for Inclusion / Exclusion
		Identifier	Release				
17	Manufacturing of XPS Foam using HBCD Powder	Site 9	Water: 0.0019 kg HBCD/yr Air: 0.15 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
18	Manufacturing of XPS Foam using HBCD Powder	Site 10	Water: 0 kg HBCD/yr Air: 0.4 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
19	Manufacturing of XPS Foam using HBCD Powder	Site 11	Water: 0 kg HBCD/yr Air: 1.8 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
20	Manufacturing of XPS Foam using HBCD Powder	Site 12	Water: 0 kg HBCD/yr Air: 1.8 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
21	Manufacturing of XPS Foam using HBCD Powder	Site 13	Water: 0.11 kg HBCD/yr Air: 1.2 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
22	Manufacturing of XPS Foam using HBCD Powder	Site 14	Water: 15 kg HBCD/yr Air: 1.5 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
23	Manufacturing of XPS Foam using HBCD Powder	Site 15	Water: 0.00004 kg HBCD/yr Air: 0.59 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
24	Manufacturing of XPS Foam using HBCD Powder	Site 16	Water: 0.0004 kg HBCD/yr Air: 0.91 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
25	Manufacturing of XPS Foam using HBCD Powder	Site 17	Water: 0.021 kg HBCD/yr Air: 3.8 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
26	Manufacturing of XPS Foam using HBCD Powder	Site 18	Water: 2.5 kg HBCD/yr Air: 0.23 kg HBCD/yr	(ECHA, 2008b)	3970747	High	
27	Manufacturing of XPS Foam using XPS Masterbatch; Manufacturing of XPS Foam using HBCD Powder; Manufacturing of EPS Foam from Imported EPS Resin Beads	Dow Chemical Company, Pevely MO	Stack air: 1.81 kg HBCD/yr Off-site transfer for Incineration/thermal treatment: 30.8 kg HBCD/yr Off-site M64, off-site transfer for disposal to other landfills: 123 kg HBCD/yr	2017 TRI, 5079078	2017 TRI	Medium	Excluded - per the company, operations with HBCD have ceased
28	Manufacturing of XPS Foam using XPS Masterbatch; Manufacturing of XPS Foam using HBCD Powder; Manufacturing of EPS Foam from Imported EPS Resin Beads	Dow Chemical Company, Dalton GA	Stack air: 21.3 kg HBCD/yr Off-site M64, off-site transfer for disposal to other landfills: 109 kg HBCD/yr Off-site M56, off-site transfer for Energy Recovery: 23.1 kg HBCD/yr	2017 TRI, 5079078	2017 TRI	Medium	Excluded - per the company, operations with HBCD have ceased
29	Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam; Installation of EPS/XPS Foam Insulation in Residential, Public and	XPS Boards	5 g XPS particles/metric ton XPS sawed	(ECHA, 2008b)	3970747	High	Included - emission factors were used in the corresponding conditions of use

Row	Condition of Use	Release Data from Source		Source	Data Identifier from Data Extraction and Evaluation (DEE)	Overall Confidence Rating from DEE	Rationale for Inclusion / Exclusion
		Identifier	Release				
	Commercial Buildings, and Other Structures						
30	Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam; Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	EPS Boards	445 g EPS particles/metric ton EPS sawed	(ECHA, 2008b)	3970747	High	
31	Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam; Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	EPS Boards	100 g EPS particles/metric ton EPS cut	ECHA, 2008(ECHA, 2008b)	3970747	High	
32	Demolition and Disposal of EPS/XPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures	Manual breaking of EPS boards	90 g EPS particles/metric ton EPS broken	(ECHA, 2008b)	3970747	High	Included - emission factor was used in corresponding condition of use
33	Demolition and Disposal of EPS/XPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures	Manual breaking of XPS boards	0 g XPS particles/metric ton XPS broken	(ECHA, 2008b)	3970747	High	Included - emission factor was used in corresponding condition of use
34	Formulation of Coatings	Flame Control Coatings LLC, Niagara NY	Fugitive air: 0.612 kg HBCD/yr Stack air: 5.505 kg HBCD/yr	2017 TRI, 5079078	2017 TRI	Medium	Excluded – this data is presented in Appendix 0, but this is not a condition of use
35	Formulation of Solder/Flux Pastes	Indium Corporation of America, Clinton, NY	Fugitive air: 0.454 kg HBCD/yr Stack air: 6.350 kg HBCD/yr Waste broker for disposal: 0.454 kg HBCD/yr Treatment via solidification/stabilization (EPA assumes this final media release is landfill) 6.350 kg HBCD/yr	2017 TRI, 5079078	2017 TRI	Medium	Included - loss quantity was used in the corresponding condition of use

Appendix E OCCUPATIONAL EXPOSURES

Table_Apx E-1 includes a crosswalk between the subcategories of use listed in the *Problem Formulation Document for Cyclic Aliphatic Bromides Cluster (HBCD)* and the conditions of use assessed in this risk evaluation, with the associated occupational and consumer exposure assessment sections.

Table_Apx E-1. Crosswalk of Subcategories of Use Listed in the Problem Formulation Document to Conditions of Use Assessed in the Risk Evaluation for Occupational and Consumer Exposure

Life Cycle Stage	Category [a]	Subcategory [b]	Assessed Condition of Use	Consumer Condition of Use
Manufacture	Import	Import	Section 2.4.1.2 – Processing: Repackaging of Import Containers	N/A
Processing	Processing - incorporated into formulation, mixture or reaction product	Flame retardants used in custom compounding of resin (e.g., compounding in XPS masterbatch) and in solder paste	Section 2.4.1.3 – Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch Section 2.4.1.12– Processing: Formulation of Flux/Solder Pastes	N/A
	Incorporated into article	Flame retardants used in plastics product manufacturing (manufacture of XPS and EPS foam; manufacture of structural insulated panels (SIPS) and automobile replacement parts from XPS and EPS foam)	Section 2.4.1.4– Processing: Manufacturing of XPS Foam using XPS Masterbatch Section 2.2.5 – Processing: Manufacturing of XPS Foam using HBCD Powder Section 2.4.1.6 – Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads Section 2.4.1.7– Processing: Manufacturing of SIPs and Automobile Replacement Parts from XPS/EPS Foam	N/A
	Recycling	Recycling of XPS and EPS foam, resin, panels containing HBCD	Section 2.4.1.11 – Recycling of EPS Foam and Reuse of XPS Foam	N/A
Distribution	Distribution	Distribution	Activities related to distribution (e.g., loading, unloading) are considered throughout the life cycle, rather than using a single distribution scenario.	

Life Cycle Stage	Category [a]	Subcategory [b]	Assessed Condition of Use	Consumer Condition of Use
Commercial/consumer Use	Building/construction materials	Plastic articles (hard): construction and building materials covering large surface areas (e.g., EPS/XPS foam insulation in residential, public and commercial buildings, and other structures) and solder paste	Section 2.4.1.9 – Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures Section 2.4.1.13 – Use of Flux/Solder Pastes	Section 2.4.2.6 – Consumer Exposures during Use of HBCD in EPS/XPS Insulation in Residences and Auto Components
	Other	Automobile replacement parts	Section 2.4.1.8 – Use: Installation of Automobile Replacement Parts	Section 2.4.2.6 – Consumer Exposures during Use of HBCD in EPS/XPS Insulation in Residences and Auto Components N/A
Disposal	Disposal	Other land disposal (e.g. Construction and Demolition Waste)	Section 2.4.1.10 – Demolition and Disposal of XPS/EPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures	N/A

[a] These categories of conditions of use appear in the Life Cycle Diagram, reflect CDR codes, and broadly represent conditions of use of HBCD in industrial and/or commercial settings.
[b] These subcategories reflect more specific uses of HBCD.

E.1 Inhalation Monitoring Data Summary

This appendix contains a summary of the available data that EPA compiled from literature sources.

EPA compiled HBCD inhalation monitoring data that was available in literature into three tables based on the associated worker activities:

- Table_Apx E-2. contains inhalation monitoring data related to the handling of HBCD in various forms, including fine grade powder, standard grade powder, and granules.
- Table_Apx E-3. contains inhalation monitoring data related to the handling and processing of XPS and EPS foam containing HBCD.

Table_Apx E-2. Inhalation Monitoring Data for Handling of HBCD

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Searl and Robertson (2005) - 1a	Manufacturing of HBCD	Standard grade HBCD	Personal Breathing Zone	Packaging, compaction, process operations, and working in the warehouse	Mean: 1.23 Median: 0.89 90th percentile: 1.89 Max: 3 mg/m^3	10	8-hr TWA	(ECHA, 2008b) (ECHA, 2009b)	High
Searl and Robertson (2005) - 1b	Manufacturing of HBCD	Fine grade HBCD	Personal Breathing Zone	Packaging, compaction, process operations, and working in the warehouse	Mean: 23 90th percentile: 35	4	8-hr TWA	(ECHA, 2008b)	High
Searl and Robertson (2005) - 1c	Manufacturing of HBCD	HBCD of unknown grade	NR	Packaging and compaction of powders	Respirable, mean: 0.18 Inhalable, Mean: 1.23	NR	NR	(ECHA, 2009c)	High
Waindzioch (2000) - 1a	Manufacturing of HBCD	HBCD of unknown grade	Area	Reactor	0.00028 - 0.0285	3	Short-term	(ECHA, 2008b)	Unacceptable
Waindzioch (2000) - 1b	Manufacturing of HBCD	HBCD of unknown grade	Area	Filling Station	0.0094 - 0.097	2	Short-term	(ECHA, 2008b)	High
Biesemeier (1996)	Manufacturing of HBCD	HBCD of unknown grade	NR	Bagging HBCD product	4.0 - 4.5	NR	NR	(ECHA, 2008b)	High
Velsicol (1978)	Manufacturing of HBCD	HBCD of unknown grade	Personal Breathing Zone	Transfer of the HBCD in the hammer-mill to 28 drums	1.9	1	300 minutes	(Velsicol Chem Corp, 1978)	High
Yi et al. (2016)	Manufacturing of HBCD	HBCD of unknown grade	Personal Breathing Zone	NR	0.0102 - 0.0283	14	NR	(Yi et al., 2016)	High
Searl and Robertson (2005) - 2a	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 2.89-21.5 Mean: 7.2 Median: 5.52	12	Short-term (13 to 56 mins)	(NICNAS, 2012b); (ECHA, 2008b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
					90th percentile: 10.5				
Searl and Robertson (2005) - 2b	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 0.12-3.36 Mean: 1 Median: 0.42 90th percentile: 1.11 (NICNAS, 2012b); 1.3 (ECHA, 2008b)	12	8-hr TWA – note these are 8-hr TWA values of the data in the above row	(NICNAS, 2012b); (ECHA, 2008b)	High
Searl and Robertson (2005) - 2c	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 0.07-14.7 Mean: 1.2 Median: 0.27 90th percentile: 1.10	18	8-hr TWA (ECHA, 2008b); 275 to 504 mins (NICNAS, 2012b)	(NICNAS, 2012b); (ECHA, 2008b)	High
Searl and Robertson (2005) - 2d	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Weighing powder prior to addition to reactor. HBCD bags were weighed and opened concurrently, or weighed in advance, in which case HBCD was transferred from 25-kg sacks using plastic scoop (full-shift measurement).	Range: 4.35-12.1 Mean: 7.2 Median: 6.19 90th percentile: 10.5 (NICNAS, 2012b); 10.5 & 10.6 (ECHA, 2008b)	4	8-hr TWA (ECHA, 2008b); 124 to 350 mins (NICNAS, 2012b)	(NICNAS, 2012b); (ECHA, 2008b)	High
Searl and Robertson (2005) - 3a	Compounding of Polystyrene resin to produce XPS	HBCD of unknown grade	Area	Weighing and mixing	Max 7.5 (for 2 hours) Mean: 1.89 Median: 0.83	10	Short-term	(ECHA, 2008b), (ECHA, 2009b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
	Masterbatch containing HBCD				90th percentile: 5.4				
Searl and Robertson (2005) - 3b	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	Area	Weighing and mixing	Mean: 0.88 90th percentile: 1.36	10	8-hr TWA	(ECHA, 2008b)	High
Searl and Robertson (2005) - 3c	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	NR	Extruder	Mean: 0.12 Median: 0.10 90th percentile: 0.16	4	5 hours	(ECHA, 2008b), (ECHA, 2009b)	High
Searl and Robertson (2005) - 3d	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	NR	Automated handling of HBCD	Negligible	3	NR	(ECHA, 2008b)	High
Abbott (2001) - 1a	Manufacture of XPS from HBCD powder or granules	Standard grade HBCD	Area	At the feed deck near typical operator positions	Range 0.24 – 1.6 Mean: 0.66 90th percentile: 1.45 (excluding 10 ND samples)	16 (10 ND)	8-hr TWA	(ECHA, 2008b)	High
Abbott (2001) - 1b	Manufacture of XPS from HBCD	HBCD granules	Mostly area and some	Feed deck near typical operator positions	Range 0.005-0.9 Mean: 0.24	43 (16 ND)	60 – 1435 minutes	(ECHA, 2008b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
	powder or granules		personal breathing zone		90th percentile: 0.47 (excluding 16 ND samples)				
Thomsen (2007) - 1a	Manufacture of XPS from HBCD powder or granules	HBCD powder and granules	Personal breathing zone	Activities in the mixer area, including operating a closed automated process excluding potential contact with neat HBCD	Range: 0.0002-0.0009 Mean: 0.0005 Median: 0.0005	6	8-hr TWA	(ECHA, 2008b) (NICNAS, 2012b)	High
Thomsen (2007) - 1b	Manufacture of XPS from HBCD powder or granules	HBCD powder and granules	Personal breathing zone	Weighing and addition of HBCD to the reactor and subsequent washing, centrifugation, sifting, and transfer of product to a silo container	Range: 0.001-0.15 Mean: 0.015 Median: 0.0027	24	8-hr TWA	(ECHA, 2008b) (NICNAS, 2012b)	High
Searl and Robertson (2005) - 4	Manufacture of XPS from HBCD powder or granules	HBCD granules	Area	Logistics, extruding, and laboratory	Mean: 0.00003 90th percentile: 0.00004	12	8-hr TWA	(ECHA, 2008b)	High
Ransbotyn (1999)	Manufacturing of EPS Resin beads	Respirable Dust Inhalable Dust	Personal	Addition of HBCDD to reactor or the supervising of the addition.	Respirable dust: <0.5 Total Inhalable dust: 2.0 Not specific to HBCD	5	Max 8-hr TWA	(ECHA, 2008b)	High
NICNAS (2012) - 1a	All industrial polymer processing sites	Standard grade HBCD	Modelled with EASE	Addition of HBCD into process operation	Typical: 2 to 5 Worst-case: 5 to 50	N/A - this is a modelled exposure	8-hr TWA	(NICNAS, 2012b)	High
NICNAS (2012) - 1b	HBCD importation / repackaging sites and all	HBCD granules	Modelled with EASE	Repackaging with the use of LEV (typical) and without LEV (worst-case)	Typical: 0.2 to 0.5 Worst-case: 0.5 to 5	N/A - this is a modelled exposure	8-hr TWA	(NICNAS, 2012b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
	industrial polymer processing sites								

NR = Not Reported; N/A = Not Applicable
a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.
b - Statistics were calculated by the cited source and are presented here as they were presented in the source.
c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.

Table_Apx E-3. Inhalation Monitoring Data For Handling of XPS and EPS Foam Containing HBCD

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Searl and Robertson (2005) - 5a	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Secondary processing of XPS foam - including cutting, sawing, and machining to manufacture shaped products	Mean: 0.08 90th percentile: 0.22 [d]	9	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Searl and Robertson (2005) - 5b	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Reclamation of XPS foam - including shredding and reprocessing of process waste	Mean: 0.02 90th percentile: 0.02 [d]	5	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High

Literature Study [a]	Condition of Use	Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3) [b]	Number of Samples	Sample Time / Type of Measurement	Source [c]	Overall Confidence Rating
Searl and Robertson (2005) - 5c	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Other process control operators	Mean: 0.03 90th percentile: 0.03 [d]	4	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Searl and Robertson (2005) - 5d	Manufacture of XPS from XPS Masterbatch	XPS foam	NR	Process operators handling XPS masterbatch	Mean: 0.03 90th percentile: 0.03 [d]	24	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	High
Zhang et al. (2012) - 1a	Thermal cutting of XPS boards	XPS foam	NR	Thermal cutting of XPS boards in a closed glovebox	Mean: 0.089	NR	NR	(Zhang et al., 2012)	High
Zhang et al. (2012) - 1b	Thermal cutting of EPS boards	EPS foam	NR	Thermal cutting of EPS boards in a closed glovebox	Mean: 0.057	NR	NR	(Zhang et al., 2012)	High

NR = Not Reported

a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.

b – Statistics were calculated by the cited source and are presented here as they were presented in the source.

c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.

d – These exposure values were all originally reported in the same study, Searl and Robertson (2005), and discussed in the EURAR (ECHA, 2008b) and an ECHA report (ECHA, 2009b). The dataset includes 42 total samples, taken at three XPS manufacturing sites in the EU. The EURAR reports that the first two rows, consisting of 14 total data points, include all non-detects, except for three samples, indicating that the exposure potential during these activities is low, despite the fact that the exposure concentrations in Searl and Robertson (2005) – 5a are the highest of the surveyed activities.

E.2 Summary of Other Assessment Approaches

EPA identified three HBCD risk assessments from other countries. These include:

- European Union (EU) – Risk Assessment, Hexabromocyclododecane (ECHA, 2008b)
- Australian Government Department of Health and Ageing, National Industrial Chemicals Notification and Assessment Scheme (NICNAS) – Priority Existing Chemical Assessment Report No. 34, Hexabromocyclododecane (NICNAS, 2012b)
- Environmental Canada (EC), Health Canada – Screening Assessment Report on Hexabromocyclododecane (EC/HC, 2011)
    - Note that this RAR only includes release assessments during raw materials handling and compounding and does not assess occupational exposures.

EPA compiled the assessment approaches from the above three sources for each condition of use assessed in this assessment below. Table_Apx E-4. and Table_Apx E-5. specifically list the inhalation exposure assessment methodology in the EU and NICNAS RARs, respectively.

Table_Apx E-6. lists methodology for oral and dermal exposure, as well as environmental release assessment methodology.

Table_Apx E-4. Summary of HBCD Occupational Inhalation Exposure Assessment Results and the Associated Assessment Basis and Assessment Approach that are Reported in EU (2008)

Assessment Parameter				
Chemical Process: Manufacture of HBCD				
Exposure Concentration	HBCD standard grade powder	RWC: 1.9 mg/m^3	The basis is the worker exposure monitoring data for the manufacture of HBCD that are reported in Searl and Robertson (2005) - 1aof Table_Apx E-2. of this report. The rationale is that this is the only worker exposure monitoring data for HBCD manufacturing that is specifically associated with the HBCD standard grade powder product. This data were also used as the basis for the assessment of exposure concentrations in the case of the HBCD granules product.	The RWC exposure concentration was assessed to be equal to the 90th percentile of the concentration measurements referenced under Basis. Typical exposure concentration: refer to footnote (1).
		Typical: 0.95 mg/m^3		
	HBCD granules	RWC: 0.19 mg/m^3		The typical exposure concentration was assumed to be equal to 10 percent of the RWC exposure concentration that was assessed in the case of the HBCD standard grade powder product. The rationale for this assumption is that ten percent of particles in the HBCD granules product were assumed to have a size of less than 100 µm, which is the assumed maximum particle size for HBCD standard grade powder. Typical exposure concentration: refer to footnote (1).
Chemical Process: Compounding of Polystyrene Resin to Produce XPS Masterbatch; Manufacture of XPS from HBCD powder, granules, or XPS masterbatch; and Manufacture of EPS resin beads				

Assessment Parameter				
Exposure Concentration	HBCD standard grade powder	RWC: 2.5 mg/m^3	The basis is the worker exposure monitoring data for the manufacture of EPS resin that are reported in Searl and Robertson (2005) – 2a-d of Table_Apx E-2. of this report. The rationale is that this data is based on a greater number of samples.	The RWC exposure concentration was assessed by accounting for both addition and weighing as follows: 1. Addition of HBCD – the 90th percentile value, 1.3 mg/m^3 (Searl and Robertson (2005) - 2b), was used. 2. Weighing of HBCD – the 90th percentile value, 10.5 mg/m^3 (Searl and Robertson (2005) – 2d), was used. This task is 10-15 percent of the long-term working time due to task rotation and therefore, only a fraction of this concentration was assessed (~10 percent or 1.1 mg/m^3). The RWC concentration used in this exposure assessment is the sum of 1.3 mg/m^3 and 1.1 mg/m^3, which is approximately equal to 2.5 mg/m^3. Typical exposure concentration: refer to footnote (1) .
		Typical: 1.25 mg/m^3		
	HBCD granules	RWC: 0.22 mg/m^3	The basis is the monitoring data for the manufacture of XPS from HBCD granules that are reported in Abbott (2001) - 1b of Table_Apx E-2. of this report.	The approach is not explained beyond that the data referenced under Basis is more representative than other similar data (i.e., Thomsen (2007) – 1a-bof Table_Apx E-2.) and that more emphasis on personal sampling was given in selecting an assessed value. Typical exposure concentration: refer to footnote (1).
		Typical: 0.11 mg/m^3		
	master batch	RWC: 0.22 mg/m^3	The basis is the monitoring data for the manufacture XPS from master batch that are reported in Searl and Robertson (2005) - 3a-dof Table_Apx E-2. of this report.	The RWC exposure concentration was assessed to be equal to the 90th percentile of the concentration measurements referenced under Basis. Typical exposure concentration: refer to footnote (1).
		Typical: 0.11 mg/m^3		

Source: (ECHA, 2008b) European Chemicals Agency. Risk Assessment for Hexabromocyclododecane: Final Report. May 2008.
RWC – Reasonable Worst Case
[1] Typical concentration was assessed to be equal to one half of the assessed RWC concentration. The rationale for this approach is that measured data indicates that the median value is approximately half the RWC.

Table_Apx E-5. Summary of HBCD Occupational Exposure Assessment Results and the Associated Assessment Basis and Approach that are Reported in NICNAS (2012)

Assessment Parameter				
Chemical Process: Compounding of Polystyrene Resin to Produce XPS Masterbatch, Manufacture of XPS from HBCD powder or granules, Manufacture of XPS from XPS Master Batch, and Manufacture of EPS Resin				
Exposure Concentration	HBCD standard grade powder	RWC: 1.1 mg/m^3 (addition) 10.5 mg/m^3 (weighing)	The basis is the worker exposure monitoring data for the manufacture of EPS resin that are reported in Searl and Robertson (2005) - 2b (for addition) and Searl and Robertson (2005) – 2d (for weighing) of Table_Apx E-2. of this report. Overseas measurements were considered applicable due to similarities in tasks. Use of the full-shift measurements for addition is preferred.	The RWC exposure concentration was assessed to be equal to the 90th percentile of the concentration measurements referenced under Basis.
		Typical: 0.27 mg/m^3 (addition) 6.19 mg/m^3 (weighing)		The typical exposure concentration was assessed to be equal to the median of the concentration measurements referenced under Basis.
	HBCD granules and XPS master batch	RWC: 0.37 mg/m^3	The basis is the worker exposure monitoring data for manufacture of XPS from HBCD granules that are reported in Abbott (2001) - 1b of Table_Apx E-2. of this report.	The RWC exposure concentration was assessed to be equal to the 90th percentile value referenced under Basis.
		Typical: 0.08 mg/m^3		The typical exposure concentration was assessed to be equal to the highest LOD, which is 0.08 mg/m^3 the median concentration is lower than the LOD for a high proportion of samples.
Exposure Duration	HBCD standard grade powder	1 hour/day	The basis for this assumption is on the weighing and addition tasks at plants producing EPS. The tasks took 10 to 15 minutes per batch. Overall, weighing and transfer of HBCD took about an hour a week.	The exposure duration is assumed to be 0.5 hour/day for addition and 0.5 hour/day for weighing.
	HBCD granules		Based on the study conducted by the European Extruded Polystyrene Insulation Board Association on the measured	

Assessment Parameter				
			airborne concentration of HBCD in the production of XPS resin from HBCD granules. The main relevant tasks were emptying boxes and cleaning the feed deck, which took approximately 0.25 hour daily and 1 hour weekly.	
Exposure Frequency	HBCD standard grade powder	1 day/year	This is based on occupational exposure scenarios for masterbatch compounding from sites in Australia.	Not applicable
	HBCD standard grade powder and HBCD granules	180 days/year	This is based on occupational exposure scenarios for EPS resin compounding from sites in Australia.	Not applicable

Table_Apx E-6. Summary of Approaches from Other Risk Assessment Reports (RARs)

Row	Life Cycle Stage	Inhalation Exposures	Oral Exposures	Dermal Exposures	Environmental Releases
1	Repackaging of import containers	See Table_Apx E-4. and Table_Apx E-5.	The EURAR and NICNAS RAR assumed 100% absorption of inhalable particulates.	Neither the EU nor the NICNAS RARs included monitoring data for dermal exposures. These RARs modelled dermal exposures using the EASE model.	EURAR assessed releases from manufacturing of HBCD and not Import / repackaging. NICNAS RAR assessed releases with the OECD ESD on Plastic Additives (OECD, 2009).
2	Compounding of polystyrene to produce XPS masterbatch	See Table_Apx E-4. and Table_Apx E-5.	The EURAR and NICNAS RAR assumed 100% absorption of inhalable particulates.	The methodology described in Row 1 was also used in this condition of use.	EURAR assessed releases with site-specific data. NICNAS RAR assessed only dust releases with the OECD ESD on Plastic Additives (OECD, 2009). Environmental Canada RAR assessed only dust releases with the OECD ESD on Plastic Additives (OECD, 2009).
3	Manufacture of XPS foam from XPS masterbatch	See Table_Apx E-4. and Table_Apx E-5.	The EURAR and NICNAS RAR assumed 100% absorption of inhalable particulates.	The methodology described in Row 1 was also used in this condition of use.	EURAR assessed releases with site-specific data. NICNAS RAR assessed only dust releases with the OECD ESD on Plastic Additives (OECD, 2009).
4	Manufacture of XPS foam using HBCD powder	See Table_Apx E-4. and Table_Apx E-5.	The EURAR and NICNAS RAR assumed 100% absorption of inhalable particulates.	The methodology described in Row 1 was also used in this condition of use.	EURAR assessed releases with site-specific data. NICNAS RAR assessed only dust releases with the OECD ESD on Plastic Additives (OECD, 2009).
5	Manufacture of EPS foam from imported EPS resin beads	See Table_Apx E-4. and Table_Apx E-5.	The EU and NICNAS RARs assessed exposures from the production of EPS resin and indicated that exposures are expected to be low during the	The EU and NICNAS RARs assessed exposures from the production of EPS resin and indicated that exposures are expected to be low during the conversion	EURAR assessed only dust releases with the OECD ESD on Plastic Additives (OECD, 2009). NICNAS RAR assessed only dust releases

Row	Life Cycle Stage	Inhalation Exposures	Oral Exposures	Dermal Exposures	Environmental Releases
			conversion of these EPS resin beads into EPS foam, thus were not assessed.	of these EPS resin beads into EPS foam, thus were not assessed.	with the OECD ESD on Plastic Additives (OECD, 2009).
6	Manufacture of SIPs and Automobile Replacement Parts from XPS or EPS	See Table_Apx E-4. and Table_Apx E-5.	Because of the low inhalation exposure potential, the EU and NICNAS RARs did not assess oral exposures during this condition of use.	The EU and NICNAS RARs indicate that, because HBCD is incorporated into the foam matrix, dermal exposure is unlikely and is not assessed.	EURAR assessed releases with data on particulate emission rates during cutting and sawing of EPS and XPS foam. NICNAS RAR did not assess this release.
7	Installation of Automotive Replacement Parts	See Table_Apx E-4. and Table_Apx E-5.	The methodology described in Row 6 was also used in this condition of use.	The methodology described in Row 6 was also used in this condition of use.	The RARs reviewed did not assess this condition of use.
8	Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	See Table_Apx E-4. and Table_Apx E-5.	The methodology described in Row 6 was also used in this condition of use.	The methodology described in Row 6 was also used in this condition of use.	EURAR assessed releases with data on particulate emission rates during cutting and sawing of EPS and XPS foam. NICNAS RAR did not assess this release.
9	Demolition and Disposal of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	The EU and NICNAS RARs did not assess occupational exposures during this condition of use.	The EU and NICNAS RARs did not assess occupational exposures during this condition of use.	The EU and NICNAS RARs did not assess occupational exposures during this condition of use.	EURAR assessed releases with data on particulate emission rates during breaking of EPS and XPS foam. The EURAR did not quantify disposal releases. NICNAS RAR assessed a steady-state scenario, where all HBCD imported is releases. NICNAS subtracted upstream losses and assumed the remaining amount was released in this condition of use.

Row	Life Cycle Stage	Inhalation Exposures	Oral Exposures	Dermal Exposures	Environmental Releases
10	Recycling of EPS Foam	The EU and NICNAS RARs did not assess occupational exposures during this condition of use.	The EU and NICNAS RARs did not assess occupational exposures during this condition of use.	The EU and NICNAS RARs did not assess occupational exposures during this condition of use.	The EU and NICNAS RARs did not assess releases during this condition of use.
11	Formulation of Flux / Solder Pastes	This condition of use was not included in the identified RARs.	This condition of use was not included in the identified RARs.	This condition of use was not included in the identified RARs.	This condition of use was not included in the identified RARs.
12	Use of Flux / Solder Pastes	This condition of use was not included in the identified RARs.	This condition of use was not included in the identified RARs.	This condition of use was not included in the identified RARs.	This condition of use was not included in the identified RARs.

E.3 Summary of Approaches Used in this Risk Evaluation

This section includes a summary of the approaches used by EPA in this assessment for the assessment of occupational exposures and environmental releases for each condition of use.

A summary of EPA's approaches is included in Table_Apx E-7. below.

Additional information on EPA's assessment approaches are described in the following sub-sections of this section.

Table_Apx E-7. Summary of Approaches Used by EPA in this Assessment

Row	Life Cycle Stage	Inhalation Exposures	Oral Exposures	Dermal Exposures	Environmental Releases
1	Repackaging of import containers	Refer to Table 2-60.	EPA did not find oral exposure monitoring data. EPA assessed oral exposures by assuming that the inhaled dust is 100% in the inhalable region (not in the respirable region), such that all inhaled dust is	EPA did not find dermal monitoring data. EPA modelled dermal exposures with the *EPA/OPPT Direct 2-Hand Dermal Contact with Solids Model*.	EPA did not find release data. EPA used the OECD ESD on Plastic Additives (OECD, 2009).

Row	Life Cycle Stage	Inhalation Exposures	Oral Exposures	Dermal Exposures	Environmental Releases
			deposited in the upper respiratory tract, where it is ingested. This approach is consistent with that in the EU and NICNAS RARs.		
2	Compounding of polystyrene to produce XPS masterbatch	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used release data from the EURAR.
3	Manufacture of XPS foam from XPS masterbatch	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used release data from the EURAR.
4	Manufacture of XPS foam using HBCD powder	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used release data from the EURAR.
5	Manufacture of EPS foam from imported EPS resin beads	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA did not assess dermal exposures during this life cycle stage.	EPA did not find release data. EPA used the OECD ESD on Plastic Additives (2009).
6	Manufacture of SIPs and Automobile Replacement Parts from XPS or EPS	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA did not assess dermal exposures during this life cycle stage.	EPA used release data from the EURAR.
7	Installation of Automotive Replacement Parts	Refer to Table 2-60.	EPA did not assess occupational exposures during this life cycle stage.	EPA did not assess occupational exposures during this life cycle stage.	EPA did not assess releases during this life cycle stage.
8	Installation of EPS/XPS Foam	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA did not assess occupational exposures during this life cycle stage.	EPA used release data from the EURAR.

Row	Life Cycle Stage	Inhalation Exposures	Oral Exposures	Dermal Exposures	Environmental Releases
	Insulation in Residential, Public and Commercial Buildings, and Other Structures				
9	Demolition of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA did not assess occupational exposures during this life cycle stage.	EPA used release data from the EURAR and literature.
10	Recycling of EPS Foam	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA did not assess occupational exposures during this life cycle stage.	EPA did not find release data. EPA used the OECD ESD on Plastic Additives (OECD, 2009).
11	Formulation of Flux / Solder Pastes	Refer to Table 2-60.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA used 2017 TRI release data.
12	Use of Flux / Solder Pastes	Refer to Table 2-60.	Because EPA does not assess inhalation exposure, oral exposures are not assessed.	EPA used the same methodology described in Row 1 for this life cycle stage.	EPA did not find release data. EPA used the OECD ESD on Chemicals used in the Electronics Industries (OECD, 2010a).

E.4 Equations for Calculating Acute and Chronic (Non-Cancer) Inhalation Exposures

This report assesses HBCD exposures to workers in occupational settings, presented as 8-hr time weighted average (TWA). The 8-hr TWA exposures are then used to calculate acute exposure, average daily dose (ADD) for chronic, non-cancer risks.

Acute workplace exposures are assumed to be equal to the contaminant concentration in air (8-hr TWA), per Equation E-4.

Equation E-1:

$$\boldsymbol{AED = \frac{C \times ED \times b}{BW}}$$

Where:

AED = Acute exposure dose (mg/kg-day)
C = Contaminant concentration in air (TWA) (mg/m^3)
ED = exposure duration (8 hr/day)
b = breathing rate (1.25 m^3/hr)
BW = body weight (80 kg)

ADD is used to estimate workplace chronic exposures for non-cancer risks. These exposures are estimated as follows:

Equation E-2:

$$\boldsymbol{ADD = \frac{C \times ED \times b \times EF \times WY}{BW \times AT}}$$

Where:

ADD = average daily dose used for chronic non-cancer risk calculations (mg/kg-day)
C = contaminant concentration in air (8-hr TWA) (mg/m^3)
ED = exposure duration (8 hr/day)
b = breathing rate (1.25 m^3/hr)
EF = exposure frequency (days/yr)
WY = exposed working years per lifetime (50th percentile = 31; 95th percentile = 40)
BW = body weight (80 kg)
AT = averaging time, non-cancer risks (WY × 365 days/yr)

Table_Apx E-8. Parameter Values for Calculating Inhalation Exposure Estimates

Parameter Name	Symbol	Value	Unit
Exposure Duration	ED	8	hr/day
Breathing Rate	b	1.25	m3/hr

Parameter Name	Symbol	Value	Unit
Exposure Frequency	EF	discussed in Section 2	days/year
Working Years	WY	31 (50th percentile) 40 (95th percentile)	years
Body Weight	BW	80	kg
Averaging Time, non-cancer	AT	11,315 (CT)[a] 14,600 (HE)[b]	days

[a] Calculated using the 50th percentile value for working years (WY)
[b] Calculated using the 95th percentile value for working years (WY)

Exposure Duration (ED)

EPA uses an exposure duration of 8 hours per day for averaging full-shift exposures.

Breathing Rate (b)

EPA uses a breathing rate of 1.25 m^3 per hour.

Exposure Frequency (EF)

EPA estimated a range of exposure frequency based on the number of operation days that EPA determined for each condition of use, except for The Installation of EPS/XPS Foam Insulation and the Demolition and Disposal of EPS/XPS Foam Insulation. For these conditions of use, EPA estimated a range of exposure frequency of 1 day/year, based on release frequency, up to 250 days/year, based on worker schedules as described below. The assessed exposure frequency did not exceed 250 days/year, based on a worker schedule of 5 days/week over 50 weeks/year. With this range of exposure frequency, EPA used the midpoint of this range to calculate central tendency average daily dose and the high-end of this range to calculate high-end average daily dose. EPA's choice of these exposure frequencies are further described in Section 2.3.

Exposure frequency (EF) is expressed as the number of days per year a worker is exposed to the chemical being assessed. In some cases, it may be reasonable to assume a worker is exposed to the chemical on each working day. In other cases, it may be more appropriate to estimate a worker's exposure to the chemical occurs during a subset of the worker's annual working days. The relationship between exposure frequency and annual working days can be described mathematically as follows:

$$EF = f \times AWD$$

Where:
EF = exposure frequency, the number of days per year a worker is exposed to the chemical (day/yr)
f = fractional number of annual working days during which a worker is exposed to the chemical (unitless)
AWD = annual working days, the number of days per year a worker works (day/yr)

BLS (2015) provides data on the total number of hours worked and total number of employees by each industry NAICS code. These data are available from the 3- to 6-digit NAICS level (where 3-digit

NAICS are less granular and 6-digit NAICS are the most granular). Dividing the total, annual hours worked by the number of employees yields the average number of hours worked per employee per year for each NAICS.

EPA has identified approximately 140 NAICS codes applicable to the multiple conditions of use for the ten chemicals undergoing risk evaluation. For each NAICS code of interest, EPA looked up the average hours worked per employee per year at the most granular NAICS level available (i.e., 4-digit, 5-digit, or 6-digit). EPA converted the working hours per employee to working days per year per employee assuming employees work an average of eight hours per day. The average number of days per year worked, or AWD, ranges from 169 to 282 days per year, with a 50th percentile value of 250 days per year. EPA repeated this analysis for all NAICS codes at the 4-digit level. The average AWD for all 4-digit NAICS codes ranges from 111 to 282 days per year, with a 50th percentile value of 228 days per year. 250 days per year is approximately the 75th percentile.

In the absence of industry- and HBCD-specific data, EPA assumes the parameter *f* is equal to one for all conditions of use.

Working Years (WY)

EPA has developed a triangular distribution for working years. EPA has defined the parameters of the triangular distribution as follows:

- Minimum value: BLS CPS tenure data with current employer as a low-end estimate of the number of lifetime working years: 10.4 years;
- Mode value: The 50th percentile tenure data with all employers from Survey of Income and Program Participation (SIPP) as a mode value for the number of lifetime working years: 36 years; and
- Maximum value: The maximum average tenure data with all employers from SIPP as a high-end estimate on the number of lifetime working years: 44 years.

This triangular distribution has a 50th percentile value of 31 years and a 95th percentile value of 40 years. EPA uses these values for central tendency and high-end ADD calculations, respectively.

The BLS (2014b, 5079079) provides information on employee tenure with *current employer* obtained from the Current Population Survey (CPS). CPS is a monthly sample survey of about 60,000 households that provides information on the labor force status of the civilian non-institutional population age 16 and over; CPS data are released every two years. The data are available by demographics and by generic industry sectors but are not available by NAICS codes.

The U.S. Census' (2016a, 5079126) Survey of Income and Program Participation (SIPP) provides information on *lifetime tenure with all employers*. SIPP is a household survey that collects data on income, labor force participation, social program participation and eligibility, and general demographic characteristics through a continuous series of national panel surveys of between 14,000 and 52,000 households (Census Bureau, 2016b, 5079077). EPA analyzed the 2008 SIPP Panel Wave 1, a panel that began in 2008 and covers the interview months of September 2008 through December 2008 (Census Bureau, 2016a-b, 5079126-5079077). For this panel, lifetime tenure data are available by Census Industry Codes, which can be cross-walked with NAICS codes.

SIPP data include fields for the industry in which each surveyed, employed individual works (TJBIND1), worker age (TAGE), and years of work experience *with all employers* over the surveyed individual's lifetime.[18] Census household surveys use different industry codes than the NAICS codes used in its firm surveys, so these were converted to NAICS using a published crosswalk (Census Bureau, 2012b, 5079076). EPA calculated the average tenure for the following age groups: 1) workers age 50 and older; 2) workers age 60 and older; and 3) workers of all ages employed at time of survey. EPA used tenure data for age group "50 and older" to determine the high-end lifetime working years, because the sample size in this age group is often substantially higher than the sample size for age group "60 and older". For some industries, the number of workers surveyed, or the *sample size*, was too small to provide a reliable representation of the worker tenure in that industry. Therefore, EPA excluded data where the sample size is less than five from our analysis.

Table_Apx E-9. summarizes the average tenure for workers age 50 and older from SIPP data. Although the tenure may differ for any given industry sector, there is no significant variability between the 50th and 95th percentile values of average tenure across manufacturing and non-manufacturing sectors.

Table_Apx E-9. Overview of Average Worker Tenure from U.S. Census SIPP (Age Group 50+)

Industry Sectors	Working Years			
	Average	50th Percentile	95th Percentile	Maximum
All industry sectors relevant to the 10 chemicals undergoing risk evaluation	35.9	36	39	44
Manufacturing sectors (NAICS 31-33)	35.7	36	39	40
Non-manufacturing sectors (NAICS 42-81)	36.1	36	39	44

Source: Census Bureau, 2016a.
Note: Industries where sample size is less than five are excluded from this analysis.

BLS CPS data provides the median years of tenure that wage and salary workers had been with their current employer. Table_Apx E-10. presents CPS data for all demographics (men and women) by age group from 2008 to 2012. To estimate the low-end value on number of working years, EPA uses the most recent (2014, 5079079) CPS data for workers age 55 to 64 years, which indicates a median tenure of 10.4 years with their current employer. The use of this low-end value represents a scenario where workers are only exposed to the chemical of interest for a portion of their lifetime working years, as they may change jobs or move from one industry to another throughout their career.

Table_Apx E-10. Median Years of Tenure with Current Employer by Age Group

Age	January 2008	January 2010	January 2012	January 2014
16 years and over	4.1	4.4	4.6	4.6
16 to 17 years	0.7	0.7	0.7	0.7
18 to 19 years	0.8	1.0	0.8	0.8

[18] To calculate the number of years of work experience we took the difference between the year first worked (TMAKMNYR) and the current data year (i.e., 2008). We then subtracted any intervening months when not working (ETIMEOFF).

Age	January 2008	January 2010	January 2012	January 2014
20 to 24 years	1.3	1.5	1.3	1.3
25 years and over	5.1	5.2	5.4	5.5
25 to 34 years	2.7	3.1	3.2	3.0
35 to 44 years	4.9	5.1	5.3	5.2
45 to 54 years	7.6	7.8	7.8	7.9
55 to 64 years	9.9	10.0	10.3	10.4
65 years and over	10.2	9.9	10.3	10.3

Source: BLS, 2014b.

Body Weight (BW)

EPA assumes a body weight of 80 kg for all worker demographics.

E.5 Sample Calculations for Calculating Acute and Chronic (Non-Cancer) Inhalation Exposure

Sample calculations for high-end and central tendency chronic exposure doses for one setting, Repackaging of Import Containers, are demonstrated below. The explanation of the equations and parameters used is provided in AppendixE.4.

Example High-End ADD

Calculate ADD_{HE}:

$$\boldsymbol{ADD_{HE} = \frac{C_{HE} \times b \times ED \times EF \times WY}{BW \times AT}}$$

$$ADD_{HE} = \frac{1.89\ \frac{mg}{m^3} \times 1.25\ \frac{m^3}{hr} \times 8\frac{hr}{day} \times 60\frac{days}{year} \times 40\ years}{80\ kg \times \left(40\ years \times 365\frac{days}{year}\right)} = 3.88 \times 10^{-2}\frac{mg}{kg - day}$$

Example Central Tendency ADD

Calculate ADD_{CT}:

$$\boldsymbol{ADD_{CT} = \frac{C_{CT} \times b \times ED \times EF \times WY}{BW \times AT_{ADD}}}$$

$$ADD_{CT} = \frac{0.89\ \frac{mg}{m^3} \times 1.25\ \frac{m^3}{hr}\ \times 8\frac{hr}{day} \times 60\frac{days}{year} \times 31\ years}{80\ kg\ \times \left(31\ years \times 365\frac{days}{year}\right)} = 1.83 \times 10^{-2}\ \frac{mg}{kg - day}$$

E.6 Approaches for Estimating Number of Workers

This appendix summarizes the methods
and provides an example of the method that EPA used to estimate the number of workers who are potentially exposed to HBCD in each of its conditions of use. The method consists of the following steps:

1. Identify the North American Industry Classification System (NAICS) codes for the industry sectors associated with each condition of use.
2. Estimate total employment by industry/occupation combination using the Bureau of Labor Statistics' Occupational Employment Statistics (OES) data (BLS, 2016, 5079087).
3. Refine the OES estimates where they are not sufficiently granular by using the U.S. Census' (2015) Statistics of U.S. Businesses (SUSB) data on total employment by 6-digit NAICS.
4. Estimate the number of potentially exposed employees per site.
5. Estimate the number of potentially exposed employees within the condition of use using the estimated number of sites.

Step 1: Identifying Affected NAICS Codes

As a first step, EPA identified NAICS industry codes associated with each condition of use. EPA generally identified NAICS industry codes for a condition of use by:

- Querying the U.S. Census Bureau's *NAICS Search* tool using keywords associated with each condition of use to identify NAICS codes with descriptions that match the condition of use.
- Referencing EPA/OPPT Generic Scenarios (GS's) and Organisation for Economic Co-operation and Development (OECD) Emission Scenario Documents (ESDs) for a condition of use to identify NAICS codes cited by the GS or ESD.
- Reviewing Chemical Data Reporting (CDR) data for the chemical, identifying the industrial sector codes reported for downstream industrial uses, and matching those industrial sector codes to NAICS codes using Table D-2 provided in the CDR reporting instructions.

Each condition of use section in the main body of this report identifies the NAICS codes EPA identified for the respective condition of use.

Step 2: Estimating Total Employment by Industry and Occupation

BLS's (2016) OES data provide employment data for workers in specific industries and occupations. The industries are classified by NAICS codes (identified previously), and occupations are classified by Standard Occupational Classification (SOC) codes.

Among the relevant NAICS codes (identified previously), EPA reviewed the occupation description and identified those occupations (SOC codes) where workers are potentially exposed. Table_Apx E-11. shows the SOC codes EPA classified as occupations potentially exposed. These occupations are classified into workers (W) and occupational non-users (O). All other SOC codes are assumed to represent occupations where exposure is unlikely. An example is provided below for a condition of use of dry cleaning.

Table_Apx E-11. SOCs with Worker and ONU Designations for All Conditions of Use

After identifying relevant NAICS and SOC codes, EPA/OPPT used BLS data to determine total employment by industry and by occupation based on the NAICS and SOC combinations. For example,

there are 1,790 employees associated with 4-digit NAICS 3259 (*Other Chemical Product and Preparation Manufacturing*) and SOC 49-9070 (*Maintenance and Repair Workers, General*).

Using a combination of NAICS and SOC codes to estimate total employment provides more accurate estimates for the number of workers than using NAICS codes alone. Using only NAICS codes to estimate number of workers typically result in an overestimate, because not all workers employed in that industry sector will be exposed. However, in some cases, BLS only provide employment data at the 4-digit or 5-digit NAICS level; therefore, further refinement of this approach may be needed (see next step).

Step 3: Refining Employment Estimates to Account for lack of NAICS Granularity

The third step in EPA's methodology was to further refine the employment estimates by using total employment data in the U.S. Census Bureau's (2015) SUSB. In some cases, BLS OES's occupation-specific data are only available at the 4-digit or 5-digit NAICS level, whereas the SUSB data are available at the 6-digit level (but are not occupation-specific). Identifying specific 6-digit NAICS will ensure that only industries with potential exposure are included. As an example, OES data are available for the 4-digit NAICS 3259 *Other Chemical Product and Preparation Manufacturing*, which includes the following 6-digit NAICS:

- NAICS 325910 Printing Ink Manufacturing;
- NAICS 325920 Explosives Manufacturing;
- NAICS 325991 Custom Compounding of Purchased Resins;
- NAICS 325992 Photographic Film, Paper, Plate, and Chemical Manufacturing; and
- NAICS 325998 All Other Miscellaneous Chemical Product and Preparation Manufacturing.

In this example, only NAICS 325991 is of interest. The Census data allow EPA to calculate employment in the specific 6-digit NAICS of interest as a percentage of employment in the BLS 4-digit NAICS.

The 6-digit NAICS 325991 comprises 23.5 percent of total employment under the 4-digit NAICS 3259. This percentage can be multiplied by the occupation-specific employment estimates given in the BLS OES data to further refine our estimates of the number of employees with potential exposure.

Table_Apx E-12. illustrates this granularity adjustment for NAICS 325991.

Table_Apx E-12. Estimated Number of Potentially Exposed Workers and ONUs under NAICS 325991

NAICS	SOC CODE	SOC Description	Occupation Designation	Employment by SOC at 4-digit NAICS level	% of Total Employment	Estimated Employment by SOC at 6-digit NAICS level
325900	17-2000	Engineers	O	3,010	23.5%	709
325900	17-3000	Drafters, Engineering Technicians, and Mapping Technicians	O	860	23.5%	202
325900	19-2031	Chemists	O	1,400	23.5%	330
325900	19-4000	Life, Physical, and Social Science Technicians	O	1,810	23.5%	426
325900	47-2000	Construction Trades Workers	W	200	23.5%	47

NAICS	SOC CODE	SOC Description	Occupation Designation	Employment by SOC at 4-digit NAICS level	% of Total Employment	Estimated Employment by SOC at 6-digit NAICS level
325900	49-1000	Supervisors of Installation, Maintenance, and Repair Workers	O	340	23.5%	80
325900	49-2000	Electrical and Electronic Equipment Mechanics, Installers, and Repairers	W	260	23.5%	61
325900	49-9010	Control and Valve Installers and Repairers	W	60	23.5%	14
325900	49-9040	Industrial Machinery Installation, Repair, and Maintenance Workers	W	1,720	23.5%	405
325900	49-9060	Precision Instrument and Equipment Repairers	W	30	23.5%	7
325900	49-9070	Maintenance and Repair Workers, General	W	1,790	23.5%	421
325900	49-9090	Miscellaneous Installation, Maintenance, and Repair Workers	W	80	23.5%	19
325900	51-1000	Supervisors of Production Workers	O	3,480	23.5%	819
325900	51-2000	Assemblers and Fabricators	W	5,270	23.5%	1,241
325900	51-4020	Forming Machine Setters, Operators, and Tenders, Metal and Plastic	W	1,170	23.5%	275
325900	51-6090	Miscellaneous Textile, Apparel, and Furnishings Workers	O	1,320	23.5%	311
325900	51-8020	Stationary Engineers and Boiler Operators	W	40	23.5%	9
325900	51-8090	Miscellaneous Plant and System Operators	W	1,530	23.5%	360
325900	51-9000	Other Production Occupations	W	24,880	23.5%	5,858
Total Potentially Exposed Employees				**49,250**		**11,597**
Total Workers						**8,719**
Total Occupational Non-Users						**2,877**

Note: numbers may not sum exactly due to rounding.
W = worker
O = occupational non-user
Source: US Census, 2015; BLS, 2016

Step 4: Estimating the Percentage of Workers Using HBCD Instead of Other Chemicals

In the final step, EPA accounted for the market share by applying a factor to the number of workers determined in Step 3. This accounts for the fact that the substance may be only one of multiple chemicals used for the applications of interest. EPA did not identify market penetration data for any conditions of use. In the absence of market penetration data for a given condition of use, EPA/OPPT assumed HBCD may be used at up to all sites and by up to all workers calculated in this method as a bounding estimate. This assumes a market penetration of 100%. Market penetration is discussed for each condition of use in the main body of this report.

Step 5: Estimating the Number of Workers per Site

EPA/OPPT calculated the number of workers and occupational non-users in each industry/occupation combination using the formula below (granularity adjustment is only applicable where SOC data are not available at the 6-digit NAICS level):

Number of Workers or ONUs in NAICS/SOC (Step 2) × Granularity Adjustment Percentage (Step 3) = Number of Workers or ONUs in the Industry/Occupation Combination

EPA/OPPT then estimated the total number of establishments by obtaining the number of establishments reported in the U.S. Census Bureau's SUSB (2015) data at the 6-digit NAICS level.

EPA then summed the number of workers and occupational non-users over all occupations within a NAICS code and divided these sums by the number of establishments in the NAICS code to calculate the average number of workers and occupational non-users per site.

Step 6: Estimating the Number of Workers and Sites for a Condition of Use

EPA estimated the number of workers and occupational non-users potentially exposed and the number of sites that use HBCD in a given condition of use through the following steps:

6.A. Obtaining the total number of establishments by:
   i. Obtaining the number of establishments from SUSB (2015) at the 6-digit NAICS level (Step 5) for each NAICS code in the condition of use and summing these values; or
   ii. Obtaining the number of establishments from the Toxics Release Inventory (TRI), Discharge Monitoring Report (DMR) data, National Emissions Inventory (NEI), or literature for the condition of use.

6.B. Estimating the number of establishments that use HBCD by taking the total number of establishments from Step 6.A and multiplying it by the market penetration factor from Step 4.

6.C. Estimating the number of workers and occupational non-users potentially exposed to HBCD by taking the number of establishments calculated in Step 6.B and multiplying it by the average number of workers and occupational non-users per site from Step 5.

E.7 Evaluation of Occupational Exposure Data Sources

EPA has reviewed acceptable sources for HBCD inhalation exposure data according to the data quality evaluation criteria found in *The Application of Systematic Review in TSCA Risk Evaluations* (U.S. EPA, 2018a). Table_Apx E-13. summarizes the results of this evaluation. The data quality evaluation of inhalation monitoring data sources indicated the quality of the sources ranges from unacceptable to high; however, unacceptable data were excluded from the assessment of occupational inhalation exposure to HBCD.

Table_Apx E-13. Summary of Inhalation Monitoring Data and Systematic Review Results

Literature Study [a]	Condition of Use	Data from source [b]						Source [c]	Data Identifier from Data Extraction and Evaluation	Overall Confidence Rating from Data Extraction and Evaluation	Rationale for Inclusion / Exclusion
		Form of HBCD Handled	Type of Sample	Worker Activity or Sampling Location	Exposure Concentration (mg/m^3)	Number of Samples	Sample Time / Type of Measurement				
Searl and Robertson (2005) - 1a	Manufacturing of HBCD	Standard grade HBCD	Personal Breathing Zone	Packaging, compaction, process operations, and working in the warehouse	Mean: 1.23 Median: 0.89 90th percentile: 1.89 Max: 3 mg/m3	10	8-hr TWA	(ECHA, 2008b) (ECHA, 2009b)	3970747; 3809166	High	Included - although manufacturing of HBCD is not a condition of use, these data are applicable to the importation of HBCD
Searl and Robertson (2005) - 1b	Manufacturing of HBCD	Fine grade HBCD	Personal Breathing Zone	Packaging, compaction, process operations, and working in the warehouse	Mean: 23 90th percentile: 35	4	8-hr TWA	(ECHA, 2008b)	3970747	High	Excluded - manufacturing is out of scope and, while this data may be applicable to other conditions of use, fine grade HBCD is not preferred
Searl and Robertson (2005) - 1c	Manufacturing of HBCD	HBCD of unknown grade	NR	Packaging and compaction of powders	Respirable, Mean: 0.18 Inhalable, Mean: 1.23	NR	NR	(ECHA, 2009c)	3970759	High	Excluded - manufacturing is out of scope and, while this data may be applicable to other conditions of use, the grade of HBCD and sample time are unknown
Waindzioch (2000) - 1a	Manufacturing of HBCD	HBCD of unknown grade	Area	Reactor	0.00028 - 0.0285	3	Short-term	(ECHA, 2008b)	3970747	Unacceptable	Excluded - manufacturing of HBCD is not a condition of use for this risk evaluation and this data is not applicable to other conditions of use
Waindzioch (2000) - 1b	Manufacturing of HBCD	HBCD of unknown grade	Area	Filling Station	0.0094 - 0.097	2	Short-term	(ECHA, 2008b)	3970747	High	Excluded - manufacturing is out of scope and, while this data may be applicable

											to other conditions of use, area samples are not preferred
Biesemeier (1996)	Manufacturing of HBCD	HBCD of unknown grade	NR	Bagging HBCD product	4.0 - 4.5	NR	NR	(ECHA, 2008b)	3970747	High	Excluded - manufacturing is out of scope and, while this data may be applicable to other conditions of use, sample type and time are unknown
Velsicol (1978)	Manufacturing of HBCD	HBCD of unknown grade	Personal Breathing Zone	Transfer of the HBCD in the hammer-mill to 28 drums	1.9	1	300 minutes	(Velsicol Chem Corp, 1978)	1928232	High	Excluded - manufacturing is out of scope and, while this data may be applicable to other conditions of use, the grade of HBCD and sample time are unknown
Yi et al. (2016)	Manufacturing of HBCD	HBCD of unknown grade	Personal Breathing Zone	NR	0.0102 - 0.0283	14	NR	(Yi et al., 2016)	3350493	High	Excluded - manufacturing is out of scope and, while this data may be applicable to other conditions of use, the grade of HBCD and sample time are unknown
Searl and Robertson (2005) - 2a	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 2.89-21.5 Mean: 7.2 Median: 5.52 90th percentile: 10.5	12	Short-term (13 to 56 mins)	(ECHA, 2008b) (NICNAS, 2012b)	3978355	High	Included - These data are the basis of the estimates developed by the EURAR for HBCD processing in the plastics industry, which were used by EPA in this risk evaluation
Searl and Robertson (2005) - 2b	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of	Range: 0.12-3.36 Mean: 1 Median: 0.42	12	8-hr TWA – Note this is the 8-hr TWA of the data in the above row	(ECHA, 2008b) (NICNAS, 2012b)	3978355	High	Included - These data are the basis of the estimates developed by the EURAR for

				EPS resin was produced	90th percentile: 1.3						HBCD processing in the plastics industry, which were used by EPA in this risk evaluation
Searl and Robertson (2005) - 2c	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Manual addition of HBCD powder to reactor each time a batch of EPS resin was produced	Range: 0.07-14.7 Mean: 1.2 Median: 0.27 90th percentile: 1.10	18	275 to 504 mins (NICNAS, 2012b)	(ECHA, 2008b) (NICNAS, 2012b)	3978355	High	Included - These data are the basis of the estimates developed by the EURAR for HBCD processing in the plastics industry, which were used by EPA in this risk evaluation
Searl and Robertson (2005) - 2d	Manufacturing of EPS Resin beads	Standard grade HBCD	Personal	Weighing powder prior to addition to reactor. HBCD bags were weighed and opened concurrently, or weighed in advance, in which case HBCD was transferred from 25-kg sacks using plastic scoop (full-shift measurement).	Range: 4.35-12.1 Mean: 7.2 Median: 6.19 90th percentile: 10.5	4	124 to 350 mins (NICNAS, 2012b)	(ECHA, 2008b) (NICNAS, 2012b)	3978355	High	Included - These data are the basis of the estimates developed by the EURAR for HBCD processing in the plastics industry, which were used by EPA in this risk evaluation
Searl and Robertson (2005) - 3a	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	Area	Weighing and mixing	Max 7.5 (for 2 hours) Mean: 1.89 Median: 0.83 90th percentile: 5.4	10	Short-term	(ECHA, 2008b) (ECHA, 2009b)	3970747; 3809166	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Searl and Robertson (2005) - 3b	Compounding of Polystyrene resin to	HBCD of unknown grade	Area	Weighing and mixing	Mean: 0.88 90th percentile: 1.36	10	8-hr TWA	(ECHA, 2008b)	3970747	High	Excluded - EPA used the estimates for HBCD

	produce XPS Masterbatch containing HBCD										processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Searl and Robertson (2005) - 3c	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	NR	Extruder	Mean: 0.12 Median: 0.10 90th percentile: 0.16	4	5 hours	(ECHA, 2008b) (ECHA, 2009b)	3970747; 3809166	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Searl and Robertson (2005) - 3d	Compounding of Polystyrene resin to produce XPS Masterbatch containing HBCD	HBCD of unknown grade	NR	Automated handling of HBCD	Negligible	3	NR	(ECHA, 2008b)	3970747	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Abbott (2001) - 1a	Manufacture of XPS from HBCD powder or granules	Standard grade HBCD	Area	At the feed deck near typical operator positions	Range 0.24 – 1.6 Mean: 0.66 90th percentile: 1.45 (excluding 10 ND samples)	16 (10 ND)	8-hr TWA	(ECHA, 2008b)	3970747	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Abbott (2001) - 1b	Manufacture of XPS from HBCD powder or granules	HBCD granules	Mostly area and some personal breathing zone	Feed deck near typical operator positions	Range 0.005-0.9 Mean: 0.24 90th percentile: 0.47 (excluding 16 ND samples)	43 (16 ND)	60 – 1435 minutes	(ECHA, 2008b)	3970747	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Thomsen (2007) - 1a	Manufacture of XPS from HBCD powder or granules	HBCD powder and granules	Personal breathing zone	Activities in the mixer area, including operating a closed	Range: 0.0002-0.0009 Mean: 0.0005 Median: 0.0005	6	8-hr TWA	(ECHA, 2008b) (NICNAS, 2012b)	3970747; 3978355	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry

				automated process excluding potential contact with neat HBCD							calculated in the EURAR from the available data (See Appendix E.2)
Thomsen (2007) - 1b	Manufacture of XPS from HBCD powder or granules	HBCD powder and granules	Personal breathing zone	Weighing and addition of HBCD to the reactor and subsequent washing, centrifugation, sifting, and transfer of product to a silo container	Range: 0.001-0.15 Mean: 0.015 Median: 0.0027	24	8-hr TWA	(ECHA, 2008b) (NICNAS, 2012b)	3970747; 3978355	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Searl and Robertson (2005) - 4	Manufacture of XPS from HBCD powder or granules	HBCD granules	Area	Logistics, extruding, and laboratory	Mean: 0.00003 90th percentile: 0.00004	12	8-hr TWA	(ECHA, 2008b)	3970747	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Ransbotyn (1999)	Manufacturing of EPS Resin beads	Respirable Dust Inhalable Dust	Personal	Addition of HBCDD to reactor or the supervising of the addition.	Respirable dust: <0.5 Total Inhalable dust: 2.0 Not specific to HBCD	5	Max 8-hr TWA	(ECHA, 2008b)	3970747	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
NICNAS (2012) - 1a	HBCD importation / repackaging sites and all industrial polymer processing sites	Standard grade HBCD	Modelled with EASE	Addition of HBCD into process operation	Typical: 2 to 5 Worst-case: 5 to 50	Not applicable - this is a modelled exposure	8-hr TWA	(NICNAS, 2012b)	3978355	High	Excluded - EPA used the estimates for HBCD processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
NICNAS (2012) - 1b	HBCD importation / repackaging	HBCD granules	Modelled with EASE	Repackaging with the use of LEV (typical)	Typical: 0.2 to 0.5	Not applicable - this is a	8-hr TWA	(NICNAS, 2012b)	3978355	High	Excluded - EPA used the estimates for HBCD

	sites and all industrial polymer processing sites			and without LEV (worst-case)	Worst-case: 0.5 to 5	modelled exposure					processing in the plastics industry calculated in the EURAR from the available data (See Appendix E.2)
Searl and Robertson (2005) - 5a	Secondary processing of XPS foam (cutting, sawing, machining)	XPS foam	NR	Secondary processing of XPS foam - including cutting, sawing, and machining to manufacture shaped products	Mean: 0.08 90th percentile: 0.22	9	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	3809166	High	Included - these data were used to estimate worker inhalation exposure in the following conditions of use: Manufacturing of XPS Foam using XPS Masterbatch; Manufacturing of EPS Foam from Imported EPS Resin Beads; Manufacturing of SIPs and Automobile Replacement Parts from EPS/XPS Foam; Installation of EPS/XPS Foam Insulation in Residential, Public and Commercial Buildings, and Other Structures; Demolition and Disposal of EPS/XPS Foam Insulation Products in Residential, Public and Commercial Buildings, and Other Structures; Recycling of EPS Foam and Reuse of XPS Foam
Searl and Robertson (2005) - 5b	Reclamation of XPS foam - including	XPS foam	NR	Reclamation of XPS foam - including	Mean: 0.02 90th percentile: 0.02	5	8-hr TWA	Original source: Searl and Robertson	3809166	High	Excluded - EPA used the data in Searl and

	shredding and reprocessing of process waste			shredding and reprocessing of process waste				(2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)			Robertson (2005) - 5a because it presents a larger range of potential exposure
Searl and Robertson (2005) - 5c	Manufacture of XPS from XPS masterbatch	XPS foam	NR	Other process control operators	Mean: 0.03 90th percentile: 0.03	4	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	3809166	High	Excluded - worker activities unknown
Searl and Robertson (2005) - 5d	Manufacture of XPS from XPS masterbatch	XPS foam	NR	Process operators handling XPS masterbatch	Mean: 0.03 90th percentile: 0.03	24	8-hr TWA	Original source: Searl and Robertson (2005) Reported in: (ECHA, 2008b); (ECHA, 2009b)	3809166	High	Excluded - EPA used the data in Searl and Robertson (2005) - 5a because it presents a larger range of potential exposure
Zhang et al. (2012) - 1a	Thermal cutting of XPS foam	XPS foam	NR	Thermal cutting of XPS boards in a closed glovebox	Mean: 0.089	NR	NR	(Zhang et al., 2012)	1927576	High	Excluded - sample time is unknown
Zhang et al. (2012) - 1b	Thermal cutting of EPS foam	EPS foam	NR	Thermal cutting of EPS boards in a closed glovebox	Mean: 0.057	NR	NR	(Zhang et al., 2012)	1927576	High	Excluded - sample time is unknown

NR = Not Reported; N/A = Not Applicable
a – Where multiple datasets were available from one literature source, EPA distinguished data as 1a, 1b, 2a, 2b, etc.
b - Statistics were calculated by the cited source and are presented here as they were presented in the source.
c – Where information is presented in multiple sources all sources are listed. Information was not combined from these sources but was presented in all sources independently.

Appendix F GENERAL POPULATION EXPOSURES

F.1 Consumer Exposure to EPS/XPS Insulation in Residences and Automobiles

EPA used the following general mass balance as defined in the user guide of the IECCU model to estimate the indoor concentrations of HBCD in indoor air and dust of a multi-zone indoor environment (EPA 2019).

Equation F-1:

$$\boldsymbol{V_i \frac{dC_i}{dt} = \sum_{j=1}^{n_1} A_j E_j - \sum_{k=0}^{n_2} Q_{ik}\, C_i + \sum_{k=0}^{n_3} Q_{ki}\, C_k - \sum_{m=1}^{n_4} S_m - \sum_{p=1}^{n_5} P_p - \sum_{q=1}^{n_6} D_q}$$

where V_i is volume of zone i (m^3)
C_i is air concentration in zone i (µg/m^3)
t is elapsed time (h)
A_j is area of source j in zone i (m^2)
E_j is emission factor for source j in zone i (µg/m^2/h)
Q_{ik} is air flow from zone i to zone k, $i \neq k$ (m^3/h)
Q_{ki} is air flow from zone k to zone i, $k \neq i$ (m^3/h)
C_k is air concentration in zone k (µg/m^3)
S_m is sorption rate onto interior surface m in zone i (µg/h)
P_p is rate of sorption by airborne particulate matter p in zone i (µg/h)
D_q is rate of sorption by settled dust q in zone i (µg/h)
Subscripts j, k, l, m, p, and q are summation counters
n_1 *through* n_6 are item numbers for their respective summations.

Equation F-1 states that the change of the concentration in air in zone i is determined by six factors: (1) the emissions from the sources in the zone, (2) the rate of chemical removed from zone i by the ventilation and interzonal air flows (Q_{ik}), (3) the rate of chemical carried into zone i by the infiltration and interzonal air flows (Q_{ki}), (4) the rate of chemical sorption by interior surfaces, (5) the rate of chemical sorption by airborne particles, and (6) the rate of chemical sorption by settled dust. Given a set of initial conditions, Equation 1 can be solved numerically.

Equation F-1 does not include the term for chemical reactions because HBCD is chemically inert at normal temperatures. Also note that the air concentrations in Equation F-1 — C_i and C_k — can be used to represent either the gas-phase or particle-phase concentrations or both.

For more information on additional equations used to estimate emissions from the source, sorption to interior surfaces, sorption to airborne particulates, and sorption to settled dust see the *Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Supplemental Information on General Population, Environmental, and Consumer Exposure Assessment. (U.S. EPA, 2019d)* and IECCU user guide (EPA 2019).

Simulation results – (1) HBCD in a "typical" home

Simulation results are presented in Figure Apx_ F-1. through Figure Apx_ F-4.. As shown in Figure Apx_ F-1., the predicted HBCD content in house dust is in line with the measured values in the literature. Table_Apx F-1. presents the mass balance results at the 100 elapsed days.

The predicted emission rates (Figure Apx_ F-4.), sorption rates (Figure Apx_ F-5.) and the mass balance (Table_Apx F-1.) were obtained with the new features recently added to IECCU.

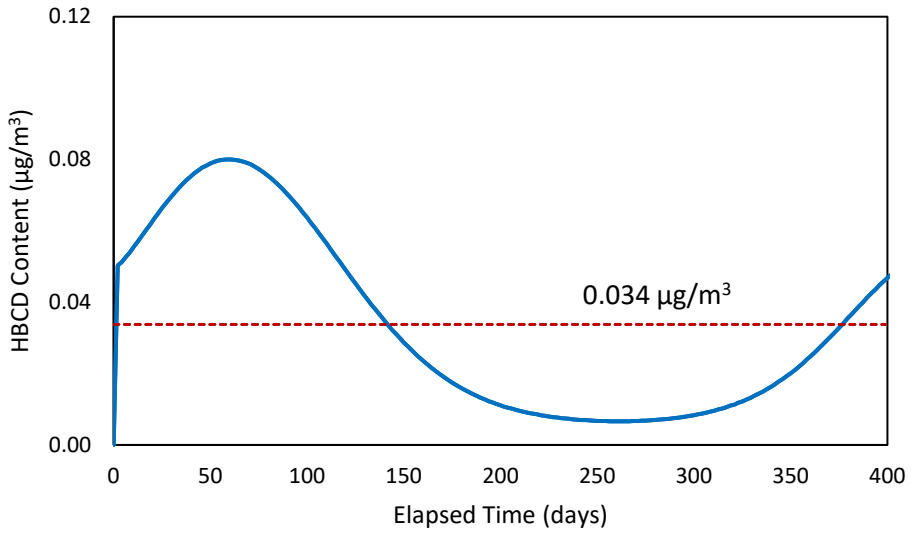

Figure Apx_ F-1. Predicted gas-phase HBCD concentration in living area.

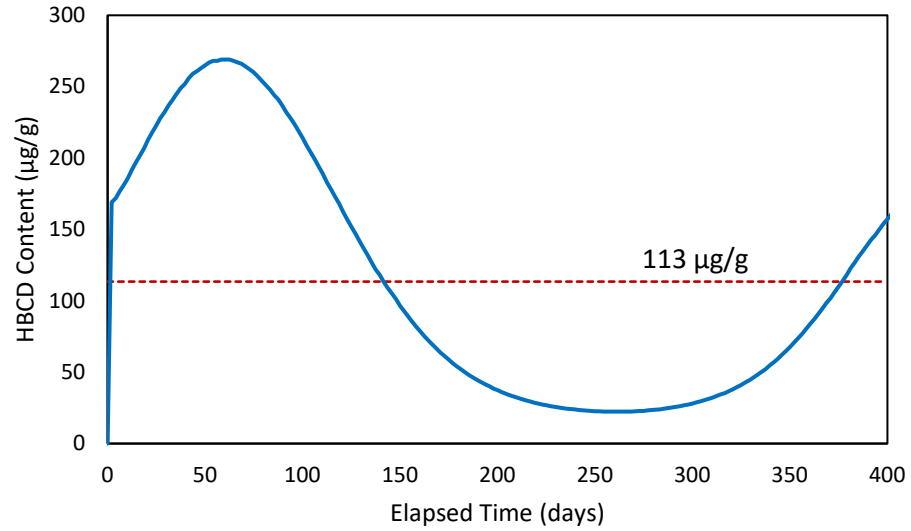

Figure Apx_ F-2. Predicted HBCD concentration in airborne PM in living area.

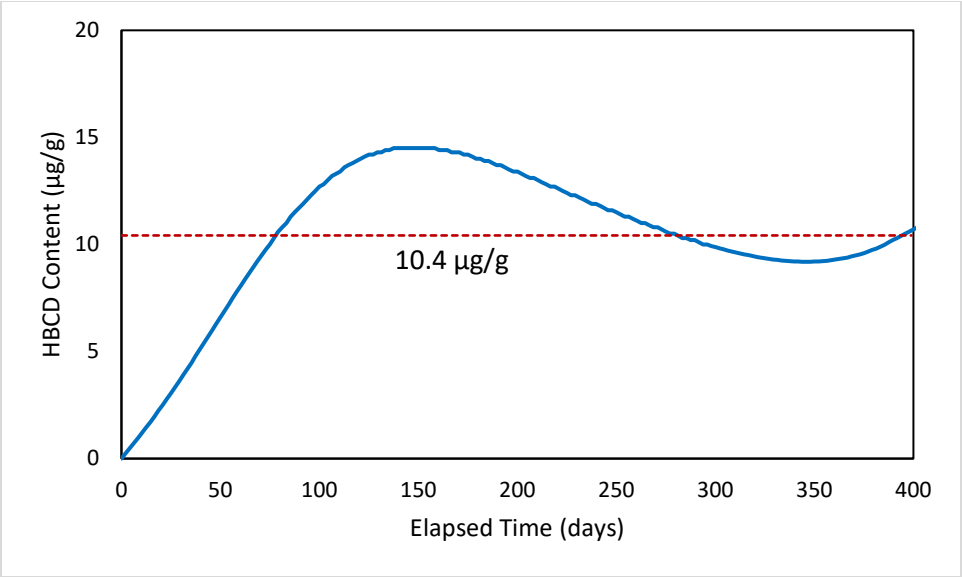

Figure Apx_ F-3. Predicted HBCD concentration in settled dust.

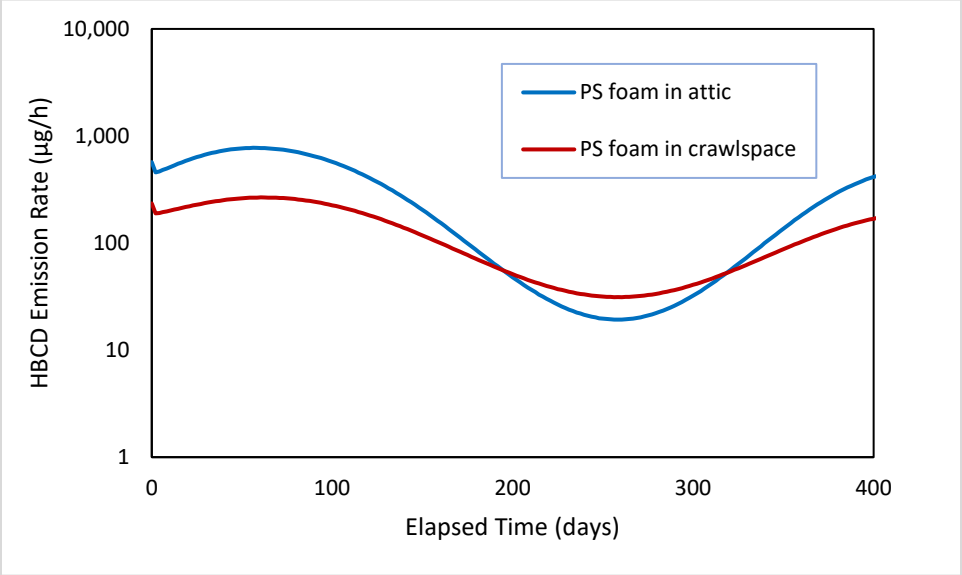

Figure Apx_ F-4. Predicted HBCD emission rates from polystyrene foam boards in attic and crawlspace.

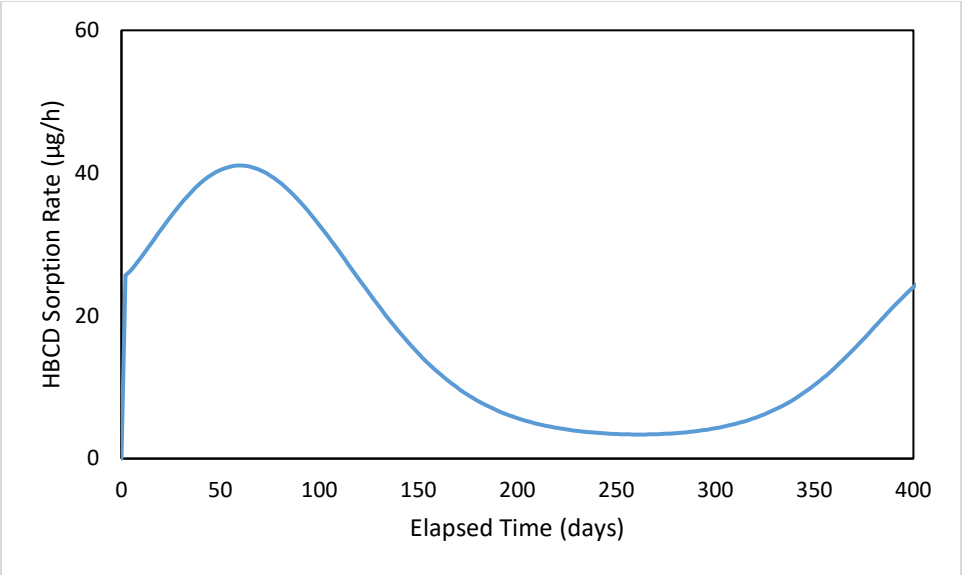

Figure Apx_ F-5. Rate of HBCD sorption by gypsum board walls.

Table_Apx F-1. Mass balance results for HBCD in the simulated home at 100 elapsed days.

Emission/Fate		**Mass (µg)**	**Percentage of of emitted**
Total HBCD Emitted		2.2E+06	
HBCD Fate	Vented out	2.1E+06	94.3%
	Remaining in air	4.9E+02	0.02%
	Absorbed by sinks	8.7E+04	4.0%
	PM deposition	7.8E+03	0.4%
	In dust	8.1E+03	0.4%
	Total	2.2E+06	100%

Simulation Results — (2) HBCD in passenger vehicles

The HBCD concentrations inside the cabin are shown in Figure Apx_ F-6. and the concentrations in the settled dust are shown in Figure Apx_ F-7.. Note that we have assumed that all the dust particles are freshly introduced and the initial HBCD concentration in the dust is zero.

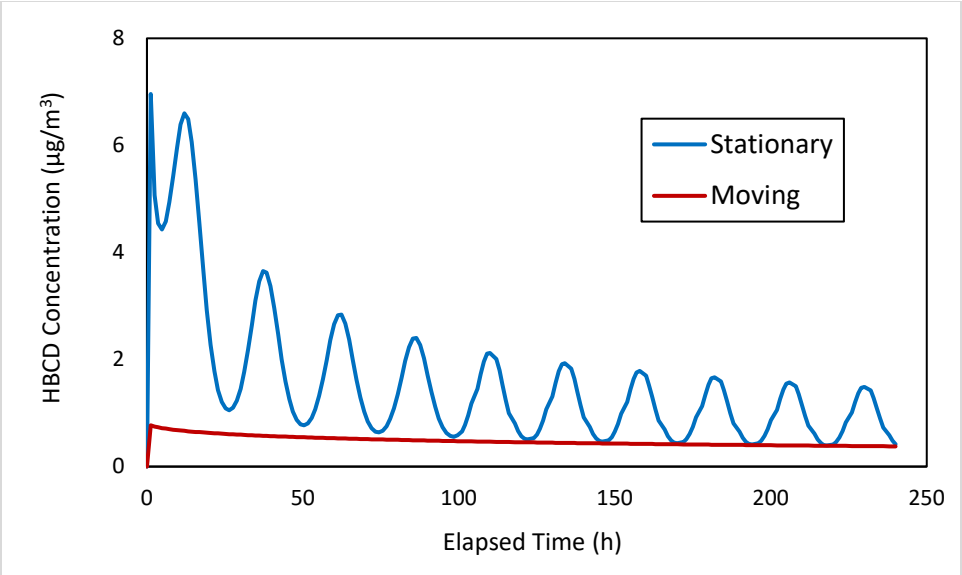

Figure Apx_ F-6. Predicted HBCD concentrations in vehicle's cabin.

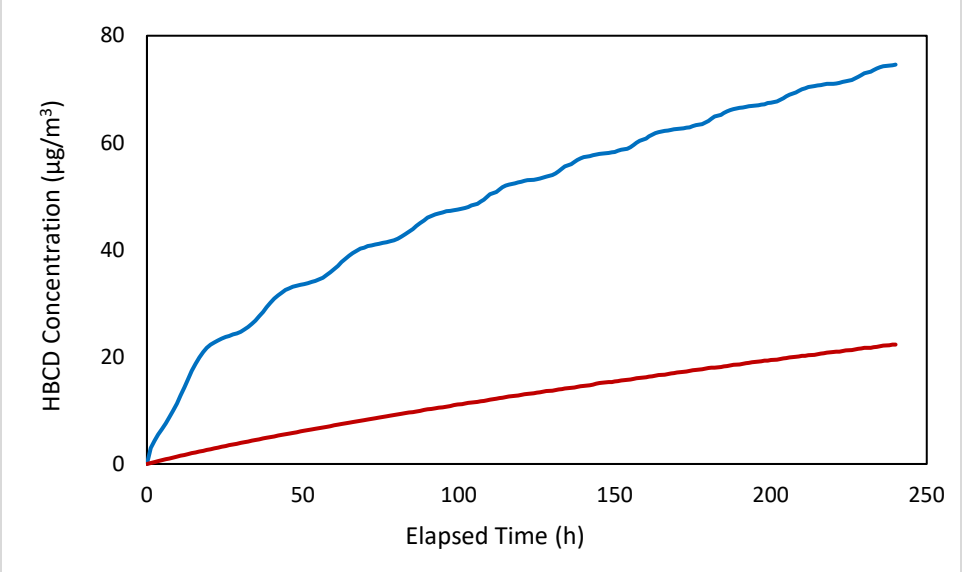

Figure Apx_ F-7. Predicted HBCD concentrations in the settled dust in vehicle's cabin. The dust contained no HBCD initially.

Discussion of XPS versus EPS foam boards

Extruded polystyrene (XPS) insulation is manufactured through an extrusion process, which produces a closed-cell rigid insulation. In contrast, expanded polystyrene (EPS) insulation is manufactured using a mold to contain small foam beads. Heat or steam is then applied to the mold, which causes the small beads to expand and fuse together. This manufacturing process produces open-cell insulation (see https://www.kingspan.com/meati/en-in/product-groups/insulation/knowledge-base/faqs/general/what-is-the-difference-between-xps-and-eps).

The presence of interconnected voids in the EPS foam facilitates both heat and mass transfers in the foam. According to website http://www.giasxps.ro/index.php/en/electronic-library-polystyrene/77-xps-eps-comparison, the resistances to water vapor diffusion are as follows:

- Air = 1
- EPS = 50 – 70
- XPS = 50 – 250

These numbers suggest that the solid-phase diffusion coefficient for the low-performance XPS foam is about the same as that for the EPS foam and that the diffusion coefficient for the high-performance XPS foam can be as small as one fourth to one fifth of that for the EPS foam.

In Huang et al. (2017), the XPS and EPS foams are lumped into a single material type. To evaluate the difference in HBCD emissions between XPS and EPS, EPA conducted several simulations in a single-zone setting (i.e., a test chamber) by varying only the solid-phase diffusion coefficient:

Table_Apx F-2. Parameters Used in Comparing EPS and XPS Foams

Parameter	Value
Diffusion coef. predicted by Huang et al. (2017):	3.2×10^{-12} (m^2/h) at 21 ºC
Diffusion coef. used in the simulations:	1×10^{-12} and 5×10^{-12} (m^2/h)
Chamber volume	30 m^3
Ventilation rate	0.5 h^{-1}
Source area	5 m^2
Source thickness	10 cm
Board density	28.9 kg/m^3
HBCD content	0.50% (equivalent to 1.45×10^8 µg/m^3)
Partition coef.	1.70×10^7 at 21 ºC
Gas-phase mass transfer coefficient	1 m/h

As shown in Figure Apx_ F-8., when D increases by a factor of 5 from 1×10^{-12} to 5×10^{-12} m^2/h, the average concentration over a year increases from 0.49 to 0.84 µg/m^3, an increase by a factor of 1.7. These results suggest that, if the XPS and EPS boards have the same HBCD content and the same density, then the emission from EPS boards can be twice as much as the emissions from high-

performance XPS boards. However, the emission from the low-performance XPS boards is expected to be similar to that from the EPS boards.

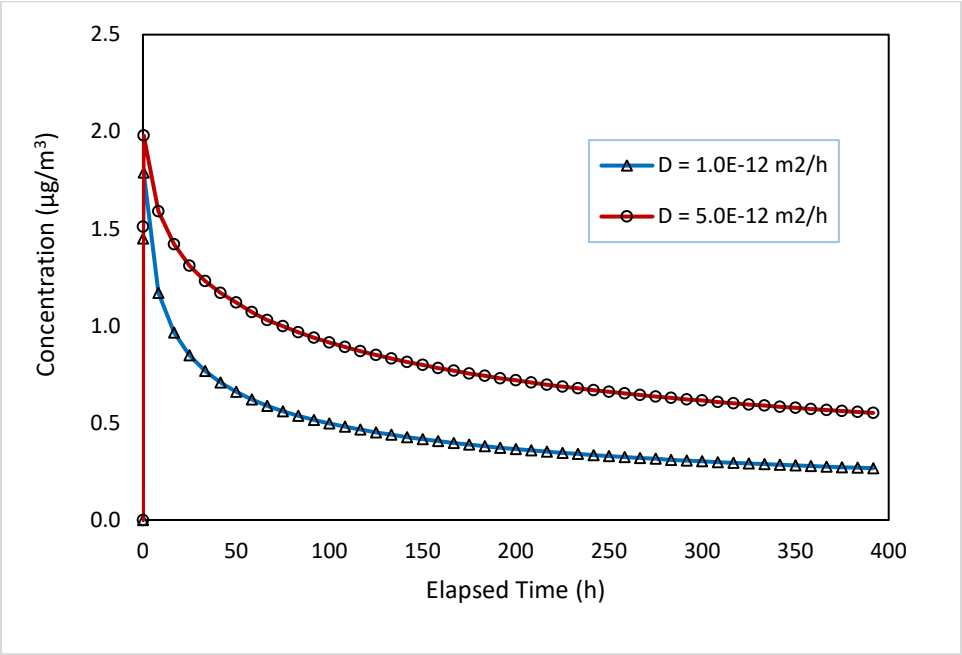

Figure Apx_ F-8. Simulated HBCD concentrations with different solid-phase diffusion coefficients.

Effect of temperature on HBCD emission rates

The temperature dependence of HBCD emission rate from polystyrene foam boards is affected by both the partition and diffusion coefficients (*K* and *D*). In this work, the temperature dependent K and D were calculated from existing empirical models. To determine whether the models we used can reasonably predict the temperature dependence of the emission rate, we compared our simulation results with those in the 2012 report by Chemicals Evaluation and Research Institute, Japan (http://www.meti.go.jp/meti_lib/report/2012fy/E001880.pdf).

To make the data comparable, we normalized the emission rates according to $N_R = \frac{R_T}{R_{T0}}$:

$$N_R = \frac{R_T}{R_{T0}}$$

where
N_R = normalized emission/diffusion rate (dimensionless)
R_T = emission rate at temperature T, µg/m^2/h,
R_{T0} = emission rate at reference temperature T_0, µg/m^2/h.

The single-zone model described was used to generate the HBCD emission rates. The temperature-dependent Ks and Ds were estimated.

As shown in , the predicted emission rates in this work are in good agreement with the data reported by the Japanese researchers (NITE 2012).

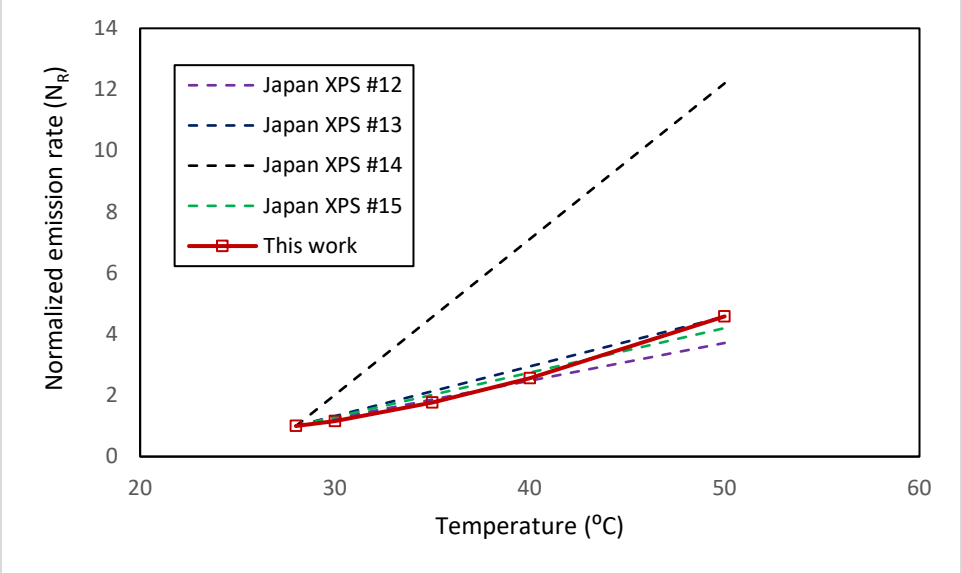

Figure Apx_ F-9. Comparison of normalized emission rates.

The four dotted lines are from Tables 3-2-25 and 3-2-26 in the Japanese report. The reference temperature is $T_0 = 28$ °C.

"Faced" versus "unfaced" insulation boards

The simulation results presented above are applicable to "unfaced" insulation boards and boards with a permeable facer (e.g., paper and fabrics). The results are not applicable to the boards with both sides covered with a nonpermeable facer such as foil. It is our understanding that most sheathing insulation boards on the market have one side covered by foil. When installed, the foil side faces the exterior of the building.

F.2 Mouthing of Plastic Articles Containing HBCD

EPA did not identify experimental data that measured migration of HBCD into saliva. EPA did, however, identify several other studies that quantified the migration rate into saliva for a variety of chemicals and consumer articles (EPA 2019). Based on this data set, EPA used a regression between concentration of chemicals present in articles and the migration rate to saliva to estimate potential migration rates for HBCD into saliva and potential exposures due to mouthing consumer articles containing HBCD.

EPA used the defaults shown in Table_Apx F-3. to estimate exposure from mouthing. EPA used central tendency estimates to calculate average daily doses (ADD) for a 1-2 year old and high-end estimates to calculate acute dose rates (ADR) for a 1-2 year old. Doses for all other age groups will be lower than those estimated for 1-2 year old children because older children spend less time mouthing objects and weigh more.

EPA used data from the following two studies to derive the HBCD concentration in consumer articles range described in Table_Apx F-4. (Abdallah et al., 2018; Vojta et al., 2017). Further, EPA used professional judgement to distinguish articles that were and were not likely to be mouthed by children.

Table_Apx F-3. Default Values used to Estimate Exposure from Mouthing of Articles

Surface Area Mouthed (Central Tendency)	Surface Area (cm^2) (High End)	Mouthing Duration (hrs) Central Tendency	Mouthing Duration (hrs) (High End)	Hours per Day Awake Child	µg to mg	Frequency (acute)	Frequency (days) (chronic)	Years of Use	Averaging Time (acute)	Averaging Time (chronic) child	Body Weight (child)
10	50	0.125	0.25	13	1.00E-03	1	250	1	1	365	11.4

Based on this data, the highest estimated exposure was 7.7E-5 mg/kg/day. The full range of estimated exposures is provided below.

Table_Apx F-4. Estimated Exposure from Mouthing of Articles

Summary Statistic	HBCD Concentration in Consumer Articles Likely to be Mouthed (ppm)	Migration Rate into Saliva ($ug/cm^2/hr$)	ADR 1-2 yrs (Central Tendency)	ADR 1-2 yrs (High End)	ADD 1-2 yrs (Central Tendency)	ADD 1-2 years (High End)
min	0.0015	3.8E-08	5.39E-11	5.39E-10	3.69E-11	3.69E-10
10th	0.003643	9.3E-08	1.33E-10	1.33E-09	9.09E-11	9.09E-10
50th	0.0915	2.2E-06	3.18E-09	3.18E-08	2.18E-09	2.18E-08
geomean	0.137864	3.3E-06	4.76E-09	4.76E-08	3.26E-09	3.26E-08
75th	0.56575	1.3E-05	1.91E-08	1.91E-07	1.31E-08	1.31E-07
90th	19.3096	4.3E-04	6.19E-07	6.19E-06	4.24E-07	4.24E-06
95th	32.66395	7.3E-04	1.04E-06	1.04E-05	7.11E-07	7.11E-06
98th	75.1788	1.7E-03	2.36E-06	2.36E-05	1.62E-06	1.62E-05
99th	90.41996	2.0E-03	2.83E-06	2.83E-05	1.94E-06	1.94E-05
max	249.7	5.4E-03	7.70E-06	7.70E-05	5.28E-06	5.28E-05

Appendix G ENVIRONMENTAL HAZARDS

G.1 Supplemental Environmental Hazard Information

See Supplemental Document:

Risk Evaluation for Cyclic Aliphatic Bromide Cluster (HBCD), Systematic Review Supplemental File: Data Extraction Tables of Environmental Hazard Studies. (U.S. EPA, 2019b)

G.2 Calculations Used to Evaluate the Potential Trophic Transfer of HBCD

The below calculations were used to calculate food and HBCD ingestion, as presented above in Table 3-2 and Table 3-3.

Legend:
$C_{predator}$: Amount of food consumed by predator
$BW_{predator}$: Predator body weight

Equation G-1: Calculation used to quantify food ingestion by a predator

$$\frac{amount\ of\ food\ consumed\ by\ predator}{BW_{predator} * day} * \%\ food\ type\ in\ predator\ diet * BW_{predator} = \frac{amount\ of\ food\ consumed\ by\ predator}{d}$$

Equation 2: Calculation used to quantify HBCD ingestion by a predator

$$\frac{g\ food\ consumed\ by\ predator}{d} * \frac{ng\ HBCD}{g\ food} = \frac{amount\ of\ HBCD\ consumed\ by\ predator}{d}$$

G.3 KABAM Outputs for Aquatic HBCD Bioaccumulation and Bioconcentration

G.3.1 10th Percentile Surface and Pore Water Concentrations

The outputs from KABAM (v1) are provided below, per sub-scenario- and HBCD-specific release information and physiochemical properties, respectively. Both sub-scenarios (3.3 and 5.7) are modeled with the assumption that the releases and subsequent surface water and pore water concentrations are based on a 75% removal of HBCD from the direct releases of HBCD into surface water. The outputs below are also based on the HBCD half-life of 128 days. Further information regarding the trophic level designations and calculations for the output parameters are available at: https://www.epa.gov/sites/production/files/2015-07/documents/kabam_v1_0_users_guide.pdf.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	Trophic Level	Total concentration (µg/kg-ww)	Lipid normalized concentration (µg/kg-lipid)	Contribution due to diet (µg/kg-ww)	Total BCF (µg/kg-ww)/(µg/L)	Total BAF (µg/kg-ww)/(µg/L)	BCF (µg/kg-lipid)/(µg/L)	BAF (µg/kg-lipid)/(µg/L)	BMF (µg/kg-lipid)/(µg/kg-lipid)	BSAF (µg/kg-lipid)/(µg/kg-OC)
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.3	100,000	Phytoplankton	18676	933799.8	N/A	20010.63	17454.2	1000532	872710.1	N/A	31.97944
			Zooplankton	16672.34	555744.6	1745.375	14257.78	15581.62	475259.4	519387.5	0.595143	19.03235
			Benthic Invertebrates	19749.81	658327.1	4696.468	15004.75	18457.77	500158.4	615259	1.339289	22.54545
			Filter Feeders	12943.12	647155.8	3029.452	9862.899	12096.37	493144.9	604818.5	1.316562	22.16287
			Small Fish	38714.05	967851.2	20981.21	19303.06	36181.35	482576.6	904533.9	1.594389	33.14559
			Medium Fish	63361.9	1584048	47561.14	19303.06	59216.73	482576.6	1480418	1.948184	54.24821
			Large Fish	154955.6	3873889	140823.3	20031.3	144818.3	500782.6	3620457	2.445563	132.6674
		50,000	Phytoplankton	9425.269	471263.4	N/A	20010.63	17454.2	1000532	872710.1	N/A	32.05874
			Zooplankton	8414.077	280469.2	880.8435	14257.78	15581.62	475259.4	519387.5	0.595143	19.07954
			Benthic Invertebrates	9966.737	332224.6	2369.987	15004.23	18456.92	500140.9	615230.7	1.339228	22.60031
			Filter Feeders	6531.74	326587	1528.758	9862.553	12095.81	493127.7	604790.7	1.316502	22.2168
			Small Fish	19537.35	488433.8	10588.38	19302.39	36180.28	482559.7	904507.1	1.594382	33.22679
			Medium Fish	31975.91	799397.8	24001.97	19302.39	59214.65	482559.7	1480366	1.948187	54.3808
			Large Fish	78199.37	1954984	71067.19	20031.3	144813.7	500782.6	3620341	2.445571	132.9921
		25,000	Phytoplankton	4695.18	234759	N/A	20010.63	17454.2	1000532	872710.1	N/A	31.94
			Zooplankton	4191.457	139715.2	438.7905	14257.78	15581.62	475259.4	519387.5	0.595143	19.00887

The outputs from KABAM (v1) are provided below, per sub-scenario- and HBCD-specific release information and physiochemical properties, respectively. Both sub-scenarios (3.3 and 5.7) are modeled with the assumption that the releases and subsequent surface water and pore water concentrations are based on a 75% removal of HBCD from the direct releases of HBCD into surface water. The outputs below are also based on the HBCD half-life of 128 days. Further information regarding the trophic level designations and calculations for the output parameters are available at: https://www.epa.gov/sites/production/files/2015-07/documents/kabam_v1_0_users_guide.pdf.

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			Benthic Invertebrates	4965.254	165508.5	1180.749	15005.01	18458.19	500167.1	615273.1	1.33932	22.51816
			Filter Feeders	3253.998	162699.9	761.6409	9863.071	12096.65	493153.6	604832.3	1.316593	22.13604
			Small Fish	9732.928	243323.2	5274.781	19303.4	36181.89	482585	904547.2	1.594393	33.1052
			Medium Fish	15929.58	398239.5	11957.17	19303.4	59217.77	482585	1480444	1.948183	54.18225
			Large Fish	38956.74	973918.4	35403.85	20031.3	144820.6	500782.6	3620515	2.445559	132.5059
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.7	100,000	Phytoplankton	774146.2	38707310	N/A	20010.63	17454.2	1000532	872710.1	N/A	10.90347
			Zooplankton	691091.8	23036392	72348.24	14257.78	15581.62	475259.4	519387.5	0.595143	6.489125
			Benthic Invertebrates	848124.8	28270827	207064.1	15415.43	19122.15	513847.7	637405.1	1.387497	7.963613
			Filter Feeders	555749	27787452	133566.5	10132.85	12530.13	506642.3	626506.7	1.363773	7.827451
			Small Fish	1641845	41046121	886675.3	19831.39	37017.67	495784.7	925441.8	1.600013	11.56229
			Medium Fish	2698514	67462850	2025624	19831.39	60841.75	495784.7	1521044	1.946504	19.00362
			Large Fish	6583312	1.65E+08	5997508	20031.3	148429.9	500782.6	3710748	2.439606	46.36135
		50,000	Phytoplankton	708116.9	35405847	N/A	20010.63	17454.2	1000532	872710.1	N/A	17.97251
			Zooplankton	632146.5	21071550	66177.44	14257.78	15581.62	475259.4	519387.5	0.595143	10.69622
			Benthic Invertebrates	759699.3	25323311	182639.8	15170.33	18725.64	505677.8	624188.1	1.358726	12.85447
			Filter Feeders	497845	24892250	117811.6	9971.739	12271.26	498587	613563	1.335597	12.63566
			Small Fish	1481558	37038940	801781.5	19516.08	36518.55	487902	912963.8	1.596683	18.80149
			Medium Fish	2429004	60725099	1823293	19516.08	59871.92	487902	1496798	1.947495	30.82492
			Large Fish	5934355	1.48E+08	5398516	20031.3	146274.5	500782.6	3656861	2.443123	75.30907

The outputs from KABAM (v1) are provided below, per sub-scenario- and HBCD-specific release information and physiochemical properties, respectively. Both sub-scenarios (3.3 and 5.7) are modeled with the assumption that the releases and subsequent surface water and pore water concentrations are based on a 75% removal of HBCD from the direct releases of HBCD into surface water. The outputs below are also based on the HBCD half-life of 128 days. Further information regarding the trophic level designations and calculations for the output parameters are available at: https://www.epa.gov/sites/production/files/2015-07/documents/kabam_v1_0_users_guide.pdf.

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		25,000	Phytoplankton	677746.6	33887332	N/A	20010.63	17454.2	1000532	872710.1	N/A	25.4792
			Zooplankton	605034.5	20167815	63339.17	14257.78	15581.62	475259.4	519387.5	0.595143	15.16377
			Benthic Invertebrates	720120.1	24004004	171865	15058.95	18545.46	501965.2	618181.9	1.345652	18.04812
			Filter Feeders	471925	23596252	110861.4	9898.528	12153.62	494926.4	607681	1.322793	17.74154
			Small Fish	1409208	35230202	763363.6	19372.79	36291.74	484319.8	907293.4	1.595144	26.48887
			Medium Fish	2307714	57692845	1732237	19372.79	59431.21	484319.8	1485780	1.947957	43.37808
			Large Fish	5641803	1.41E+08	5128946	20031.3	145295	500782.6	3632374	2.444758	106.0489

G.3.2 50th Percentile Surface and Pore Water Concentrations

The outputs from KABAM (v1) are provided below, per sub-scenario- and HBCD-specific release information and physiochemical properties, respectively. Both sub-scenarios (3.3 and 5.7) are modeled with the assumption that the releases and subsequent surface water and pore water concentrations are based on a 75% removal of HBCD from the direct releases of HBCD into surface water. The outputs below are also based on the HBCD half-life of 128 days. Further information regarding the trophic level designations and calculations for the output parameters are available at: https://www.epa.gov/sites/production/files/2015-07/documents/kabam_v1_0_users_guide.pdf.

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Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.3	100,000	Phytoplankton	453.8092	22690.46	N/A	20010.63	17454.2	1000532	872710.1	N/A	30.66279
			Zooplankton	405.1222	13504.07	42.41098	14257.78	15581.62	475259.4	519387.5	0.595143	18.24875
			Benthic Invertebrates	480.2857	16009.52	114.2811	15013.87	18472.53	500462.5	615751	1.34036	21.63449
			Filter Feeders	314.7561	15737.81	73.71692	9868.896	12106.01	493444.8	605300.3	1.317611	21.26731
			Small Fish	941.1983	23529.96	510.0448	19314.8	36199.93	482870	904998.3	1.594516	31.79724
			Medium Fish	1540.574	38514.34	1156.396	19314.8	59252.83	482870	1481321	1.948146	52.04641
			Large Fish	3767.361	94184.03	3423.96	20031.3	144898.5	500782.6	3622463	2.445428	127.2757
		50,000	Phytoplankton	232.1409	11607.04	N/A	20010.63	17454.2	1000532	872710.1	N/A	29.01761
			Zooplankton	207.2356	6907.853	21.69485	14257.78	15581.62	475259.4	519387.5	0.595143	17.26963
			Benthic Invertebrates	245.9549	8198.498	58.57284	15026.44	18492.85	500881.3	616428.4	1.341835	20.49624
			Filter Feeders	161.1863	8059.317	37.78235	9877.153	12119.27	493857.7	605963.7	1.319055	20.14829
			Small Fish	481.7994	12044.98	261.0632	19330.96	36225.52	483274	905637.9	1.594691	30.11246
			Medium Fish	788.7238	19718.1	592.0379	19330.96	59302.54	483274	1482564	1.948093	49.29524
			Large Fish	1928.62	48215.49	1752.956	20031.3	145009	500782.6	3625225	2.445241	120.5387
		25,000	Phytoplankton	116.9431	5847.157	N/A	20010.63	17454.2	1000532	872710.1	N/A	31.43633

The outputs from KABAM (v1) are provided below, per sub-scenario- and HBCD-specific release information and physiochemical properties, respectively. Both sub-scenarios (3.3 and 5.7) are modeled with the assumption that the releases and subsequent surface water and pore water concentrations are based on a 75% removal of HBCD from the direct releases of HBCD into surface water. The outputs below are also based on the HBCD half-life of 128 days. Further information regarding the trophic level designations and calculations for the output parameters are available at: https://www.epa.gov/sites/production/files/2015-07/documents/kabam_v1_0_users_guide.pdf.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	Trophic Level	Total concentration (µg/kg-ww)	Lipid normalized concentration (µg/kg-lipid)	Contribution due to diet (µg/kg-ww)	Total BCF (µg/kg-ww)/(µg/L)	Total BAF (µg/kg-ww)/(µg/L)	BCF (µg/kg-lipid)/(µg/L)	BAF (µg/kg-lipid)/(µg/L)	BMF (µg/kg-lipid)/(µg/kg-lipid)	BSAF (µg/kg-lipid)/(µg/kg-OC)
			Zooplankton	104.3969	3479.896	10.92898	14257.78	15581.62	475259.4	519387.5	0.595143	18.70912
			Benthic Invertebrates	123.7068	4123.561	29.42452	15008.42	18463.71	500280.7	615456.9	1.33972	22.16969
			Filter Feeders	81.07165	4053.583	18.98026	9865.312	12100.25	493265.6	605012.3	1.316984	21.79345
			Small Fish	242.4652	6061.629	131.4006	19307.79	36188.83	482694.6	904720.7	1.59444	32.5894
			Medium Fish	396.8494	9921.236	297.8858	19307.79	59231.26	482694.6	1480781	1.948169	53.33998
			Large Fish	970.4987	24262.47	882.0068	20031.3	144850.6	500782.6	3621264	2.445509	130.4434
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.7	100,000	Phytoplankton	16511.67	825583.7	N/A	20010.63	17454.2	1000532	872710.1	N/A	10.89161
			Zooplankton	14740.22	491340.5	1543.107	14257.78	15581.62	475259.4	519387.5	0.595143	6.482065
			Benthic Invertebrates	18090.59	603019.8	4416.883	15416.11	19123.25	513870.4	637441.7	1.387576	7.955406
			Filter Feeders	11854.18	592709.2	2849.106	10133.29	12530.85	506664.6	626542.5	1.363851	7.819383
			Small Fish	35020.03	875500.6	18912.39	19832.26	37019.05	495806.5	925476.4	1.600023	11.55014
			Medium Fish	57558.83	1438971	43206.2	19832.26	60844.43	495806.5	1521111	1.946501	18.98378
			Large Fish	140420.3	3510508	127925.8	20031.3	148435.9	500782.6	3710897	2.439597	46.31278
		50,000	Phytoplankton	16511.67	825583.7	N/A	20010.63	17454.2	1000532	872710.1	N/A	19.19962
			Zooplankton	14740.22	491340.5	1543.107	14257.78	15581.62	475259.4	519387.5	0.595143	11.42652

The outputs from KABAM (v1) are provided below, per sub-scenario- and HBCD-specific release information and physiochemical properties, respectively. Both sub-scenarios (3.3 and 5.7) are modeled with the assumption that the releases and subsequent surface water and pore water concentrations are based on a 75% removal of HBCD from the direct releases of HBCD into surface water. The outputs below are also based on the HBCD half-life of 128 days. Further information regarding the trophic level designations and calculations for the output parameters are available at: https://www.epa.gov/sites/production/files/2015-07/documents/kabam_v1_0_users_guide.pdf.

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			Benthic Invertebrates	17677.48	589249.4	4243.198	15146.17	18686.55	504872.4	622885.1	1.35589	13.70347
			Filter Feeders	11584.47	579223.5	2737.071	9955.857	12245.74	497792.9	612287	1.33282	13.47031
			Small Fish	34500	862500.1	18674.42	19485	36469.35	487124.9	911733.7	1.59635	20.05814
			Medium Fish	56548.4	1413710	42447.08	19485	59776.32	487124.9	1494408	1.947595	32.87697
			Large Fish	138174.6	3454365	125680.1	20031.3	146062	500782.6	3651549	2.443475	80.33408
		25,000	Phytoplankton	16511.67	825583.7	N/A	20010.63	17454.2	1000532	872710.1	N/A	26.89198
			Zooplankton	14740.22	491340.5	1543.107	14257.78	15581.62	475259.4	519387.5	0.595143	16.00458
			Benthic Invertebrates	17522.56	584085.4	4178.066	15044.95	18522.79	501498.2	617426.5	1.344007	19.02558
			Filter Feeders	11483.33	574166.3	2695.058	9889.319	12138.82	494465.9	606941.1	1.321183	18.70249
			Small Fish	34304.99	857624.8	18585.18	19354.77	36263.21	483869.3	906580.2	1.594949	27.93566
			Medium Fish	56169.48	1404237	42162.41	19354.77	59375.77	483869.3	1484394	1.948016	45.74062
			Large Fish	137332.5	3433312	124837.9	20031.3	145171.7	500782.6	3629294	2.444966	111.8343

Appendix H HUMAN HEALTH HAZARDS - TOXICOKINETICS

H.1 Toxicokinetics

H.1.1 Absorption

Absorption in the human gastrointestinal (GI) tract is expected given the detection of hexabromocyclododecane (HBCD) in samples of human milk, maternal blood/cord blood, or fetal tissue, and in food samples collected in several regions of the world (Rawn et al., 2014a; Rawn et al., 2014b; NICNAS, 2012a; Environment Canada, 2011).

HBCD isomers were rapidly and extensively absorbed in the GI tracts of mice given single oral doses of γ-[14C]-HBCD (Szabo et al., 2010), α [14C] HBCD (Szabo et al., 2011b), or β-HBCD (Sanders et al., 2013) and rats given single oral doses of [14C]- γ-HBCD (mixed with technical-grade HBCD containing ~75% γ-HBCD) (Yu and Atallah, 1980). For example, the rat study indicated nearly complete absorption; after 72 hours, 72% of the administered radioactivity was detected in feces (as nonidentified metabolites), 16% in urine, and 17% in tissues excluding the GI tract (Yu and Atallah, 1980). In studies of mice, absorption percentages between 85 and 90% were reported, based on tissue levels and cumulative fecal and urinary excretion of radioactivity (Sanders et al., 2013; Szabo et al., 2011b, 2010).

The dermal absorption of HBCD has also been investigated in a few studies. Various ex vivo and in vitro skin models demonstrate that ~30-50% of dermally exposed HBCD will partition into skin tissue (Pawar et al., 2016; Abdallah et al., 2015). The absorption of HBCD is influenced by both the composition of skin and the relative isomeric mixture of HBCD. HBCD is preferentially absorbed into sebum compared to sweat, and absorption increases from γ-HBCD < β-HBCD < α-HBCD. Substantially less HBCD penetrates through skin for systemic absorption. One study estimated 2-4% systemic absorption (Yi et al., 2016) depending on particle size. Data from skin models suggests that 4.95 – 6.46% of α-HBCD is absorbed, with other isomers permeating even less (Abdallah et al., 2015).

H.1.2 Distribution

Numerous studies of HBCD concentrations in samples of human milk, blood, fatty tissues, or fetal tissues have noted that α-HBCD is the predominant isomer detected, even though γ-HBCD is the predominant isomer in commercial HBCD products (for reviews, see Rawn et al., 2014a; Rawn et al., 2014b; NICNAS, 2012a; Environment Canada, 2011). These results indicate preferential tissue accumulation (especially in fat) of α-HBCD, compared with γ-HBCD or β-HBCD. In these studies, measurements of HBCD in maternal serum and umbilical cord serum of pregnant women have demonstrated that HBCD can cross the placenta and enter the fetal circulatory system.

In rats and mice, radioactivity from oral or intravenous (i.v.) administered [14C]-HBCD distributes widely in the body, with the highest levels in fat, liver, skeletal muscle, and skin (Sanders et al., 2013; Szabo et al., 2011a; Szabo et al., 2010; Yu and Atallah, 1980). For example, 8 hours after administration of a single oral dose of [14C]- γ-HBCD (mixed with technical-grade HBCD) in female rats, radioactivity was detected in the fat (20% of administered dose), muscle (14%), and liver (7%) with smaller amounts (<1%) in the blood, heart, lung, gonads, uterus, spleen, kidney, and brain (Yu and Atallah, 1980). A similar relative distribution pattern was observed in male rats, except that the levels of radioactivity (expressed as a percentage of administered dose) in fat and muscle of males were lower (about one-half to three-quarters of the levels in females). Radioactivity in most tissues decreased over the course of 72

hours, but remained elevated in the fat. Nonpolar metabolites of HBCD accounted for all of the radioactivity in fat; isomeric composition in the fat was not determined.

The three HBCD isomers exhibit differential accumulation in mice exposed by gavage (Sanders et al., 2013; Szabo et al., 2011a; Szabo et al., 2010). At 1–3 hours after single radiolabeled doses of 3 mg/kg of each isomer were given, concentrations of HBCD-derived radioactivity were highest in the liver, followed by the adrenals, kidneys, and bladder (after exposure to γ-HBCD); fat, kidneys, and lung (after exposure to β-HBCD); or blood, kidney, and brain (after exposure to α HBCD). Tissue concentrations were markedly higher after exposure to α-HBCD (e.g., peak of 47,628 ng/g liver) than after exposure to the other isomers (peaks of 4,462 ng/g liver for β-HBCD and 2,309 ng/g liver for γ-HBCD). Tissue concentrations peaked 3−8 hours after exposure to either β or γ-HBCD, and declined steadily thereafter. In contrast, after exposure to α-HBCD, concentrations in the skin, muscle, and adipose tissue peaked 1−2 days later, indicating redistribution and accumulation of radioactivity in these tissues. Four days after exposure to each isomer, concentrations were markedly decreased in all tissues; at that time, the highest tissue concentrations were in the fat after exposure to β- and α HBCD (13,320 and 498 ng/g, respectively), and in the adrenal glands after exposure to γ-HBCD (492 ng/g) (Sanders et al., 2013; Szabo et al., 2011a; Szabo et al., 2010). The results indicate greater deposition of α-HBCD or its metabolites in most tissues, especially fat, compared with γ-HBCD and β-HBCD. Similar findings were reported by (WIL Research, 2001) based on data from fat tissue samples collected from rats exposed to technical-grade HBCD for 90 days at a gavage dose of 1,000 mg/kg-day; β and γ-HBCD tissue concentrations were only 8–18% of the concentration of α-HBCD.

Sex-dependent differences in distribution were observed in rats exposed by gavage for 28 days to commercial HBCD at doses from 0.3 to 200 mg/kg-day (van der Ven et al., 2006). Concentrations of total HBCD were higher (on average 5-fold higher) in livers of female than male rats over the entire dose range. Fat tissue from female rats contained HBCD concentrations approximately 4.5-fold higher than those measured in male fat tissue (based on data from two rats/sex in the 10 mg/kg-day dose group). Findings from the 90-day rat study by (WIL Research, 2001) showed a smaller sex-dependent difference in fat tissue concentrations. In rats193193 exposed by gavage at a dose of 1,000 mg/kg-day, the mean α-HBCD concentrations in fat tissues was only 40% greater in female rats than males at exposure day 89; the mean concentrations of β- and γ-HBCD in fat tissues in males and females were similar. Based on same collections on days 2, 6, 13, 20, 27, 55, 89, 104, and 118 of the study, the patterns of distribution into fat tissues in males and females were similar.

H.1.3 Metabolism

Studies in laboratory animals and in vitro studies show that HBCD isomers can undergo stereoisomerization, hydroxylation, and debromination, and that γ-HBCD and β-HBCD are more rapidly and extensively metabolized than α-HBCD. The results also indicate that cytochrome P450 (CYP450) enzymes are involved in metabolism of HBCD, but the predominant metabolic pathways and terminal excretory metabolites have not been fully characterized. Debrominated metabolites of HBCD have been detected in human breast milk samples, suggesting that debromination steps inferred from metabolites identified in laboratory animals are applicable to humans (Abdallah and Harrad, 2011).

In vivo stereoisomerization of the γ- to the α-isomer has been demonstrated in toxicity studies of rats, and available data suggest that stereoisomerization is more important at higher doses. Dose-dependent stereoisomerization was observed in rats repeatedly exposed to commercial HBCD (with composition 10% α, 9% β, and 81% γ) by gavage (van der Ven et al., 2006; WIL Research, 2001) or dietary administration (van der Ven et al., 2009). In these studies, the ratios of the lipid-normalized

concentrations of γ-isomer to the α-isomer (measured as parent compound using liquid chromatography/mass spectrometry [LC/MS]) in liver differed from the ratios in the administered material, and these ratios declined with increasing dose. For example, in adult rats exposed for 28 days (van der Ven et al., 2006), the ratios of the γ-isomer to the α-isomer (β-HBCD comprised <1.5% of the total HBCD in tissues) in females ranged from 4.2 at the low dose (0.3 mg/kg-day) to 0.4 at the high dose (200 mg/kg-day); in males, at the same doses, the ratios ranged from 2.3 at the low dose to 0.9 at the high dose. These values were all lower than the ratio of 8.1 in the administered material. This dose-dependent shift in the ratio of γ:α isomers was also observed in 11-week-old offspring of rats exposed before and during mating and during gestation and lactation (van der Ven et al., 2009).

Analysis of excreta and tissues following oral administration of [14C]-HBCD to rats (Yu and Atallah, 1980) showed extensive metabolism of γ-HBCD. None of the radioactivity recovered in urine or feces could be identified as parent γ-HBCD following oral administration of [14C]-γ-HBCD (mixed with technical-grade HBCD containing ~75% γ-HBCD). Several polar metabolites of uncharacterized structure were found in extracts of feces and urine; these metabolites constituted 88% of the cumulative radioactivity excreted during the 72 hours after dosing (Yu and Atallah, 1980).

Results of oral exposure studies in mice given the same dose of each isomer demonstrated more extensive metabolism of β- and γ-HBCD compared with α-HBCD (Sanders et al., 2013; Szabo et al., 2011b, 2010). For example, more radioactivity was excreted in the urine after oral dosing with β-HBCD (~45% of administered dose over 4 days) than after the same dose of either α- or γ HBCD (~20−28% of administered dose). The urine contained only metabolites; none of the radioactivity in the urine was associated with the parent isomers (Sanders et al., 2013; Szabo et al., 2011b, 2010). Extraction of feces samples for thin layer chromatography analysis of radioactivity showed that a significant proportion of fecal radioactivity was not extractable after exposure to α HBCD (64%) or γ-HBCD (52%), while a lower proportion was not extractable after exposure to β HBCD (30%). (Szabo et al., 2010) hypothesized that nonextractable radioactivity in feces represented remnants from reactive metabolites covalently bound to proteins or lipids. Of the extractable radioactivity in feces, polar metabolites comprised the largest percentage of extractable fecal radioactivity after dosing with γ HBCD (85%); polar metabolites comprised smaller percentages after dosing with α-HBCD (66%) or β-HBCD (39%). After exposure to β- and γ-HBCD, but not α HBCD, isomerization products were detected in feces. Total extractable fecal radioactivity contained 4% β-HBCD and 7% α-HBCD after exposure to γ-HBCD, and 16% γ-HBCD after exposure to β-HBCD. No isomerization of α-HBCD was evident in any of the matrices examined. Data on the excretion of parent compound provide the strongest evidence for greater metabolism of β- and γ HBCD compared with α-HBCD: a larger percentage of extractable fecal radioactivity was associated with parent compound after administration of α-HBCD (34%) than after dosing with β HBCD (14%) or γ-HBCD (4%). Given that oral absorption of all three isomers was similar (85−90%), the differences in excreted parent compound appear to reflect greater metabolism of the β- and γ-isomers.

More rapid metabolism of β- and γ-HBCD relative to α-HBCD was demonstrated in in vitro studies using rat liver microsomes (Abdallah et al., 2014; Esslinger et al., 2011a; Zegers et al., 2005). Following incubation of the microsomes with NADPH and a 1:1:1 mixture of α-, β-, and γ-HBCD, LC/MS peaks for β- and γ HBCD in the incubation fluid were greatly diminished after 90 minutes, whereas the peak for α HBCD was essentially unchanged. In addition, degradation rates for enantiomeric isomers (+) α and (−) α-HBCD were faster in rat liver microsomes than rates for (+) β-, (−) β-, or (−) γ-HBCD (Esslinger et al., 2011a). (Abdallah et al., 2014) calculated half-times of 17.14,

11.92, and 6.34 seconds for in vitro rat liver microsomal metabolism of α-, γ-, and β-HBCD, respectively.

Hydroxylation and debromination have been identified as metabolic pathways for HBCD isomers based on partial characterization of metabolites in animal and in vitro studies. Analysis of adipose, liver, muscle, and lung tissue extracts from rats exposed to 100 mg/kg-day commercial HBCD (enriched in the γ-isomer) for 28 days identified mono- and dihydroxylated metabolites of HBCD as well as monohydroxylated derivatives of the debrominated metabolites pentabromocyclo¬dodecene and tetrabromocyclododecene (Brandsma et al., 2009). No sex dependent differences in metabolite profiles were observed (Brandsma et al., 2009). Hydroxylated metabolites of β- and γ HBCD, along with other unidentified metabolites, were also detected by LC/MS of incubation fluid after rat liver microsomes were incubated with a mixture of α-, β-, and γ-HBCD (1:1:1) and NADPH (Zegers et al., 2005).

Although specific enzymatic pathways for metabolism of HBCD have not yet been identified, results of animal in vivo and in vitro studies are consistent with hydroxylation catalyzed by CYP450 enzymes, as suggested by the observation that HBCD induced messenger ribonucleic acid (mRNA) levels for CYP2B1/2 and CYP3A1/3 in livers of rats following 28 days of dietary exposure to commercial HBCD (Cantón et al., 2008; Germer et al., 2006). There are no data describing the potential contribution of gut-mediated HBCD metabolism. However, it is likely that fecal metabolites are predominantly liver-derived, as only radioactive metabolites (no parent compounds) were found in the bile of mice orally exposed to α- or γ-[14C]-HBCD (Szabo et al., 2011b, 2010).

The available data are consistent with the proposed generalized metabolic pathways shown in Figure Apx_ H-1., in which debromination occurs via undetermined enzymes and hydroxylation occurs via CYP450 oxygenases (Brandsma et al., 2009). The generalized metabolic scheme in Figure Apx_ H-1. does not capture in vivo and in vitro evidence that isomer-specific metabolic pathways may exist in laboratory animals, or the evidence that HBCD metabolites may be conjugated prior to excretion. (Hakk et al., 2012) found evidence for different metabolic products of γ-HBCD and α-HBCD using LC/MS analysis of extractable and nonextractable HBCD metabolites in blood, fat, brain, bile, urine, and feces collected in the toxicokinetic studies of mice exposed to radiolabeled γ-HBCD (Szabo et al., 2010) and α-HBCD (Szabo et al., 2011b). After α-HBCD exposure, two glutathione conjugates of a tri- or tetra-brominated, unsaturated C6 hydrocarbon were identified in urine, and a monohydroxylated, hexabrominated metabolite was identified in feces (Hakk et al., 2012). After γ HBCD exposure, greater numbers of metabolites were identified in urine and feces: (1) two carboxylic acid derivatives (indicative of ring opening), a hydroxylated, pentabrominated derivative, and a putative methyl mercapturate of a tetrabrominated derivative in urine; and (2) three debrominated and oxidized derivatives in feces (Hakk et al., 2012). In rat liver microsomes tested in vitro, varied monohydroxylated HBCD products for each of several tested enantiomeric substrates were detected: one from (+) α-HBCD; three from (−) α-HBCD; two from (+) γ-HBCD; and three from (−) γ-HBCD (Esslinger et al., 2011a).

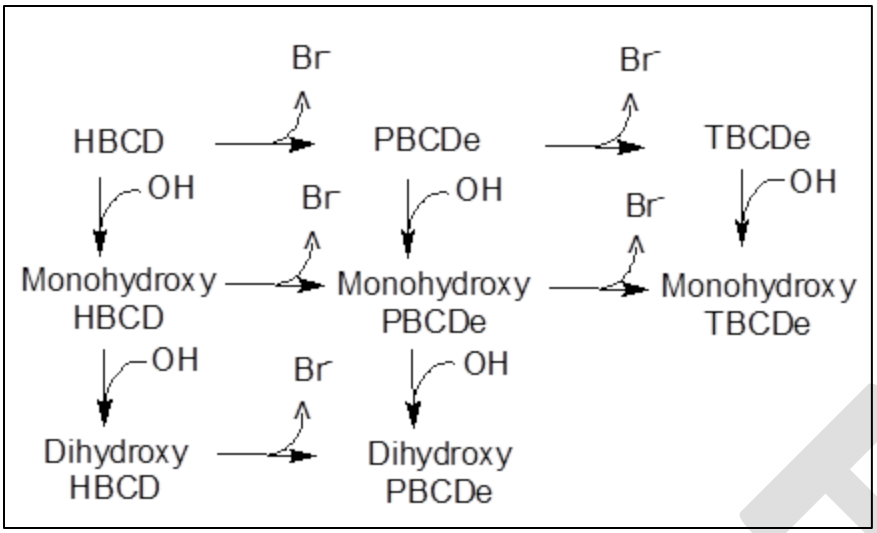


Figure Apx_ H-1. Proposed Pathways for Metabolism of HBCD in Rats
HBCD = hexabromocyclododecane; PBCDe = pentabromocyclododecene; TBCDe = tetrabromocyclododecene
Source: Adapted from (Brandsma et al., 2009).

H.1.4 Elimination

Elimination of radioactivity associated with administration of HBCD isomers is rapid, with most eliminated over the first 24 hours post administration, after either oral or i.v. dosing in female mice (Sanders et al., 2013; Szabo et al., 2011b, 2010) or oral administration in the rat (Yu and Atallah, 1980). Fecal and urinary excretion are the primary excretory pathways for absorbed HBCD, although the detection of HBCD isomers in many studies of human breast milk samples indicates that breast milk fat represents an additional elimination pathway.

The fecal:urine excretion ratios (based on samples collected over 48 hours postdosing) for absorbed HBCD in mice exposed by gavage to 3 mg/kg were approximately 2.4 for α-[14C]-HBCD, 1.2 for β-[14C]-HBCD, and 2.1 for γ [14C] HBCD (Sanders et al., 2013; Szabo et al., 2011b, 2010). Similar ratios were seen after i.v. dosing at the same exposure level (Sanders et al., 2013; Szabo et al., 2011b, 2010). Together, urinary and fecal excretion 48 hours after dosing accounted for ~70% of the administered radioactivity (at 3 mg/kg) after exposure to the α isomer and ~90% after exposure to the β- and γ isomers (Sanders et al., 2013; Szabo et al., 2011b, 2010). Excretion was essentially complete within 48 hours after either oral or i.v. dosing; studies evaluating elimination over longer time periods showed little additional excretion after 48 hours (Szabo et al., 2011b, 2010).

The overall kinetics of urinary and fecal elimination in the rat is similar to mice, but sex-dependent differences were suggested by data in rats. Forty-eight hours after dosing with [14C] γ HBCD (mixed with technical-grade HBCD containing ~75% γ-HBCD), fecal elimination accounted for 63% of radioactivity in four female rats and 95% in two male rats (Yu and Atallah, 1980). Over the same time frame, urinary elimination accounted for 4.8 and 15.3% of radioactivity in female and male rats, respectively.

In female mice administered α-[14C]-HBCD by gavage, a dose-dependent shift in fecal elimination was observed (Szabo et al., 2011b). Fecal elimination accounted for about 48% of the administered

radiolabel at 3 mg/kg, but only about 32% following a 100 mg/kg dose (Szabo et al., 2011b). The mechanism for the dose-dependent decrease in fecal excretion has not been identified; however, since radioactivity derived from absorbed α-[14C]-HBCD is extensively excreted into feces, this outcome suggests a possible capacity limitation in the secretion (e.g., biliary) mechanism. This dose-dependency was not observed in similar studies of γ-[14C]-HBCD in mice (Szabo et al., 2010). In mice given single doses of β-[14C]-HBCD of 3, 30, or 100 mg/kg, the amount of administered radioactivity in 24-hour feces was greater after 3 mg/kg (~50%) than after 100 mg/kg (~30%), but no dose-dependent difference was noted in cumulative 96-hour feces (Sanders et al., 2013).

Biphasic elimination kinetics of radioactivity from blood and tissues of mice were observed following oral administration of α-, β-, or γ-[14C]-HBCD in corn oil vehicle (Sanders et al., 2013; Szabo et al., 2011b, 2010). Tissue half-life values for the rapid phase in mice ranged from 0.1 to 0.4 days for α-HBCD, from 0.02 to 0.2 days for β-HBCD, and from 0.3 to 1 day for γ-HBCD. Terminal tissue half-life values were longer for α HBCD (range, 0.5−17 days) than for γ-HBCD (range, 0.8−5.2 days) or β-HBCD (0.2−7 days). In particular, the terminal half-lives for fat tissue were 17 days for α-HBCD, 3.6 days for γ-HBCD, and 2.5 days for β HBCD, indicating that, with repeated oral exposures, α-HBCD would be expected to accumulate in fat to a greater extent than γ HBCD or β-HBCD. Similar biphasic excretory kinetics were observed in rats following single gavage doses of commercial HBCD with γ-[14C]-HBCD (Yu and Atallah, 1980). At the higher end of the range, (Geyer et al., 2004) derived an HBCD terminal elimination half-life of 64 days via estimation of human daily intake and body burden (estimate for breast milk) as well as via estimation of half-life in adipose tissue of rats. Tissue excretory kinetic data for humans are not available.

Breast milk lipid represents an additional elimination pathway for HBCD, and concentrations of HBCD in human breast milk samples have been well studied; only a few reports are summarized here. Most biomonitoring studies report total HBCD concentrations in breast milk around 1 ng/g. For example, the following lipid-normalized median concentrations were reported: 0.9 ng/g lipid (range: 0.3−2.2 ng/g) and 0.4 ng/g (range: 0.2−1.2 ng/g) for populations in the United States (Texas) in 2002 and 2004, respectively (Ryan and Rawn, 2014); 0.7 ng/g (range: 0.1−28.2 ng/g) in Ontario, Canada; 3.83 ng/g (range 1−22 ng/g) in the United Kingdom (Abdallah and Harrad, 2011); 0.6 ng/g (range: 0.6−5.7 ng/g) in Belgium (Roosens et al., 2010); and 0.86 ng/g (range: less than the limit of quantitation [LOQ] −31 ng/g) in Norway (Thomsen et al., 2010). (Ryan et al., 2006) reported that most of the HBCD detected in breast milk from Texas women was the α-isomer, whereas in Japanese women, mean lipid-normalized concentrations of α-, β-, and γ-HBCD in breast milk were 1.5, <0.1, and 2.6 ng/g, respectively (Kakimoto et al., 2008).

H.2 Description of Toxicokinetic Models

No physiologically based pharmacokinetic (PBPK) models are available for HBCD. An unpublished, empirical two-compartment open kinetic model for orally-administered 14C-HBCD was developed from data collected using Sprague-Dawley rats given single oral doses of commercial HBCD labeled with γ-[14C]-HBCD (7−9 mg/kg) (Yu and Atallah, 1980). The model did not explicitly describe the metabolism of HBCD; however, the model did estimate an elimination constant. The elimination constant accounted for metabolism of HBCD and excretion of metabolites into urine and feces. The central compartment of the model comprised blood, muscle, liver, kidney, heart, spleen, lung, gonads, and uterus, and the remaining compartment represented fatty tissues. The calculated concentrations of radioactivity in the central and fat compartments were compared with respective observed concentrations in the blood and fat. The pattern of predicted values of radiolabel in blood and fat

generally reflected the pattern of observed values in blood and fat. This kinetic model addressed the distribution of radioactivity only, and did not explicitly describe metabolism.

(Aylward and Hays, 2011a) proposed the use of lipid-adjusted tissue concentrations of HBCD as an internal dose metric that would reduce uncertainties associated with the inter- and intraspecies extrapolation based on external dose. They derived a simple first-order elimination model to estimate the steady-state lipid concentration of HBCD (in ng/g lipid) corresponding to a given daily HBCD intake (in mg/kg-day) as follows:

$$D = Cl \times Fl \times k$$

where D = chronic daily dose in mg/kg day, Cl = lipid concentration (in mg/kg lipid), Fl = fraction of body weight that is lipid (assumed to be 25%), and k = elimination rate calculated from the half-life (HL, assumed to be 64 days in days) as k = ln (2)/HL.

As noted by (Aylward and Hays, 2011a), uncertainty in the steady-state lipid concentration of HBCD derived using this model comes from the assumed values for the half-life of HBCD (which is on the higher end of estimates from several studies [see Section H.1.4]) and the proportion of lipid in the body. If used for purposes of interspecies extrapolation, uncertainty is also introduced by potential toxicokinetics differences across species (e.g., differences in rates of metabolism of the different HBCD isomers), and consideration of whether summed or isomer-specific doses should be used. If humans clear individual isomers at a different rate than animals, and if the toxicity of individual isomers differs, the internal summed dose could either over- or underpredict the response. Finally, it should be noted that a systematic examination of whether lipid-adjusted tissue concentrations better correlate with response than other measures of dose (e.g., blood concentration, total concentration) has not been conducted.

Appendix I BMD MODELING RESULTS FOR SELECTED PODs

I.1 Noncancer Endpoints for BMD Modeling

The noncancer endpoints that were selected for dose-response modeling are presented in Table_Apx I-1. For each endpoint, the doses and response data used for the modeling are presented.

Table_Apx I-1. Noncancer endpoints selected for dose-response modeling for HBCD

Endpoint	Species (strain)/sex	Dose (mg/kg-d)[a]	Incidence [%] or mean ± SD (number of animals or litters)	BMR(s)
Thyroid				
↓T4 Ema et al. (2008)	F0 rats (CRL Sprague-Dawley)/male	0 10 101 1,008 TWA of lifetime exposure, F0	4.04 ± 1.42 (8) 3.98 ± 0.89 (8) 2.97 ± 0.76 (8) 2.49 ± 0.55 (8)	10% RD, 15% RD, 20% RD, 1 SD
↓T4 Ema et al. (2008)	F0 rats (CRL Sprague-Dawley)/female	0 14 141 1,363 TWA of lifetime exposure, F0	2.84 ± 0.61 (8) 3.14 ± 0.48 (8) 3.00 ± 0.77 (8) 1.96 ± 0.55 (8)	10% RD, 15% RD, 20% RD, 1 SD
↓T4 Ema et al. (2008)	F1 rats (CRL Sprague-Dawley)/female	0 14.3 138 1,363 TWA of lifetime exposure, F1	3.59 ± 1.08 (8) 3.56 ± 0.53 (8) 3.39 ± 1.21 (8) 2.58 ± 0.37 (8)	10% RD, 15% RD, 20% RD, 1 SD
Liver				
Relative liver weight Ema et al. (2008)	F1 rats (CRL Sprague-Dawley)/male weanlings, PND 26	0 16.5 168 1,570 TWA of F0 gestational and lactational doses	4.6 ± 0.37 (23) 4.6 ± 0.32 (21) 5.05 ± 0.32 (20) 6 ± 0.44 (17)	10% RD, 1 SD
Relative liver weight Ema et al. (2008)	F1 rats (CRL Sprague-Dawley)/female weanlings, PND 26	0 16.5 168 1,570 TWA of F0 gestational and lactational doses	4.57 ± 0.35 (23) 4.59 ± 0.28 (21) 5.02 ± 0.32 (20) 6.07 ± 0.36 (14)	10% RD, 1 SD
Relative liver weight Ema et al. (2008)	F1 rats (CRL Sprague-Dawley)/male adults	0 11.4 115 1,142	3.27 ± 0.18 (24) 3.34 ± 0.26 (24) 3.37 ± 0.25 (22) 3.86 ± 0.28 (24)	10% RD, 1 SD

Endpoint	Species (strain)/sex	Dose (mg/kg-d)[a]	Incidence [%] or mean ± SD (number of animals or litters)	BMR(s)
		TWA of lifetime exposure, F1		
Relative liver weight Ema et al. (2008)	F1 rats (CRL Sprague-Dawley)/female adults	0 14.3 138 1,363 TWA of lifetime exposure, F1	4.18 ± 0.42 (22) 4.39 ± 0.44 (22) 4.38 ± 0.47 (20) 5.05 ± 0.50 (13)	10% RD, 1 SD
Relative liver weight Ema et al. (2008)	F2 rats (CRL Sprague-Dawley)/male weanlings, PND 26	0 14.7 139 1,360 TWA of F1 gestational and lactational doses	4.72 ± 0.59 (22) 4.74 ± 0.35 (22) 5.04 ± 0.4 (18) 6.0 ± 0.25 (13)	10% RD, 1 SD
Relative liver weight Ema et al. (2008)	F2 rats (CRL Sprague-Dawley)/female weanlings, PND 26	0 14.7 139 1,360 TWA of F1 gestational and lactational doses	4.70 ± 0.27 (21) 4.70 ± 0.28 (22) 4.94 ± 0.32 (20) 5.89 ± 0.44 (13)	10% RD, 1 SD
Relative liver weight WIL Research (2001)	Rats (Sprague-Dawley)/male	0 100 300 1,000	2.709 ± 0.1193 (10) 3.175 ± 0.2293 (10) 3.183 ± 0.2653 (10) 3.855 ± 0.1557 (9)	10% RD, 1 SD
Relative liver weight WIL Research (2001)	Rats (Sprague-Dawley)/female	0 100 300 1,000	2.887 ± 0.2062 (10) 3.583 ± 0.2734 (10) 3.578 ± 0.3454 (10) 4.314 ± 0.2869 (10)	10% RD, 1 SD
Reproductive				
Primordial follicles Ema et al. (2008) (supplemental)	F1 parental rat (CRL Sprague-Dawley)/female	0 9.6 96 941 The F0 adult female gestational doses	316.3 ± 119.5 (10) 294.2 ± 66.3 (10) 197.9 ± 76.9 (10) 203.4 ± 79.5 (10)	1% RD, 5% RD, 10% RD
Incidence of non-pregnancy Ema et al. (2008)	F0 and F1 parental rats combined (CRL Sprague-Dawley)/female	0 13.3 132 1,302 TWA F0, F1 female pre-mating doses	1/48 [2%] 3/48 [6.2%] 7/48 [14.5%] 7/47 [14.9%]	5% ER, 10% ER
Developmental				

Endpoint	Species (strain)/sex	Dose (mg/kg-d)[a]	Incidence [%] or mean ± SD (number of animals or litters)	BMR(s)
Offspring loss at PND 4 Ema et al. (2008)	F2 offspring rats (CRL Sprague-Dawley)	0 9.7 100 995 The F1 adult female gestational doses	28/132 [21%] 26/135 [19.3%] 23/118 [19.5%] 47/120 [39.2%]	1% ER, 5% ER
Offspring loss at PND 21 Ema et al. (2008)	F2 offspring rats (CRL Sprague-Dawley)	0 19.6 179 1,724 The F1 adult female lactational doses	11/70 [15.7%] 7/70 [10.0%] 18/64 [28.1%] 32/64 [50.0%]	1% ER, 5% ER
Pup weight during lactation at PND 21 Ema et al. (2008)	F2 offspring rats (CRL Sprague-Dawley)/male	0 19.6 179 1,724 The F1 adult female lactational doses	53 ± 12.6 (22) 56.2 ± 6.7 (22) 54.1 ± 10.1 (18) 42.6 ± 8.3 (13)	5% RD, 10% RD, 0.5 SD, 1 SD
Pup weight during lactation at PND 21 Ema et al. (2008)	F2 offspring rats (CRL Sprague-Dawley)/female	0 19.6 179 1,724 The F1 adult female lactational doses	52 ± 10 (21) 52.8 ± 6.6 (22) 51.2 ± 10.8 (20) 41.6 ± 8.4 (13)	5% RD, 10% RD, 0.5 SD, 1 SD

[a]Doses were calculated as TWA doses using weekly average doses (in mg/kg-day) as reported in Table 10 of the Supplemental Materials to Ema et al. (2008).

BMR = benchmark response; ER = extra risk; PND = postnatal day; RD = relative deviation; SD = standard deviation; T4 = thyroxine; TWA = time-weighted average

I.1.1 Thyroid Effects

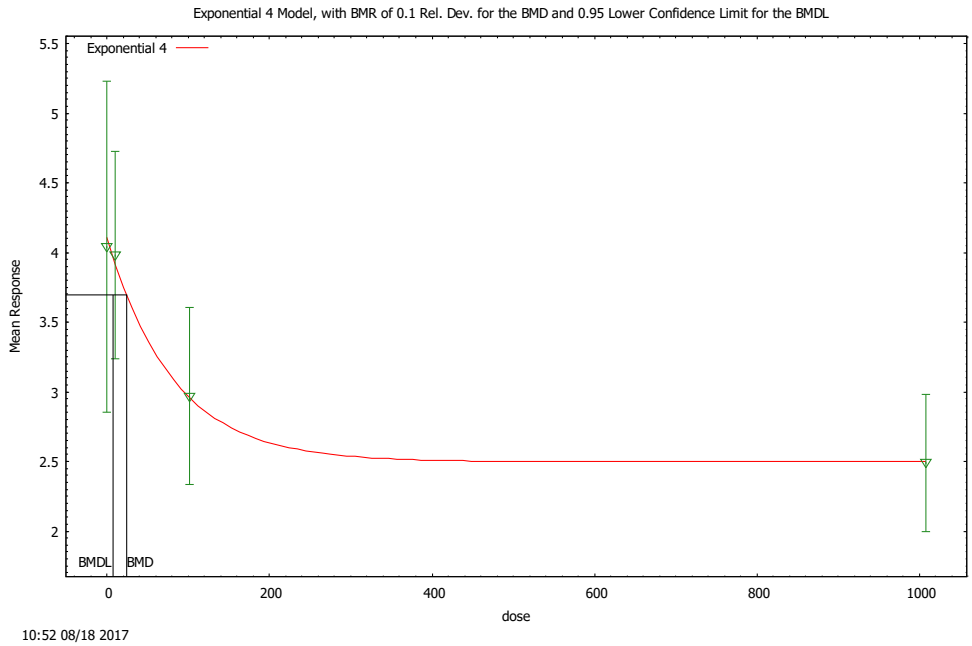
Table_Apx I-2. Summary of BMD modeling results for T4 in F0 parental male CRL Sprague-Dawley rats exposed to HBCD by diet for 18 weeks (Ema et al., 2008); BMR = 10% RD from control mean

Model[a]	Goodness of fit		BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	BMD_{15RD} (mg/kg-d)	$BMDL_{15RD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Exponential (M2) Exponential (M3)[b]	0.0473	33.926	259	177	399	274	Of the models without saturation that provided an adequate fit and a valid BMDL estimate, the Exponential 4 model with modeled variance was selected
Exponential (M4) Exponential (M5)[c]	**0.742**	**29.933**	**23.9**	**6.99**	39.1	11.5	
Hill	0.949	29.829	14.4	3.21	25.6	5.66	
Power[d] Polynomial 3°[e] Polynomial 2°[f] Linear	0.0418	34.174	303	227	455	341	

Model[a]	Goodness of fit		BMD_{20RD} (mg/kg-d)	$BMDL_{20RD}$ (mg/kg-d)	BMD_{1SD} (mg/kg-d)	$BMDL_{1SD}$ (mg/kg-d)	based on lowest AIC (BMDLs differed by <3).
	p-value	AIC					
Exponential (M2) Exponential (M3)[b]	0.0473	33.926	548	376	866	511	
Exponential (M4) Exponential (M5)[c]	0.742	29.933	57.9	17.2	101	29.5	
Hill	0.949	29.829	42.0	9.11	94.9	Errorg	
Power[d] Polynomial 3°[e] Polynomial 2°[f] Linear	0.0418	34.174	607	454	906	595	

[a]Modeled variance case presented (BMDS Test 2 *p*-value = 0.0756, BMDS Test 3 *p*-value = 0.553), selected model in bold; scaled residuals for selected model for doses 0, 10.2, 101, and 1,008 mg/kg-day were -0.1665, 0.166, 0.03642, and -0.03619, respectively.
[b]For the Exponential (M3) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M2) model.
[c]For the Exponential (M5) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M4) model.
[d]For the Power model, the power parameter estimate was 1. The models in this row reduced to the Linear model.
[e]For the Polynomial 3° model, the b3 coefficient estimate was 0 (boundary of parameters space). The models in this row reduced to the Polynomial 2° model. For the Polynomial 3° model, the b3 and b2 coefficient estimates were 0 (boundary of parameters space). The models in this row reduced to the Linear model.
[f]For the Polynomial 2° model, the b2 coefficient estimate was 0 (boundary of parameters space). The models in this row reduced to the Linear model.
[g]BMD or BMDL computation failed for this model.

Data from Ema et al. (2008)



BMR = 10% RD from control mean; dose shown in mg/kg-day.

Figure Apx_ I-1. Plot of mean response by dose, with fitted curve for Exponential 4 Model, for T4 in F0 parental CRL Sprague-Dawley male rats exposed to HBCD by diet for 18 weeks (Ema et al., 2008).

Exponential 4 Model (Version: 1.10; Date: 01/12/2015)
The form of the response function is:
Model 4: Y[dose] = a * [c-(c-1) * exp{-b * dose}]
A modeled variance is fit

Benchmark Dose Computation
BMR = 10% RD
BMD = 23.8946
BMDL at the 95% confidence level = 6.99406

Parameter Estimates

Variable	Estimate	Default initial parameter values
lalpha	-3.94284	-3.54227
rho	2.98463	2.72754
a	4.1075	4.242
b	0.0123219	0.00282274
d	1 (specified)	1 (specified)

Table of Data and Estimated Values of Interest

Dose	N	Observed mean	Estimated mean	Observed SD	Estimated SD	Scaled residuals
0	8	4.04	4.11	1.42	1.15	-0.167
10.2	8	3.98	3.92	0.89	1.07	0.166
101	8	2.97	2.961	0.76	0.71	0.036
1,008	8	2.49	2.50	0.59	0.56	-0.036

Likelihoods of Interest

Model	Log (likelihood)	Number of parameters	AIC
A1	-12.76333	5	35.52665
A2	-9.319925	8	34.63985
A3	-9.91228	6	31.82456
fitted	-9.966286	5	29.93257
R	-19.64317	2	43.28634

Tests of Interest

Test	−2*log (likelihood ratio)	Test df	p-value
Test 1	20.65	6	0.002123
Test 2	6.887	3	0.07559
Test 3	1.185	2	0.553
Test 6a	0.108	1	0.7424

df = degree(s) of freedom

I.1.2 Liver Effects

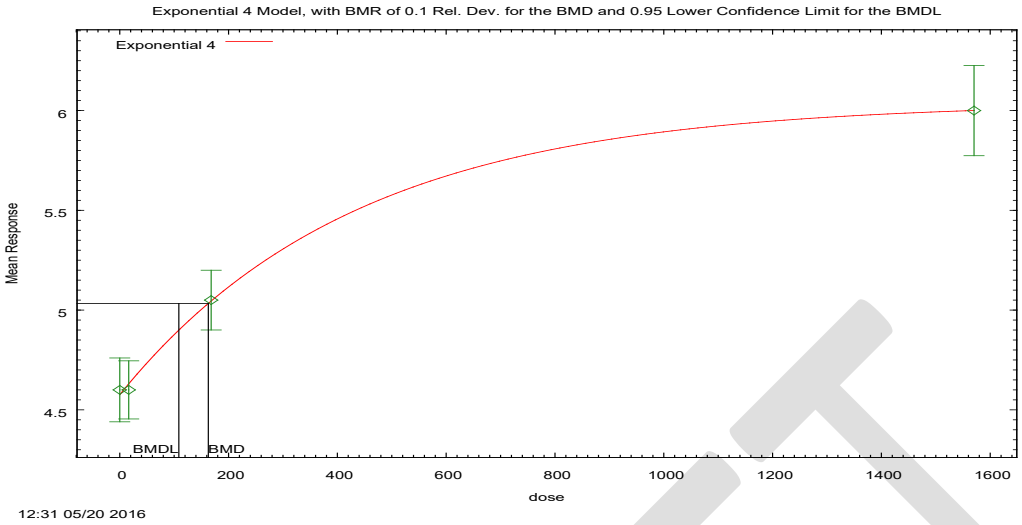
Data from (Ema et al., 2008)

Table_Apx I-3. Summary of BMD modeling results for relative liver weight (g/100 g BW) in male F1 CRL rats exposed to HBCD on GD 0−PND 26, dose TWA gestation through lactation (Ema et al., 2008); BMR = 10% RD from control mean and 1 SD change from control mean

Model[a]	Goodness of fit		BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	BMD_{1SD} (mg/kg-d)	$BMDL_{1SD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Exponential (M2) Exponential (M3)[b]	0.00369	−70.405	599	533	488	417	Of the models that provided an adequate fit and a valid BMDL estimate, the Exponential M4 constant variance model was selected based on lowest AIC and visual fit.
Exponential (M4)	**0.606**	**−79.345**	**163**	**109**	**120**	**80.5**	
Exponential (M5)	N/A[c]	−77.611	169	111	157	82.0	
Hill	N/A[c]	−77.611	169	104	156	75.4	
Powerd Polynomial 3°[e] Polynomial 2°[f] Linear	0.00590	−71.344	548	480	440	371	

[a]Constant variance case presented (BMDS Test 2 *p*-value = 0.462), selected model in bold; scaled residuals for selected model for doses 0, 16.5, 168, and 1,570 mg/kg-day were 0.3267, −0.3947, 0.05759, and −0.003788, respectively.
[b]For the Exponential (M3) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M2) model.
[c]No available degrees of freedom to calculate a goodness-of-fit value.
[d]For the Power model, the power parameter estimate was 1. The models in this row reduced to the Linear model.
[e]For the Polynomial 3° model, the b3 and b2 coefficient estimates were 0 (boundary of parameters space). The models in this row reduced to the Linear model.
[f]For the Polynomial 2° model, the b2 coefficient estimate was 0 (boundary of parameters space). The models in this row reduced to the Linear model.

Data from Ema et al. (2008)



BMR = 10% RD from control mean; dose shown in mg/kg-day.

Figure Apx_ I-2. Plot of mean response by dose with fitted curve for Exponential (M4) model with constant variance for relative liver weight (g/100 g BW) in F1 weanling male CRL Sprague-Dawley rats exposed to HBCD on GD 0−PND 26, dose TWA gestation through lactation (Ema et al., 2008).

Exponential Model (Version: 1.10; Date: 01/12/2015)
The form of the response function is: Y[dose] = a * [c-(c-1) * exp(-b * dose)]
A constant variance model is fit

Benchmark Dose Computation
BMR = 10% RD
BMD = 162.81
BMDL at the 95% confidence level = 108.569

Parameter Estimates

Variable	Estimate	Default initial parameter values
lnalpha	−2.07833	−2.08162
rho	N/A	0
a	4.5759	4.37
b	0.00230233	0.00120199
c	1.3199	1.44165
d	N/A	1

Table of Data and Estimated Values of Interest

Dose	N	Observed mean	Estimated mean	Observed SD	Estimated SD	Scaled residuals
0	23	4.6	4.576	0.37	0.3538	0.3267
16.5	21	4.6	4.63	0.32	0.3538	−0.3947

168	20	5.05	5.045	0.32	0.3538	0.05759
1,570	17	6	6	0.44	0.3538	−0.003788

Likelihoods of Interest

Model	Log (likelihood)	Number of parameters	AIC
A1	43.80548	5	−77.61096
A2	45.09301	8	−74.18602
A3	43.80548	5	−77.61096
R	−5.569318	2	15.13864
4	43.67234	4	−79.34469

Tests of Interest

Test	−2*log (likelihood ratio)	Test df	p-value
Test 1	101.3	6	<0.0001
Test 2	2.575	3	0.4619
Test 3	2.575	3	0.4619
Test 6a	0.2663	1	0.6058

Table_Apx I-4. Summary of BMD modeling results for relative liver weight (g/100 g BW) in male CRL Sprague-Dawley rats exposed to HBCD by gavage for 13 weeks (WIL Research, 2001); BMR = 10% RD from control mean and 1 SD change from control mean

Model[a]	Goodness of fit		BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	BMD_{1SD} (mg/kg-d)	$BMDL_{1SD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Modeled with constant variance							No model showed adequate fit. Dropping highest dose is not expected to help in this case.
Exponential (M2) Exponential (M3)[b]	3.14 × 10−4	−67.830	328	283	269	219	
Exponential (M4)[c]	3.92 × 10−4	−69.396	164	97.7	128	77.9	
Exponential (M5)[d]	3.92 × 10−4	−69.396	164	97.7	128	77.9	
Hill	4.91 × 10−4	−69.815	145	74.8	113	59.7	
Power[e] Polynomial 3°[f] Polynomial 2°[g] Linear	5.14 × 10−4	−68.817	290	244	234	187	
Modeled with modeled variance							
Exponential (M2) Exponential (M3)[b]	0.00119	−68.721	337	295	320	245	
Exponential (M4)[c]	5.50 × 10−4	−68.244	204	103	187	67.5	

Model[a]	Goodness of fit		BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	BMD_{1SD} (mg/kg-d)	$BMDL_{1SD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Exponential (M5)[d]	5.50 × 10−4	−68.244	204	103	187	67.5	
Hill	5.84 × 10−4	−68.355	192	35.9	173	106	
Power[e] Polynomial 3°[f] Polynomial 2°[g] Linear	0.00161	−69.324	299	256	282	210	

[a]Constant variance (BMDS Test 2 *p*-value = 0.0644, BMDS Test 3 *p*-value = 0.0644) and nonconstant variance cases presented, no model was selected as a best-fitting model.
[b]For the Exponential (M3) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M2) model.
[c]The Exponential (M4) model may appear equivalent to the Exponential (M5) model; however, differences exist in digits not displayed in the table.
[d]The Exponential (M5) model may appear equivalent to the Exponential (M4) model; however, differences exist in digits not displayed in the table.
[e]For the Power model, the power parameter estimate was 1. The models in this row reduced to the Linear model.
[f]For the Polynomial 3° model, the b3 and b2 coefficient estimates were 0 (boundary of parameters space). The models in this row reduced to the Linear model.
[g]For the Polynomial 2° model, the b2 coefficient estimate was 0 (boundary of parameters space). The models in this row reduced to the Linear model.

Data from (WIL Research, 2001)

Table_Apx I-5. Summary of BMD modeling results for relative liver weight (g/100 g BW) in female CRL Sprague-Dawley rats exposed to HBCD by gavage for 13 weeks (WIL Research, 2001); BMR = 10% RD from control mean and 1 SD change from control mean

Model[a]	Goodness of fit		BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	BMD_{1SD} (mg/kg-d)	$BMDL_{1SD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Modeled with constant variance							
Exponential (M2) Exponential (M3)[b]	<0.0001	−39.545	310	261	332	267	No model showed adequate fit. Dropping highest dose is not expected to help in this case
Exponential (M4) Exponential (M5)[c]	2.59 × 10−4	−44.035	101	56.0	106	61.8	
Hill	5.71 × 10−4	−45.515	69.3	30.6	73.3	34.6	
Power[d] Polynomial 3°[e] Polynomial 2°[f] Linear	<0.0001	−40.679	270	220	287	226	
Modeled with modeled variance							
Exponential (M2) Exponential (M3)[b]	<0.0001	−38.793	319	269	374	282	

Exponential (M4) Exponential (M5)[c]	1.72 × 10−4	−42.217	53.4	28.5	38.3	16.0	
Hill	0.00115	−45.763	39.2	20.7	26.0	11.6	
Powerd Polynomial 3°[e] Polynomial 2°[f] Linear	<0.0001	−39.727	278	227	327	237	

[a]Constant variance (BMDS Test 2 *p*-value = 0.461, BMDS Test 3 *p*-value = 0.461) and nonconstant variance presented; no model was selected as a best-fitting model.
[b]For the Exponential (M3) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M2) model.
[c]For the Exponential (M5) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M4) model.
[d]For the Power model, the power parameter estimate was 1. The models in this row reduced to the Linear model.
[e]For the Polynomial 3° model, the b3 and b2 coefficient estimates were 0 (boundary of parameters space). The models in this row reduced to the Linear model.
[f]For the Polynomial 2° model, the b2 coefficient estimate was 0 (boundary of parameters space). The models in this row reduced to the Linear model.

I.1.3 Reproductive Effects

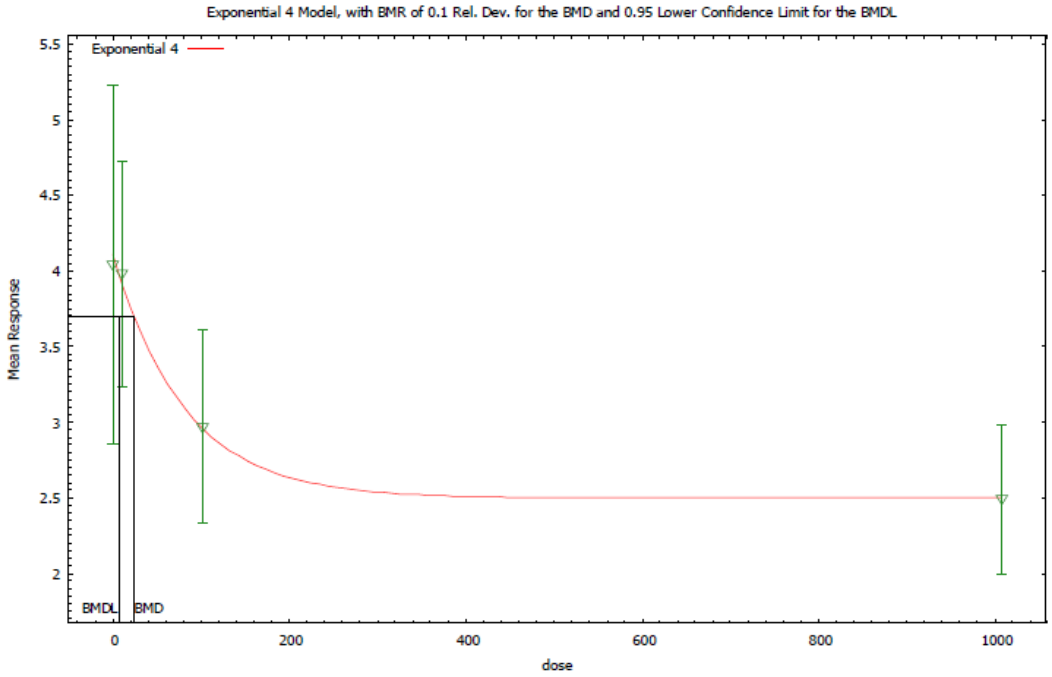
Reduced Primordial Follicles

Table_Apx I-6. Summary of BMD modeling results for primordial follicles in F1 parental female CRL Sprague-Dawley rats exposed to HBCD by diet for 18 weeks (Ema et al., 2008); BMR = 1% RD from control mean, 5% RD from control mean, and 10% RD from control mean

Model[a]	Goodness of fit		BMD_{1RD} (mg/kg-d)	$BMDL_{1RD}$ (mg/kg-d)	BMD_{5RD} (mg/kg-d)	$BMDL_{5RD}$ (mg/kg-d)	BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC							
Exponential (M2) Exponential (M3)[b]	0.0130	408.57	26.8	13.9	137	71.0	281	146	Exponential M4 constant variance selected as only model with adequate fit.
Exponential (M4)	**0.688**	**402.05**	0.883	0.252	4.67	1.33	**10.1**	**2.87**	
Exponential (M5)	N/A[c]	403.91	4.09	0.259	8.23	1.37	11.4	2.95	
Hill	N/A[c]	403.91	8.00	error[d]	9.28	1.10	9.99	2.50	
Power[e] Polynomial 2°[f] Linear Polynomial 3°[g]	0.0117	408.78	33.1	19.8	165	99.0	331	198	

[a]Constant variance case presented (BMDS Test 2 *p*-value = 0.242), selected model in bold; scaled residuals for selected model for doses 0, 9.6, 96.3, and 940.7 mg/kg-day were −0.129, 0.1915, −0.2611, and 0.1987, respectively.
[b]For the Exponential (M3) model, the estimate of d was 1 (boundary). The models in this row reduced to the Exponential (M2) model.
[c]No available degrees of freedom to calculate a goodness-of-fit value.
[d]BMD or BMDL computation failed for this model.
[e]For the Power model, the power parameter estimate was 1. The models in this row reduced to the Linear model.
[f]For the Polynomial 2° model, the b2 coefficient estimate was 0 (boundary of parameters space). The models in this row reduced to the Linear model.

[g]The Polynomial 3° model may appear equivalent to the Linear model; however, differences exist in digits not displayed in the table.



BMR = 10% RD from control mean; dose shown in mg/kg-day.

Figure Apx_ I-3. Plot of mean response by dose, with fitted curve for Exponential M4, for primordial follicles in F1 parental female CRL Sprague-Dawley rats exposed to HBCD by diet for 18 weeks (Ema et al., 2008).

Exponential Model (Version: 1.9; Date: 01/29/2013)
The form of the response function is: Y[dose] = a * [c-(c-1) * exp(-b * dose)]
A constant variance model is fit

Benchmark Dose Computation
BMR = 10% RD
BMD = 10.1143
BMDL at the 95% confidence level = 2.86589

Parameter Estimates

Variable	Estimate	Default initial parameter values
lnalpha	8.85121	8.84717
rho(S)	N/A	0
a	319.71	332.115
b	0.0301725	0.0026785
c	0.619779	0.567503
d	1	1

Table of Data and Estimated Values of Interest

Dose	N	Observed mean	Estimated mean	Observed SD	Estimated SD	Scaled residuals
0	10	316.3	319.7	119.5	83.56	−0.129
9.6	10	294.2	289.1	66.3	83.56	0.1915
96.3	10	197.9	204.8	76.9	83.56	−0.2611
940.7	10	203.4	198.1	79.5	83.56	0.1987

Likelihoods of Interest

Model	Log (likelihood)	Number of parameters	AIC
A1	−196.9435	5	403.8869
A2	−194.8505	8	405.701
A3	−196.9435	5	403.8869
R	−203.7104	2	411.4207
4	−197.0241	4	402.0483

Tests of Interest

Test	−2*log (likelihood ratio)	Test df	p-value
Test 1	17.72	6	0.006972
Test 2	4.186	3	0.2421
Test 3	4.186	3	0.2421
Test 6a	0.1613	1	0.6879

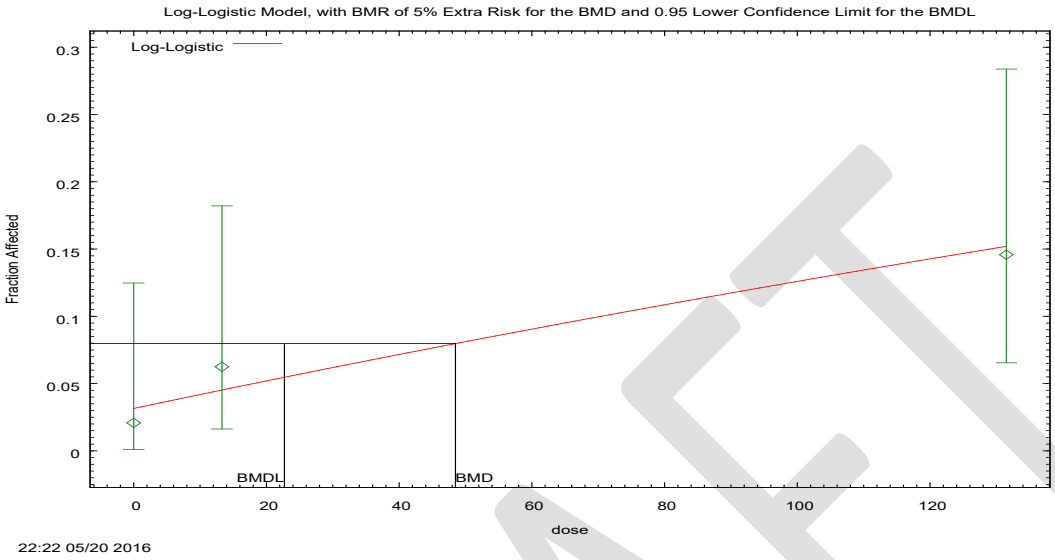
Increased Incidence of Non-Pregnancy

Table_Apx I-7. Summary of BMD modeling results for incidence of non-pregnancy in F0 and F1 CRL female rats combined exposed to HBCD in diet for 14 weeks, TWA F0 and F1 premating dose, high dose dropped (Ema et al., 2008); BMR = 5% ER and 10% ER.

Model[a]	Goodness of fit		BMD_{5ER} (mg/kg-d)	$BMDL_{5ER}$ (mg/kg-d)	BMD_{10ER} (mg/kg-d)	$BMDL_{10ER}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Gamma[b]	0.457	76.591	51.1	25.6	105	52.5	Of the models that provided an adequate fit and a valid BMDL estimate, the LogLogistic model was selected based on lowest AIC.
Logistic	0.374	76.860	77.3	53.3	121	85.5	
LogLogistic	**0.469**	**76.560**	**48.5**	**22.7**	102	47.9	
Probit	0.382	76.832	73.6	49.3	120	81.1	
LogProbit	N/A[c]	78.045	18.0	error[d]	74.8	error[d]	
Weibull[e] Quantal-Linear[f]	0.457	76.591	51.1	25.6	105	52.5	
Multistage 2°[g]	0.457	76.591	51.1	25.6	105	52.5	

[a]Selected model in bold; scaled residuals for selected model for doses 0, 13.3, and 131.5 mg/kg-day were −0.422, 0.575, and −0.128, respectively.
[b]The Gamma model may appear equivalent to the Weibull model; however, differences exist in digits not displayed in the table. This also applies to the Multistage 2° and Quantal-Linear models.
[c]No available degrees of freedom to calculate a goodness-of-fit value.

[d]BMD or BMDL computation failed for this model.
[e]For the Weibull model, the power parameter estimate was 1. The models in this row reduced to the Quantal-Linear model.
[f]The Quantal-Linear model may appear equivalent to the Gamma model; however, differences exist in digits not displayed in the table. This also applies to the Multistage 2° model.
[g]The Multistage 2° model may appear equivalent to the Gamma model; however, differences exist in digits not displayed in the table. This also applies to the Weibull and Quantal-Linear models.



BMR = 5% ER; dose shown in mg/kg-day.

Figure Apx_ I-4. Plot of incidence rate by dose with fitted curve for LogLogistic model for incidence of non-pregnancy in F0 and F1 CRL female rats combined exposed to HBCD in diet for 14 weeks, TWA F0 and F1 premating dose, high dose dropped (Ema et al., 2008).

Logistic Model (Version: 2.14; Date: 2/28/2013)
The form of the probability function is: P[response] = background+(1-background)/[1+EXP(-intercept-slope*Log(dose))]
Slope parameter is restricted as slope >= 1

Benchmark Dose Computation
BMR = 5% ER
BMD = 48.4809
BMDL at the 95% confidence level = 22.7093

Parameter Estimates

Variable	Estimate	Default initial parameter values
background	0.0314626	0.0208333
intercept	−6.8256E+00	−6.4682E+00
slope	1	1

Analysis of Deviance Table

Model	Log (likelihood)	Number of parameters	Deviance	Test df	p-value
Full model	−36.0225	3			

Fitted model	−36.28	2	0.514904	1	0.473
Reduced model	−38.8598	1	5.6746	2	0.05858

AIC: = 76.56

Goodness-of-Fit Table

Dose	Est. Prob.	Expected	Observed	Size	Scaled residuals
0	0.0315	1.51	1	48	−0.422
13.3	0.0452	2.172	3	48	0.575
131.5	0.1525	7.318	7	48	−0.128

Chi^2 = 0.52, df = 1, p-value = 0.4687

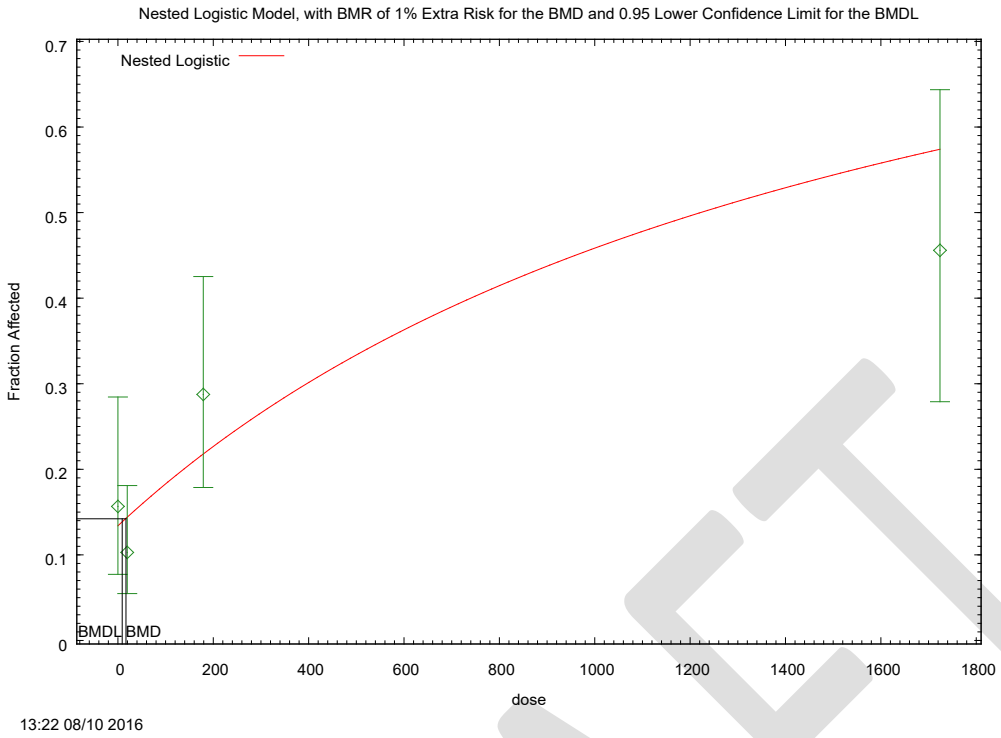
I.1.4 Developmental Effects

Offspring Loss

Table_Apx I-8. Summary of BMD modeling results for offspring loss from PND 4 through PND 21 in F2 offspring CRL Sprague-Dawley rats; lactational doses of F1 dams (Ema et al., 2008); BMR = 1% ER and 5% ER

Model[a]	Goodness of Fit		BMD_{1ER} (mg/kg-d)	$BMDL_{1ER}$ (mg/kg-d)	BMD_{5ER} (mg/kg-d)	$BMDL_{5ER}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Litter-specific covariate = implantation size; intra-litter correlations estimated							Of the models that provided an adequate fit, a valid BMDL estimate and BMD/BMDL <5, the Nested Logistic model (litter-specific covariate not used; intra-litter correlations estimated) was selected based on lowest AIC (BMDLs differed by <3).
Nested Logistic	0.4417	561.04	20.4	10.1841	106.295	53.0644	
NCTR	0.4114	561.816	25.079	12.5395	127.994	63.997	
Rai and Van Ryzin	0.4056	564.38	25.8561	1.00024	131.96	5.9492	
Litter-specific covariate = implantation size; intra-litter correlations assumed to be zero							
Nested Logistic	0.0000	643.52	36.1762	22.5296	188.497	117.391	
NCTR	0.0000	650.146	33.8744	16.9372	172.883	86.4414	
Rai and Van Ryzin	0.0000	660.111	35.975	17.9875	183.603	91.8017	
Litter-specific covariate not used; intra-litter correlations estimated							
Nested Logistic	**0.3944**	**559.472**	**16.9114**	**9.03491**	88.1172	47.0766	
NCTR[b] Rai and Van Ryzin	0.4051	560.38	25.8566	12.9283	131.963	65.9814	
Litter-specific covariate not used; intra-litter correlations assumed to be zero							
Nested Logistic	0.0000	654.556	26.3666	18.3313	137.384	95.5159	
NCTR[b] Rai and Van Ryzin	0.0000	656.111	35.975	17.9875	183.603	91.8017	

[a]Because the individual animal data were available, the BMDS nested models were fitted, with the selected model in bold. For the selected model, the proportion of litters with scaled residuals above 2 in absolute value for doses 0, 19.6, 179, and 1,724 mg/kg-d were 2/22, 0/22, 2/20, and 0/20, respectively.
[b]With the litter-specific covariate not used, the NCTR and Rai and van Ryzin models yielded identical results.



BMR = 1% ER; dose shown in mg/kg-day.

Figure Apx_ I-5. Plot of incidence rate by dose, with fitted curve for the nested logistic model where the litter specific covariate was not used and the intra-litter correlations were estimated, for incidence of offspring loss from PND 4 through PND 21 in F2 offspring CRL Sprague-Dawley rats; lactational doses of F1 dams (Ema et al., 2008).

Nested Logistic Model (Version: 2.20; Date: 04/27/2015)
The form of the probability function is:
Prob. = alpha + theta1*Rij + [1 - alpha - theta1*Rij]/
[1+exp(-beta-theta2*Rij-rho*log(Dose))],
where Rij is the litter specific covariate.
Restrict Power rho >= 1.

Benchmark Dose Computation
To calculate the BMD and BMDL, the litter specific covariate is fixed at the mean litter specific covariate of all the data: 14.654762
BMR = 1% ER
BMD = 16.9114
BMDL at the 95% confidence level = 9.03491

Parameter Estimates

Variable	Estimate	(Default) Initial Parameter Values
alpha	0.133513	0.133513
beta	−7.42311	−7.42311
rho	1	1

phi1	0.229222	0.229222
phi2	0.152985	0.152985
phi3	0.247495	0.247495
phi4	0.586386	0.586386

Log-likelihood: −273.736 AIC: 559.472

Goodness-of-Fit Table

Dose	Lit.-Spec. Cov.	Litter Est. Prob.	Size	Expected	Scaled Observed	Residual
0.0000	9.0000	0.134	6	0.801	0	−0.6563
0.0000	10.0000	0.134	6	0.801	1	0.1630
0.0000	11.0000	0.134	8	1.068	0	−0.6880
0.0000	11.0000	0.134	6	0.801	0	−0.6563
0.0000	12.0000	0.134	8	1.068	1	−0.0439
0.0000	13.0000	0.134	8	1.068	6	3.1766
0.0000	13.0000	0.134	8	1.068	0	−0.6880
0.0000	13.0000	0.134	8	1.068	3	1.2443
0.0000	13.0000	0.134	8	1.068	0	−0.6880
0.0000	14.0000	0.134	8	1.068	1	−0.0439
0.0000	14.0000	0.134	8	1.068	0	−0.6880
0.0000	15.0000	0.134	4	0.534	0	−0.6043
0.0000	16.0000	0.134	8	1.068	1	−0.0439
0.0000	16.0000	0.134	8	1.068	1	−0.0439
0.0000	16.0000	0.134	8	1.068	0	−0.6880
0.0000	16.0000	0.134	8	1.068	2	0.6002
0.0000	16.0000	0.134	8	1.068	1	−0.0439
0.0000	16.0000	0.134	8	1.068	4	1.8884
0.0000	17.0000	0.134	8	1.068	0	−0.6880
0.0000	17.0000	0.134	8	1.068	0	−0.6880
0.0000	17.0000	0.134	8	1.068	5	2.5325
0.0000	18.0000	0.134	8	1.068	0	−0.6880
19.6000	12.0000	0.144	7	1.005	2	0.7747
19.6000	13.0000	0.144	8	1.148	1	−0.1039
19.6000	13.0000	0.144	8	1.148	0	−0.8046
19.6000	13.0000	0.144	8	1.148	3	1.2975
19.6000	14.0000	0.144	8	1.148	2	0.5968
19.6000	14.0000	0.144	8	1.148	0	−0.8046
19.6000	14.0000	0.144	8	1.148	0	−0.8046
19.6000	14.0000	0.144	8	1.148	0	−0.8046
19.6000	14.0000	0.144	8	1.148	0	−0.8046
19.6000	15.0000	0.144	8	1.148	1	−0.1039
19.6000	15.0000	0.144	8	1.148	3	1.2975
19.6000	15.0000	0.144	8	1.148	0	−0.8046
19.6000	15.0000	0.144	8	1.148	1	−0.1039
19.6000	16.0000	0.144	8	1.148	0	−0.8046
19.6000	16.0000	0.144	8	1.148	0	−0.8046
19.6000	16.0000	0.144	8	1.148	0	−0.8046
19.6000	16.0000	0.144	8	1.148	0	−0.8046
19.6000	17.0000	0.144	8	1.148	1	−0.1039
19.6000	17.0000	0.144	8	1.148	0	−0.8046
19.6000	17.0000	0.144	8	1.148	3	1.2975
19.6000	18.0000	0.144	8	1.148	1	−0.1039
19.6000	21.0000	0.144	8	1.148	0	−0.8046

179.0000	11.0000	0.217	8	1.738	4	1.1735
179.0000	11.0000	0.217	8	1.738	2	0.1361
179.0000	12.0000	0.217	8	1.738	2	0.1361
179.0000	13.0000	0.217	8	1.738	0	−0.9013
179.0000	14.0000	0.217	8	1.738	2	0.1361
179.0000	14.0000	0.217	8	1.738	5	1.6922
179.0000	14.0000	0.217	8	1.738	3	0.6548
179.0000	14.0000	0.217	8	1.738	1	−0.3826
179.0000	14.0000	0.217	8	1.738	4	1.1735
179.0000	14.0000	0.217	8	1.738	1	−0.3826
179.0000	14.0000	0.217	8	1.738	6	2.2109
179.0000	15.0000	0.217	8	1.738	0	−0.9013
179.0000	15.0000	0.217	8	1.738	0	−0.9013
179.0000	15.0000	0.217	8	1.738	1	−0.3826
179.0000	15.0000	0.217	8	1.738	6	2.2109
179.0000	16.0000	0.217	8	1.738	0	−0.9013
179.0000	16.0000	0.217	8	1.738	4	1.1735
179.0000	17.0000	0.217	8	1.738	0	−0.9013
179.0000	17.0000	0.217	8	1.738	0	−0.9013
179.0000	19.0000	0.217	8	1.738	5	1.6922
1,724.0000	10.0000	0.573	8	4.585	4	−0.1850
1,724.0000	11.0000	0.573	8	4.585	2	−0.8178
1,724.0000	12.0000	0.573	8	4.585	1	−1.1341
1,724.0000	12.0000	0.573	6	3.439	0	−1.4313
1,724.0000	13.0000	0.573	4	2.292	1	−0.7865
1,724.0000	14.0000	0.573	8	4.585	8	1.0805
1,724.0000	14.0000	0.573	8	4.585	1	−1.1341
1,724.0000	14.0000	0.573	8	4.585	0	−1.4505
1,724.0000	14.0000	0.573	4	2.292	4	1.0392
1,724.0000	15.0000	0.573	7	4.012	3	−0.3637
1,724.0000	15.0000	0.573	8	4.585	0	−1.4505
1,724.0000	15.0000	0.573	6	3.439	6	1.0662
1,724.0000	15.0000	0.573	4	2.292	4	1.0392
1,724.0000	16.0000	0.573	1	0.573	1	0.8631
1,724.0000	16.0000	0.573	8	4.585	5	0.1313
1,724.0000	16.0000	0.573	8	4.585	0	−1.4505
1,724.0000	17.0000	0.573	8	4.585	3	−0.5014
1,724.0000	17.0000	0.573	8	4.585	8	1.0805
1,724.0000	17.0000	0.573	8	4.585	3	−0.5014
1,724.0000	20.0000	0.573	8	4.585	8	1.0805

Observed Chi-square = 86.7400 Bootstrap Iterations per run = 10,000
p-value = 0.3944

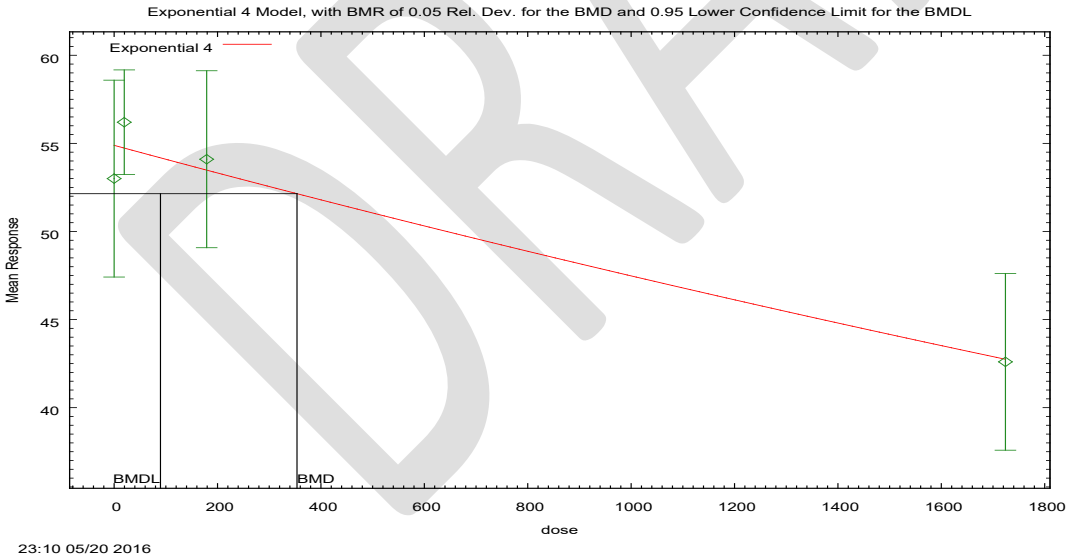
Reduced Pup Body Weight

Table_Apx I-9. Summary of BMD modeling results for pup weight during lactation in F2 male offspring CRL Sprague-Dawley rats (PND 21) exposed to HBCD by diet for 3 weeks, lactational dose((Ema et al., 2008); BMR = 5% RD from control mean, 10% RD from control mean, 0.5 SD change from control mean, and 1 SD change from control mean

Model[a]	Goodness of fit		BMD_{5RD} (mg/kg-d)	$BMDL_{5RD}$ (mg/kg-d)	BMD_{10RD} (mg/kg-d)	$BMDL_{10RD}$ (mg/kg-d)	Basis for model selection
	p-value	AIC					
Exponential (M2)	0.486	420.90	354	240	727	494	Of the models that provided an adequate fit, a valid BMDL estimate and
Exponential (M3)	0.266	422.69	651	244	1016	500	
Exponential (M4)	**0.486**	**420.90**	**354**	**89.6**	727	206	
Exponential (M5)	N/A[b]	424.68	230	94.0	258	181	

Hill	N/A[b]	424.68	230	89.2	264	errorc	BMD/BMDL <5, the Exponential M4 constant variance model was selected based on lowest BMDL (BMDLs differed by >3).
Power	0.266	422.69	676	282	1,049	565	
Polynomial 3° Polynomial 2°	0.264	422.70	817	282	1,161	564	
Linear	0.497	420.85	389	280	779	560	
Model[a]	Goodness of fit		$BMD_{0.5SD}$ (mg/kg-d)	$BMDL_{0.5SD}$ (mg/kg-d)	BMD_{1SD} (mg/kg-d)	$BMDL_{1SD}$ (mg/kg-d)	
	p-value	AIC					
Exponential (M2)	0.486	420.90	634	419	1,332	879	
Exponential (M3)	0.266	422.69	937	425	1,483	891	
Exponential (M4)	0.486	420.90	634	172	1,332	468	
Exponential (M5)	N/Ab	424.68	252	176	296	189	
Hill	N/Ab	424.68	256	176	324	error[c]	
Power	0.266	422.69	969	482	1,503	965	
Polynomial 3° Polynomial 2°	0.264	422.70	1,091	482	1,549	964	
Linear	0.497	420.85	684	478	1,368	956	

[a]Constant variance case presented (BMDS Test 2 p-value = 0.0278), selected model in bold; scaled residuals for selected model for doses 0, 19.6, 179, and 1,724 mg/kg-day were −0.92, 0.71, 0.27, and −0.06, respectively.
[b]No available degrees of freedom to calculate a goodness-of-fit value.
[c]BMD or BMDL computation failed for this model.



BMR = 5% RD from control mean; dose shown in mg/kg-day.

Figure Apx_ I-6. Plot of mean response by dose with fitted curve for Exponential (M4) model with constant variance for pup weight during lactation in F2 male offspring CRL Sprague-Dawley rats (PND 21) exposed to HBCD by diet for 3 weeks, lactational dose (Ema et al., 2008).

Exponential Model (Version: 1.10; Date: 01/12/2015)
The form of the response function is: Y[dose] = a * [c-(c-1) * exp(-b * dose)]
A constant variance model is fit

Benchmark Dose Computation
BMR = 5% RD
BMD = 353.728
BMDL at the 95% confidence level = 89.5935

Parameter Estimates

Variable	Estimate	Default initial parameter values
lnalpha	4.53195	4.51269
rho	N/A	0
a	54.8883	59.01
b	0.000145008	0.00128594
c	0	0.687535
d	N/A	1

Table of Data and Estimated Values of Interest

Dose	N	Observed mean	Estimated mean	Observed SD	Estimated SD	Scaled residuals
0	22	53	54.89	12.6	9.64	−0.9187
19.6	22	56.2	54.73	6.7	9.64	0.714
179	18	54.1	53.48	10.1	9.64	0.272
1,724	13	42.6	42.75	8.3	9.64	−0.0551

Likelihoods of Interest

Model	Log (likelihood)	Number of parameters	AIC
A1	−206.7258	5	423.4517
A2	−202.1665	8	420.333
A3	−206.7258	5	423.4517
R	−214.7267	2	433.4535
4	−207.4482	3	420.8963

Tests of Interest

Test	−2*log (likelihood ratio)	Test df	p-value
Test 1	25.12	6	0.0003244
Test 2	9.119	3	0.02775
Test 3	9.119	3	0.02775
Test 6a	1.445	2	0.4856

Appendix J ENVIRONMENTAL RISK

J.1 Risk Quotients based on a Production Volume of 100,000 lbs/yr and 0% removal from Direct Releases

J.1.1 E-FAST Initial Screening for Surface Water Concentrations

Table_Apx J-1. Calculated Risk Quotients based on Estimated HBCD Surface Water Concentrations (µg/L) Using E-FAST (0% Removal)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute or chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively.

Condition of Use	Sub-Scenario	Days of Release	10th Percentile 7Q10			50th percentile: 7Q10		
			SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)	SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)
Import and Re-packaging/ Processing: Repackaging of Import Containers	1.1	29	19.45	**7.78**	**46.64**	0.39	0.16	0.94
	1.2	300	1.87	0.75	**4.48**	0.04	0.01	0.09
	1.3	29	97.51	**39.00***	**233.84***	1.94	0.78	**4.65**
	1.4	300	9.43	**3.77**	**22.61**	0.19	0.08	0.46
	1.5	29	20.10	**8.04**	**48.20**	2.00	0.80	**4.80**
	1.6	300	1.93	0.77	**4.63**	0.19	0.08	0.46
	1.7	29	100.77	**40.31***	**241.65***	10.00	**4.00**	**23.98**
	1.8	300	9.74	**3.90**	**23.36**	0.97	0.39	**2.33**
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	2.1	10	18.70	**7.48**	**44.84**	0.37	0.15	0.89
	2.2	60	3.04	**1.22**	**7.29**	0.06	0.02	0.15
	2.3	10	42.02	**16.81**	**100.77**	0.84	0.34	**2.01**
	2.4	60	7.00	**2.80**	**16.79**	0.14	0.06	0.34
	2.5	10	1.87	0.75	**4.48**	0.04	0.01	0.09
	2.6	60	0.30	0.12	0.72	0.01	0.00	0.01

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute or chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively.

Condition of Use	Sub-Scenario	Days of Release	10th Percentile 7Q10			50th percentile: 7Q10		
			SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)	SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)
	2.7	10	4.20	**1.68**	**10.07**	0.08	0.03	0.20
	2.8	60	0.70	0.28	**1.68**	0.01	0.01	0.03
	2.9	10	1.93	0.77	**4.63**	0.19	0.08	0.46
	2.10	60	0.31	0.12	0.74	0.03	0.01	0.07
	2.11	10	4.34	**1.74**	**10.41**	0.43	0.17	**1.03**
	2.12	60	0.72	0.29	**1.73**	0.07	0.03	0.17
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.1	1	60.60	**24.24**	**145.32**	1.20	0.48	**2.88**
	3.2	15	4.04	**1.62**	**9.69**	0.08	0.03	0.19
	3.3	1	148.38	**59.35***	**355.83***	2.95	**1.18**	**7.07**
	3.4	15	9.98	**3.99**	**23.93**	0.20	0.08	0.48
	3.5	1	6.06	**2.42**	**14.53**	0.12	0.05	0.29
	3.6	15	0.40	0.16	0.97	0.01	0.00	0.02
	3.7	1	14.84	**5.94**	**35.58**	0.30	0.12	0.71
	3.8	15	1.00	0.40	**2.39**	0.02	0.01	0.05
	3.9	1	6.26	**2.51**	**15.02**	0.62	0.25	**1.49**
	3.10	15	0.42	0.17	**1.00**	0.04	0.02	0.10
	3.11	1	15.34	**6.13**	**36.77**	1.52	0.61	**3.65**
	3.12	15	1.03	0.41	**2.47**	0.10	0.04	0.24
Processing: Manufacturing of XPS Foam using HBCD Powder	4.1	1	57.73	**23.09**	**138.44**	1.15	0.46	**2.76**
	4.2	12	4.86	**1.94**	**11.65**	0.10	0.04	0.23
	4.3	1	5.77	**2.31**	**13.84**	0.12	0.05	0.28
	4.4	12	0.49	0.19	**1.17**	0.01	0.00	0.02
	4.5	1	5.97	**2.39**	**14.32**	0.59	0.24	**1.41**
	4.6	12	0.50	0.20	**1.20**	0.05	0.02	0.12
	5.1	16	3881.55	**1552.62***	**9308.27***	77.16	**30.86***	**185.04***

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute or chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively.

Condition of Use	Sub-Scenario	Days of Release	10th Percentile 7Q10			50th percentile: 7Q10		
			SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)	SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.2	16	388.16	**155.26***	**930.83***	7.72	**3.09**	**18.50**
	5.3	16	401.16	**160.46***	**962.01***	39.82	**15.93**	**95.49**
	5.4	140	444.39	**177.76***	**1065.68***	8.83	**3.53**	**21.18**
	5.5	140	44.44	**17.78**	**106.57**	0.88	0.35	**2.12**
	5.6	140	45.93	**18.37**	**110.14**	4.56	**1.82**	**10.94**
	5.7	16	5295.51	**2118.20***	**12699.06***	105.26	**42.10***	**252.42***
	5.8	16	529.55	**211.82***	**1269.91***	10.53	**4.21**	**25.24**
	5.9	16	547.29	**218.92***	**1312.45***	54.32	**21.73**	**130.26**
	5.10	140	605.99	**242.40***	**1453.21***	12.05	**4.82**	**28.90**
	5.11	140	60.60	**24.24**	**145.32**	1.21	0.48	**2.89**
	5.12	140	62.63	**25.05**	**150.19**	6.22	**2.49**	**14.92**
Processing: Manufacturing of Structurally Insulated Panels (SIPs) and Automotive Replacement Parts from XPS/EPS Foam	6.1	16	17.83	**7.13**	**42.76**	0.35	0.14	0.84
	6.2	16	1.78	0.71	**4.28**	0.04	0.01	0.08
	6.3	16	1.84	0.74	**4.41**	0.18	0.07	0.43
	6.4	300	0.95	0.38	**2.28**	0.02	0.01	0.05
	6.5	300	0.10	0.04	0.23	0.00	0.00	0.00
	6.6	300	0.10	0.04	0.24	0.01	0.00	0.02
	6.7	16	79.60	**31.84***	**190.89***	1.60	0.64	**3.84**
	6.8	16	7.96	**3.18**	**19.09**	0.16	0.06	0.38
	6.9	16	8.25	**3.30**	**19.78**	0.82	0.33	**1.97**
	6.10	300	4.20	**1.68**	**10.07**	0.08	0.03	0.20
	6.11	300	0.42	0.17	**1.01**	0.01	0.00	0.02
	6.12	300	0.44	0.18	**1.06**	0.04	0.02	0.10
Use: Installation of XPS/EPS Foam	8.1	1	0.08	0.03	0.19	0.00	0.00	0.01
	8.2	1	0.01	0.00	0.02	0.00	0.00	0.00

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute or chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively.

Condition of Use	Sub-Scenario	Days of Release	10th Percentile 7Q10			50th percentile: 7Q10		
			SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)	SWC (µg/L)	Acute RQ (COC: 2.5 µg/L)	Chronic RQ (COC: 0.417 µg/L)
Insulation in Residential, Public, and Commercial Buildings, and Other Structures	8.3	3	9.43	**3.77**	**22.61**	0.37	0.15	0.89
	8.4	3	0.94	0.38	**2.26**	0.04	0.01	0.09
Processing: Recycling of EPS Foam and Reuse of XPS Foam	10.1	1	83.14	**33.26***	**199.38***	1.65	0.66	**3.96**
	10.2	1	8.31	**3.33**	**19.94**	0.17	0.07	0.40
	10.3	1	8.59	**3.44**	**20.60**	0.85	0.34	**2.04**
	10.4	140	0.59	0.24	**1.41**	0.01	0.00	0.03
	10.5	140	0.06	0.02	0.14	0.00	0.00	0.00
	10.6	140	0.06	0.02	0.15	0.01	0.00	0.01
	10.7	1	99.00	**39.60***	**237.41***	1.97	0.79	**4.72**
	10.8	1	9.90	**3.96**	**23.74**	0.20	0.08	0.47
	10.9	1	10.23	**4.09**	**24.53**	1.02	0.41	**2.45**
	10.10	140	0.71	0.28	**1.70**	0.01	0.01	0.03
	10.11	140	0.07	0.03	0.17	0.00	0.00	0.00
	10.12	140	0.07	0.03	0.18	0.01	0.00	0.02
Use of Flux/Solder Pastes	12.1	4	0.31	0.12	0.74	0.01	0.00	0.01
	12.2	4	0.32	0.13	0.77	0.03	0.01	0.08
	12.3	300	0.00	0.00	0.01	0.00	0.00	0.00
	12.4	300	0.00	0.00	0.01	0.00	0.00	0.00
	12.5	4	0.62	0.25	**1.49**	0.01	0.00	0.03
	12.6	4	0.64	0.26	**1.53**	0.06	0.03	0.15
	12.7	300	0.01	0.00	0.02	0.00	0.00	0.00
	12.8	300	0.01	0.00	0.02	0.00	0.00	0.00

J.1.2 PSC Predicted Surface Water and Sediment Concentrations

Table_Apx J-2. Calculated Risk Quotients based on Estimated HBCD Surface Water Concentrations (µg/L) Using PSC (0% Removal)

The bold values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 8 (8.3), there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
		1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
Import and Re-packaging/ Processing: Repackaging of Import Containers	1.1	14.70	**5.88**	1.71	**4.10**	0.38	0.15	0.04	0.09
	1.2	1.72	0.69	1.46	**3.50**	0.04	0.01	0.03	0.07
	1.3	73.70	**29.48**	8.59	**20.60**	1.93	0.77	0.18	0.44
	1.4	8.69	**3.48**	7.35	**17.63**	0.19	0.07	0.15	0.36
	1.5	15.10	**6.04**	1.77	**4.24**	1.93	0.77	0.19	0.45
	1.6	1.78	0.71	1.51	**3.62**	0.19	0.08	0.16	0.37
	1.7	75.60	**30.24**	8.85	**21.22**	9.68	**3.87**	0.94	**2.26**
	1.8	8.96	**3.58**	7.59	**18.20**	0.96	0.38	0.78	**1.87**
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	2.1	13.90	**5.56**	0.79	**1.88**	0.37	0.15	0.02	0.04
	2.2	2.36	0.94	0.54	**1.30**	0.06	0.02	0.02	0.04
	2.3	31.30	**12.52**	1.76	**4.22**	0.83	0.33	0.04	0.10
	2.4	5.43	**2.17**	1.25	**3.00**	0.14	0.06	0.03	0.06
	2.7	3.13	**1.25**	0.18	0.42	0.08	0.03	0.00	0.01
	2.11	3.21	**1.28**	0.18	0.44	0.42	0.17	0.02	0.05
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.1	44.90	**17.96**	2.31	**5.54**	1.20	0.48	0.06	0.14
	3.2	3.02	**1.21**	0.18	0.43	0.08	0.03	0.00	0.01
	3.3	110.00	**44.00***	5.65	**13.55**	2.93	**1.17**	0.14	0.34
	3.4	7.46	**2.98**	0.45	**1.07**	0.20	0.08	0.01	0.02
	3.5	4.49	**1.80**	0.23	0.55	0.12	0.05	0.01	0.01
	3.7	11.00	**4.40**	0.57	**1.35**	0.29	0.12	0.01	0.03
	3.9	4.60	**1.84**	0.24	0.57	0.60	0.24	0.03	0.07

The bold values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 8 (8.3), there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
		1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
	3.11	11.30	**4.52**	0.58	**1.39**	1.47	0.59	0.07	0.17
Processing: Manufacturing of XPS Foam using HBCD Powder	4.1	42.80	**17.12**	2.19	**5.25**	1.14	0.46	0.05	0.13
	4.2	3.63	**1.45**	0.21	0.49	0.10	0.04	0.00	0.01
	4.3	4.28	**1.71**	0.22	0.53	0.11	0.05	0.01	0.01
	4.5	4.38	**1.75**	0.23	0.54	0.57	0.23	0.03	0.07
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	2900.00	**1160.00***	172.00	**412.47**	76.60	**30.64**	3.67	**8.80**
	5.2	290.00	**116.00***	17.20	**41.25**	7.66	**3.06**	0.37	0.88
	5.3	297.00	**118.80***	17.70	**42.45**	38.50	**15.40**	1.88	**4.51**
	5.4	358.00	**143.20***	140.00	**335.73**	8.78	**3.51**	2.94	**7.05**
	5.5	35.80	**14.32**	14.00	**33.57**	0.88	0.35	0.29	0.71
	5.6	36.80	**14.72**	14.40	**34.53**	4.44	**1.78**	1.51	**3.62**
	5.7	3960.00	**1584.00***	235.00	**563.55***	105.00	**42.00***	5.01	**12.01**
	5.8	396.00	**158.40***	23.50	**56.35**	10.50	**4.20**	0.50	**1.20**
	5.9	406.00	**162.40***	24.20	**58.03**	52.50	**21.00**	2.57	**6.16**
	5.10	489.00	**195.60***	191.00	**458.03***	12.00	**4.80**	4.01	**9.62**
	5.11	48.90	**19.56**	19.10	**45.80**	1.20	0.48	0.40	0.96
	5.12	50.30	**20.12**	19.70	**47.24**	6.06	**2.42**	2.06	**4.94**
Processing: Manufacturing of Stuctural Insulated Panels (SIPs) and Automotive Replacement Parts from XPS/EPS Foam	6.1	13.30	**5.32**	0.79	**1.89**	0.35	0.14	0.02	0.04
	6.4	0.87	0.35	0.77	**1.84**	0.02	0.01	0.02	0.04
	6.7	59.50	**23.80**	3.53	**8.47**	1.57	0.63	0.08	0.18
	6.8	5.95	**2.38**	0.35	0.85	0.16	0.06	0.01	0.02
	6.9	6.10	**2.44**	0.36	0.87	0.79	0.32	0.04	0.09
	6.10	3.87	**1.55**	3.41	**8.18**	0.08	0.03	0.07	0.17
Processing: Recycling of EPS Foam and Reuse of XPS Foam	10.1	61.60	**24.64**	3.16	**7.58**	1.64	0.66	0.08	0.19
	10.2	6.16	**2.46**	0.32	0.76	0.16	0.07	0.01	0.02
	10.3	6.31	**2.52**	0.33	0.78	0.82	0.33	0.04	0.09
	10.7	73.30	**29.32**	3.76	**9.02**	1.95	0.78	0.09	0.22

The bold values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 8 (8.3), there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
		1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
	10.8	7.33	**2.93**	0.38	0.90	0.20	0.08	0.01	0.02
	10.9	7.51	**3.00**	0.39	0.93	0.98	0.39	0.05	0.11

Table_Apx J-3. Calculated Risk Quotients based on Estimated HBCD Sediment Concentrations (µg/kg) Using PSC (0% Removal)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1.

Condition of Use	Sub-Scenario	Acute (11-d half-life): 10th percentile		Chronic (128-d half-life): 10th percentile		Acute (11-d half-life): 50th percentile		Chronic (128-d half-life): 50th percentile	
		Sediment: µg/kg	RQ (COC: 1,570 µg/kg)	Sediment: µg/kg	RQ (COC: 1,570 µg/kg)	Sediment: µg/kg	RQ (COC: 1,570 µg/kg)	Sediment: µg/kg	RQ (COC: 1,570 µg/kg)
Processing: Repackaging of Import Containers	1.1	1400	0.89	3620	**2.31**	34.4	0.02	77	0.05
	1.2	1380	0.88	3600	**2.29**	33.8	0.02	76.7	0.05
	1.3	7040	**4.48**	18200	**11.59**	172	0.11	386	0.25
	1.4	6980	**4.45**	18200	**11.59**	170	0.11	385	0.25
	1.5	1440	0.92	3730	**2.38**	174	0.11	395	0.25
	1.6	1420	0.9	3720	**2.37**	171	0.11	393	0.25
	1.7	7230	**4.61**	18700	**11.91**	872	0.56	1980	**1.26**
	1.8	7170	**4.57**	18700	**11.91**	862	0.55	1980	**1.26**
Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch	2.3	1210	0.77	2920	**1.86**	29.8	0.02	62.8	0.04
	2.4	1080	0.69	2810	**1.79**	26.5	0.02	59.7	0.04
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.1	1430	0.91	1910	**1.22**	36.4	0.02	48.3	0.03
	3.3	3490	**2.22**	4670	**2.97**	89.1	0.06	118	0.08
Processing: Manufacturing of XPS Foam	4.1	1360	0.87	1820	**1.16**	34.7	0.02	46	0.03

The bolded values denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1.									
Condition of Use	**Sub-Scenario**	**Acute (11-d half-life): 10th percentile**		**Chronic (128-d half-life): 10th percentile**		**Acute (11-d half-life): 50th percentile**		**Chronic (128-d half-life): 50th percentile**	
		Sediment: µg/kg	**RQ (COC: 1,570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1,570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1,570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1,570 µg/kg)**
using HBCD Powder									
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	165000	**105.1**	417000	**265.61**	4050	**2.58**	8910	**5.68**
	5.2	16500	**10.51**	41700	**26.56**	405	0.26	891	0.57
	5.3	16900	**10.76**	42900	**27.32**	2050	**1.31**	4560	**2.9**
	5.4	137000	**87.26**	356000	**226.75**	3340	**2.13**	7560	**4.82**
	5.5	13700	**8.73**	35600	**22.68**	334	0.21	756	0.48
	5.6	14100	**8.98**	36800	**23.44**	1690	**1.08**	3880	**2.47**
	5.7	225000	**143.31**	568000	**361.78**	5530	**3.52**	12200	**7.77**
	5.8	22500	**14.33**	56800	**36.18**	553	0.35	1220	0.78
	5.9	23100	**14.71**	58600	**37.32**	2800	**1.78**	6230	**3.97**
	5.1	187000	**119.11**	487000	**310.19**	4560	**2.9**	10300	**6.56**
	5.11	18700	**11.91**	48700	**31.02**	456	0.29	1030	0.66
	5.12	19200	**12.23**	50200	**31.97**	2330	**1.48**	5300	**3.38**
Processing: Manufacturing of SIPs and Automotive Replacement Parts from XPS/EPS Foam	6.1	758	0.48	1910	**1.22**	18.6	0.01	40.9	0.03
	6.4	735	0.47	1910	**1.22**	17.9	0.01	40.6	0.03
	6.7	3380	**2.15**	8540	**5.44**	83	0.05	183	0.12
	6.10	3270	**2.08**	8510	**5.42**	79.8	0.05	181	0.12

The bolded values denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1.									
Condition of Use	**Sub-Scenario**	**Acute (11-d half-life): 10th percentile**		**Chronic (128-d half-life): 10th percentile**		**Acute (11-d half-life): 50th percentile**		**Chronic (128-d half-life): 50th percentile**	
		Sediment: µg/kg	**RQ (COC: 1,570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1,570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1,570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1,570 µg/kg)**
Processing: Recycling of EPS Foam and Reuse of XPS Foam	10.1	1960	**1.25**	2620	**1.67**	49.9	0.03	66.3	0.04
	10.7	2330	**1.48**	3110	**1.98**	59.5	0.04	95.6	0.06

J.2 Targeted Sensitivity Analysis

J.2.1 Condition of Use 1: Import and Re-packaging/ Processing: Repackaging of Import Containers

This condition of use does not have direct releases of HBCD into surface water, therefore the targeted sensitivity analysis only considers the impact of production volume on risk estimates.

Table_Apx J-4. Calculated Risk Quotients based on Estimated HBCD Surface Water Concentrations (µg/L) Using PSC (Targeted Sensitivity Analysis Parameter: Production Volume)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 1 (1.2) for a production volume of 25,000 lbs/yr, there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
			1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
Import and Re-packaging/ Processing: Repackaging of Import Containers	1.1	100,000	14.70	**5.88**	1.71	**4.10**	0.38	0.15	0.04	0.09
	1.2		1.72	0.69	1.46	**3.50**	0.04	0.01	0.03	0.07
	1.3		73.70	**29.48***	8.59	**20.60**	1.93	0.77	0.18	0.44
	1.4		8.69	**3.48**	7.35	**17.63**	0.19	0.07	0.15	0.36
	1.5		15.10	**6.04**	1.77	**4.24**	1.93	0.77	0.19	0.45
	1.6		1.78	0.71	1.51	**3.62**	0.19	0.08	0.16	0.37
	1.7		75.60	**30.24***	8.85	**21.22**	9.68	**3.87**	0.94	**2.26**
	1.8		8.96	**3.58**	7.59	**18.20**	0.96	0.38	0.78	**1.87**
Import and Re-packaging/ Processing: Repackaging of Import Containers	1.1	50,000	14.10	**5.64**	0.83	**1.99**	0.37	0.15	0.02	0.04
	1.2		1.57	0.63	0.92	**2.20**	0.04	0.01	0.02	0.05
	1.3		70.50	**28.20***	4.15	**9.95**	1.86	0.74	0.09	0.21
	1.4		7.94	**3.18**	4.62	**11.08**	0.19	0.07	0.10	0.24
	1.5		14.40	**5.76**	0.85	**2.05**	1.87	0.75	0.09	0.22

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 1 (1.2) for a production volume of 25,000 lbs/yr, there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
			1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
	1.6		1.62	0.65	0.95	**2.27**	0.19	0.08	0.10	0.24
	1.7		72.20	**28.88***	4.27	**10.24**	9.35	**3.74**	0.46	**1.10**
	1.8		8.16	**3.26**	4.77	**11.44**	0.95	0.38	0.50	**1.21**
Import and Re-packaging/ Processing: Repackaging of Import Containers	1.1	25,000	15.00	**6.00**	0.81	**1.94**	0.40	0.16	0.02	0.05
	1.3		75.00	**30.00***	4.06	**9.74**	1.99	0.80	0.10	0.23
	1.4		7.35	**2.94**	2.05	**4.92**	0.19	0.07	0.04	0.11
	1.5		15.40	**6.16**	0.83	**2.00**	2.00	0.80	0.10	0.23
	1.6		1.50	0.60	0.42	**1.00**	0.19	0.07	0.05	0.11
	1.7		76.90	**30.76***	4.17	**10.00**	10.00	**4.00**	0.48	**1.16**
	1.8		7.54	**3.02**	2.11	**5.06**	0.94	0.38	0.23	0.55

Table_Apx J-5. Calculated Risk Quotients based on Estimated HBCD Sediment Concentrations (µg/kg) Using PSC (Targeted Sensitivity Analysis Parameter: Production Volume)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	11-d half-life: 10th percentile		128-d half-life: 10th percentile		11-d half-life: 50th percentile		128-d half-life: 50th percentile	
			Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)
Import and Re-packaging/ Processing: Repackaging of Import Containers+A5:C28	**1.1**	**100,000**	1400	0.89	3620	**2.31**	34.4	0.02	77	0.05
	1.2		1380	0.88	3600	**2.29**	33.8	0.02	76.7	0.05
	1.3		7040	**4.48**	18200	**11.59**	172	0.11	386	0.25
	1.4		6980	**4.45**	18200	**11.59**	170	0.11	385	0.25
	1.5		1440	0.92	3730	**2.38**	174	0.11	395	0.25
	1.6		1420	0.9	3720	**2.37**	171	0.11	393	0.25
	1.7		7230	**4.61**	18700	**11.91**	872	0.56	1980	**1.26**
	1.8		7170	**4.57**	18700	**11.91**	862	0.55	1980	**1.26**
Import and Re-packaging/ Processing: Repackaging of Import Containers	**1.1**	**50,000**	760	0.48	1930	**1.23**	18.7	0.01	41.3	0.03
	1.2		865	0.55	2250	**1.43**	21.1	0.01	47.8	0.03
	1.3		3810	**2.43**	9660	**6.15**	93.5	0.06	207	0.13
	1.4		4360	**2.78**	11400	**7.26**	106	0.07	241	0.15
	1.5		781	0.5	1990	**1.27**	94.5	0.06	212	0.14
	1.6		888	0.57	2320	**1.48**	107	0.07	245	0.16
	1.7		3910	**2.49**	9960	**6.34**	473	0.3	1060	0.68
	1.8		4480	**2.85**	11700	**7.45**	538	0.34	1240	0.79
Import and Re-packaging/ Processing: Repackaging of Import Containers	**1.3**	**25,000**	2560	**1.63**	5580	**3.55**	63.9	0.04	123	0.08
	1.4		1750	**1.11**	4550	**2.9**	42.7	0.03	96.5	0.06
	1.7		2630	**1.68**	5740	**3.66**	323	0.21	630	0.4
	1.8		1800	**1.15**	4690	**2.99**	216	0.14	495	0

J.2.2 Condition of Use 3: Processing: Manufacturing of XPS Foam using XPS Masterbatch

This condition of use does have direct releases of HBCD into surface water, therefore the targeted sensitivity analysis considers both the impact of production volume and percent of HBCD removal from direct releases into surface water on risk estimates.

Table_Apx J-6. Calculated Risk Quotients based on Estimated HBCD Surface Water Concentrations (µg/L) Using PSC (Targeted Sensitivity Analysis Parameters: Production Volume and Percentage of HBCD Removed from Direct Releases)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 3 (3.9) for a production volume of 50,000 lbs/yr, there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releases[a]	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
				1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.1	100,000	0	44.9	**17.96**	2.31	**5.54**	1.2	0.48	0.0571	0.14
			75	11.30	**4.52**	0.44	**1.06**	0.30	0.12	0.01	0.03
	3.2		0	3.02	**1.208**	0.18	0.43	0.08	0.032	0.00	0.01
	3.3		0	110.00	**44**	5.65	**13.55**	2.93	**1.17**	0.14	0.36
			75	27.50	**11**	1.41	**3.38**	0.73	0.29	0.04	0.08
	3.4		0	7.46	**2.984**	0.45	**1.07**	0.20	0.08	0.01	0.02
	3.5		N/A	4.49	**1.796**	0.23	0.55	0.12	0.05	0.01	0.01
	3.7		N/A	11.00	**4.4**	0.57	**1.35**	0.29	0.12	0.01	0.03
	3.9		N/A	4.60	**1.84**	0.24	0.57	0.60	0.24	0.03	0.07
	3.11		N/A	11.30	**4.52**	0.58	**1.39**	1.47	0.59	0.07	0.17
Processing: Manufacturing of XPS Foam	3.1	50,000	0	22.4	**8.96**	1.15	**2.76**	0.598	0.24	0.0285	0.07
			75	5.61	**2.244**	0.29	0.69	0.15	0.06	0.01	0.02
	3.3		0	55.40	**22.16**	2.84	**6.81**	1.48	0.59	0.07	0.17
			75	13.90	**5.56**	0.71	**1.71**	0.37	0.15	0.02	0.04

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. An asterisk indicates when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile SWC predictions that are ≥1. Please note that in COU 3 (3.9) for a production volume of 50,000 lbs/yr, there is one calculated RQ that is within 10% of 1, using the 10th percentile SWC predictions (predicted SWCs are at most 10% less than the either the acute or chronic COCs).

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releases[a]	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
				1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
using XPS Masterbatch	3.4		0	3.73	**1.492**	0.22	0.53	0.10	0.04	0.00	0.01
	3.5		N/A	2.24	0.896	0.12	0.28	0.06	0.02	0.00	0.01
	3.7		N/A	5.54	**2.216**	0.28	0.68	0.15	0.06	0.01	0.02
	3.11		N/A	5.68	**2.272**	0.29	0.70	0.74	0.30	0.04	0.09
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.1	25,000	0	11.2	**4.48**	0.574	**1.38**	0.298	0.12	0.0142	0.03
			75	2.79	**1.116**	0.14	0.34	0.07	0.03	0.00	0.01
	3.3		0	27.70	**11.08**	1.42	**3.41**	0.74	0.30	0.04	0.081
			75	6.93	**2.772**	0.36	0.85	0.19	0.07	0.01	0.021
	3.7		N/A	2.77	**1.108**	0.00	0.01	0.07	0.03	0.00	0.01
	3.11		N/A	2.84	**1.136**	0.15	0.35	0.37	0.15	0.02	0.04

Table_Apx J-7. Calculated Risk Quotients based on Estimated HBCD Sediment Concentrations (µg/kg) Using PSC (Targeted Sensitivity Analysis Parameters: Production Volume and Percentage of HBCD Removed from Direct Releases)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. The shaded sub-scenarios in green represent sub-scenarios that have direct releases of HBCD into surface water. Sub-scenarios were removed if there were not any RQs calculated based on either 10th or 50th percentile sediment concentration predictions that are ≥1.											
Condition of Use	**Sub-Scenario**	**PV**	**% removal**	**11-d half-life: 10th percentile**		**128-d half-life: 10th percentile**		**11-d half-life: 50th percentile**		**128-d half-life: 50th percentile**	
				Sediment: µg/kg	**RQ (COC: 1570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1570 µg/kg)**	**Sediment: µg/kg**	**RQ (COC: 1570 µg/kg)**
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.1	100,000	0	1430	0.91	1910	**1.22**	36.4	0.02	48.3	0.03
	3.3		0	3490	**2.22**	4670	**2.97**	89.1	0.06	118	0.08
	3.3	50,000	0	1760	**1.12**	2350	**1.5**	44.9	0.03	59.6	0.04

J.2.3 Condition of Use 5: Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads

This condition of use does have direct releases of HBCD into surface water, therefore the targeted sensitivity analysis considers both the impact of production volume and percent of HBCD removal from direct releases into surface water on risk estimates.

Table_Apx J-8. Calculated Risk Quotients based on Estimated HBCD Surface Water Concentrations (µg/L) Using PSC (Targeted Sensitivity Analysis Parameters: Production Volume and Percentage of HBCD Removed from Direct Releases)

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. The asterisks indicate when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. There were not any sub-scenarios removed because there was at least one RQ calculated based on either 10th or 50th percentile SWC predictions that are ≥1.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releases	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
				1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	100,000	0	2900.00	**1160.00**	172.00	**412.47**	76.60	**30.64**	3.67	**8.80**
			75	725.00	**290.00**	43.00	**103.12**	19.20	**7.68**	0.92	**2.20**
	5.2		N/A	290.00	**116.00**	17.20	**41.25**	7.66	**3.06**	0.37	0.88
	5.3		N/A	297.00	**118.80**	17.70	**42.45**	38.50	**15.40**	1.88	**4.51**
	5.4		0	358.00	**143.20**	0.05	0.11	8.78	**3.51**	2.94	**7.05**
			75	89.70	**35.88**	35.00	**83.93**	2.20	0.88	0.74	**1.76**
	5.5		N/A	35.80	**14.32**	14.00	**33.57**	0.88	0.35	0.29	0.70
	5.6		N/A	36.80	**14.72**	14.40	**34.53**	4.44	**1.78**	1.51	**3.62**
	5.7		0	3960.00	**1584.00**	0.05	0.11	105.00	**42.00**	5.01	**12.01**
			75	988.00	**395.20**	58.60	**140.53**	26.10	**10.44**	1.25	**3.00**
	5.8		N/A	396.00	**158.40**	23.50	**56.35**	10.50	**4.20**	0.50	**1.20**
	5.9		N/A	406.00	**162.40**	24.20	**58.03**	52.50	**21.00**	2.57	**6.16**
	5.10		0	489.00	**195.60**	191.00	**458.03**	12.00	**4.80**	4.01	**9.62**
			75	123.00	**49.20**	47.90	**114.87**	3.01	**1.20**	1.01	**2.42**
	5.11		N/A	48.90	**19.56**	19.10	**45.80**	1.20	0.48	0.40	0.96

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. The asterisks indicate when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. There were not any sub-scenarios removed because there was at least one RQ calculated based on either 10th or 50th percentile SWC predictions that are ≥1.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releases	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
				1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
	5.12		N/A	50.30	**20.12**	19.70	**47.24**	6.06	**2.42**	2.06	**4.94**
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	50,000	0	2880.00	**1152.00**	157.00	**376.50**	76.60	**30.64**	3.66	**8.78**
			75	721.00	**288.40**	39.40	**94.48**	19.20	**7.68**	0.92	**2.19**
	5.2		N/A	289.00	**115.60**	15.70	**37.65**	7.66	**3.06**	0.37	0.88
	5.3		N/A	296.00	**118.40**	16.20	**38.85**	38.50	**15.40**	1.86	**4.46**
	5.4		0	179.00	**71.60**	69.90	**167.63**	4.39	**1.76**	1.47	**3.53**
			75	44.90	**17.96**	17.50	**41.97**	1.10	0.44	0.37	0.88
	5.5		N/A	17.90	**7.16**	6.99	**16.76**	0.44	0.18	0.15	0.35
	5.6		N/A	18.40	**7.36**	7.21	**17.29**	2.22	0.89	0.76	**1.81**
	5.7		0	3940.00	**1576.00**	215.00	**515.59**	105.00	**42.00**	5.00	**11.99**
			75	983.00	**393.20**	53.60	**128.54**	26.10	**10.44**	1.25	**3.00**
	5.8		N/A	392.00	**156.80**	19.90	**47.72**	10.50	**4.20**	0.50	**1.20**
	5.9		N/A	402.00	**160.80**	20.50	**49.16**	52.50	**21.00**	2.54	**6.09**
	5.10		0	245.00	**98.00**	95.50	**229.02**	5.99	**2.40**	2.01	**4.82**
			75	61.20	**24.48**	23.90	**57.31**	1.50	0.60	0.50	**1.20**
	5.11		N/A	23.20	**9.28**	8.27	**19.83**	0.60	0.24	0.22	0.52
	5.12		N/A	23.80	**9.52**	8.49	**20.36**	3.03	**1.21**	1.03	**2.47**
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	25,000	0	2880.00	**1152.00**	151.00	**362.11**	76.60	**30.64**	3.66	**8.78**
			75	719.00	**287.60**	37.60	**90.17**	19.20	**7.68**	0.91	**2.19**
	5.2		N/A	288.00	**115.20**	15.10	**36.21**	7.66	**3.06**	0.37	0.88
	5.3		N/A	295.00	**118.00**	15.50	**37.17**	38.50	**15.40**	1.85	**4.44**
	5.4		0	89.70	**35.88**	35.00	**83.93**	2.20	0.88	0.74	**1.76**
			75	22.40	**8.96**	8.75	**20.98**	0.55	0.22	0.18	0.44

The bolded values denote a risk (RQ≥1) to the aquatic environment where the surface water concentration (SWC) exceeds the concentration of concern (COC) for acute and chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. The asterisks indicate when the predicted surface water release of HBCD for a sub-scenario exceeds the water solubility of HBCD (66 µg/L), resulting in either acute or chronic RQs greater than 26.4 and 158.3, respectively. There were not any sub-scenarios removed because there was at least one RQ calculated based on either 10th or 50th percentile SWC predictions that are ≥1.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releases	Acute: 10th percentile		Chronic: 10th percentile		Acute: 50th percentile		Chronic: 50th percentile	
				1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)	1-day SWC: µg/L	RQ (COC: 2.5 µg/L)	21-day SWC: µg/L	RQ (COC: 0.417 µg/L)
	5.5		N/A	8.97	**3.59**	3.50	**8.39**	0.22	0.09	0.07	0.18
	5.6		N/A	9.21	**3.68**	3.61	**8.66**	1.11	0.44	0.38	0.91
	5.7		0	3930.00	**1572.00**	205.00	**491.61**	105.00	**42.00**	4.99	**11.97**
			75	980.00	**392.00**	51.30	**123.02**	26.10	**10.44**	1.25	**3.00**
	5.8		N/A	7.29	**2.92**	1.86	**4.46**	0.94	0.38	0.23	0.55
	5.9		N/A	402.00	**160.80**	20.30	**48.68**	52.50	**21.00**	2.53	**6.07**
	5.10		0	122.00	**48.80**	47.50	**113.91**	2.98	**1.19**	1.00	**2.40**
			75	30.50	**12.20**	11.90	**28.54**	0.75	0.30	0.25	0.60
	5.11		N/A	11.50	**4.60**	4.12	**9.88**	0.30	0.12	0.10	0.24
	5.12		N/A	11.80	**4.72**	4.23	**10.14**	1.51	0.60	0.51	**1.23**

Table_Apx J-9. Calculated Risk Quotients based on Estimated HBCD Sediment Concentrations (µg/kg) Using PSC (Targeted Sensitivity Analysis Parameters: Production Volume and Percentage of HBCD Removed from Direct Releases)

The values in bold denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. There are not any sub-scenarios with calculated RQs <1 based on either 10th or 50th percentile sediment concentration predictions.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releasesa	11-d half-life: 10th percentile		128-d half-life: 10th percentile		11-d half-life: 50th percentile		128-d half-life: 50th percentile	
				Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	100,000	0	165000	**105.1**	417000	**265.61**	4050	**2.58**	8910	**5.68**
			75	41200	**26.24**	104000	**66.24**	1010	0.64	2230	**1.42**
	5.2		N/A	16500	**10.51**	41700	**26.56**	405	0.26	891	0.57
	5.3		N/A	16900	**10.76**	42900	**27.32**	2050	**1.31**	4560	**2.9**
	5.4		0	137000	**87.26**	356000	**226.75**	3340	**2.13**	7560	**4.82**
			75	34300	**21.85**	89200	**56.82**	836	0.53	1890	**1.2**
	5.5		N/A	13700	**8.73**	35600	**22.68**	334	0.21	756	0.48
	5.6		N/A	14100	**8.98**	36800	**23.44**	1690	**1.08**	3880	**2.47**
	5.7		0	225000	**143.31**	568000	**361.78**	5530	**3.52**	12200	**7.77**
			75	56200	**35.8**	142000	**90.45**	1380	0.88	3030	**1.93**
	5.8		N/A	22500	**14.33**	56800	**36.18**	553	0.35	1220	0.78
	5.9		N/A	23100	**14.71**	58600	**37.32**	2800	**1.78**	6230	**3.97**
	5.10		0	187000	**119.11**	487000	**310.19**	4560	**2.9**	10300	**6.56**
			75	46900	**29.87**	122000	**77.71**	1150	0.73	2590	**1.65**
	5.11		N/A	18700	**11.91**	48700	**31.02**	456	0.29	1030	0.66
	5.12		N/A	19200	**12.23**	50200	**31.97**	2330	**1.48**	5300	**3.38**
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	50,000	0	102000	**64.97**	231000	**147.13**	2560	**1.63**	5050	**3.22**
			75	25600	**16.31**	57800	**36.82**	641	0.41	1260	0.8
	5.2		N/A	10300	**6.56**	23100	**14.71**	256	0.16	505	0.32
	5.3		N/A	10500	**6.69**	23800	**15.16**	1290	0.82	2590	**1.65**
	5.4		0	68500	**43.63**	178000	**113.38**	1670	**1.06**	3780	**2.41**
			75	17200	**10.96**	44700	**28.47**	419	0.27	948	0.6
	5.5		N/A	6850	**4.36**	17800	**11.34**	167	0.11	378	0.24

The values in bold denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. There are not any sub-scenarios with calculated RQs <1 based on either 10th or 50th percentile sediment concentration predictions.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releasesa	11-d half-life: 10th percentile		128-d half-life: 10th percentile		11-d half-life: 50th percentile		128-d half-life: 50th percentile	
				Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)
	5.6		N/A	7030	**4.48**	18400	**11.72**	846	0.54	1940	**1.24**
	5.7		0	140000	**89.17**	316000	**201.27**	3500	**2.23**	6900	**4.39**
			75	34900	**22.23**	78800	**50.19**	873	0.56	1720	**1.1**
	5.8		N/A	13600	**8.66**	29700	**18.92**	341	0.22	655	0.42
	5.9		N/A	13900	**8.85**	30600	**19.49**	1720	**1.1**	3350	**2.13**
	5.10		0	93500	**59.55**	243000	**154.78**	2280	**1.45**	5160	**3.29**
			75	23400	**14.9**	60800	**38.73**	570	0.36	1290	0.82
	5.11		N/A	9350	**5.96**	24300	**15.48**	228	0.15	516	0.33
	5.12		N/A	9600	**6.11**	25100	**15.99**	1160	0.74	2650	**1.69**
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.1	25,000	0	91800	**58.47**	156000	**99.36**	2340	**1.49**	3600	**2.29**
			75	22900	**14.59**	38900	**24.78**	585	0.37	901	0.57
	5.2		N/A	9180	**5.85**	15600	**9.94**	234	0.15	360	0.23
	5.3		N/A	9420	**6**	16000	**10.19**	1180	0.75	1830	**1.17**
	5.4		0	34300	**21.85**	89200	**56.82**	836	0.53	1890	**1.2**
			75	8570	**5.46**	22300	**14.2**	209	0.13	473	0.3
	5.5		N/A	3430	**2.18**	8920	**5.68**	83.6	0.05	189	0.12
	5.6		N/A	3520	**2.24**	9200	**5.86**	424	0.27	972	0.62
	5.7		0	125000	**79.62**	212000	**135.03**	3190	2.03	4920	**3.13**
			75	31300	**19.94**	53000	**33.76**	796	0.51	1230	0.78
	5.8		N/A	1800	**1.15**	4690	**2.99**	216	0.14	495	0.32
	5.9		N/A	12900	**8.22**	21900	**13.95**	1610	1.03	2500	**1.59**
	5.10		0	46600	**29.68**	121000	**77.07**	1140	0.73	2570	**1.64**
			75	11600	**7.39**	30300	**19.3**	284	0.18	643	0.41
	5.11		N/A	4660	**2.97**	12100	**7.71**	114	0.07	257	0.16

The values in bold denote a risk (RQ≥1) to the aquatic environment where the sediment HBCD concentration exceeds the concentration of concern (COC) for chronic environmental hazard. The shaded sub-scenarios represent sub-scenarios that have direct releases of HBCD into surface water. There are not any sub-scenarios with calculated RQs <1 based on either 10th or 50th percentile sediment concentration predictions.

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releasesa	11-d half-life: 10th percentile		128-d half-life: 10th percentile		11-d half-life: 50th percentile		128-d half-life: 50th percentile	
				Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)	Sediment: µg/kg	RQ (COC: 1570 µg/kg)
	5.12		N/A	4780	**3.04**	12500	**7.96**	575	0.37	1320	0.84

J.2.4 Trophic Transfer: Risk Quotients for Terrestrial Mammals based on KABAM

Table_Apx J-10. Chemical Properties: Input Parameters for KABAM (v1) based on Estimated HBCD Surface Water and Sediment Concentrations (µg/kg) Using PSC

Condition of Use	Sub-Scenario	Production Volume (lbs/yr)	% WWTP Removal for Direct Releasesa	Physiochemical Properties		21-day SWC: µg/L: 10th percentile	128-d half-life: 10th percentile	21-day SWC: µg/L: 50th percentile	128-d half-life: 50th percentile
				Log Kow	Koc (L/kg OC)	Surface Water Concentration: Dissolved Fraction (µg/L)	Pore Water Concentration (µg/L)	Surface Water Concentration: Dissolved Fraction (µg/L)	Pore Water Concentration (µg/L
Processing: Manufacturing of XPS Foam using XPS Masterbatch	3.3	100,000	75	5.62	100,000	1.067	0.292	0.0264	0.0074
		50,000	75	5.62	100,000	0.538	0.147	0.0133	0.00373
		25,000	75	5.62	100,000	0.269	0.0735	0.00667	0.00186
Processing: Manufacturing of EPS Foam from Imported EPS Resin beads	5.7	100,000	75	5.62	100,000	44.353	35.5	0.946	0.758
		50,000	75	5.62	100,000	40.56902	19.7	0.946	0.43
		25,000	75	5.62	100,000	38.828185	13.3	0.946	0.307

Table_Apx J-11. HBCD Hazard Data: Input Parameters for KABAM (v1)

Avian Toxicity Data					Mammalian Toxicity Data				
Avian Species	**Avian NOAEC (mg/kg-diet)**	**Endpoint**	**References**	**Data Evaluation Score**	**Mammalian Species**	**Mammalian LOEC (mg/kg-bw)**	**Endpoint**	**References**	**Data Evaluation Score**
Japanese Quail	125	Development	(MOEJ, 2009)	High	Rat	10	Thyroid	(Ema et al., 2008)	High

Table_Apx J-12. Calculated Risk Quotients based on KABAM (v1) based on Estimated HBCD Surface Water and Sediment Concentrations (µg/kg) Using PSC

The values in **bold** denote a risk (RQ≥1) to the terrestrial environment, based on input parameters for KABAM (v1).

Wildlife Species	**10th Percentile Surface Water and Sediment Concentrations**						**50th Percentile Surface Water and Sediment Concentrations**					
	(COU 3.3)Processing: Manufacturing of XPS Foam using XPS Masterbatch			**(COU 5.7) Processing: Manufacturing of EPS Foam from Imported EPS Resin beads**			**(COU 3.3)Processing: Manufacturing of XPS Foam using XPS Masterbatch**			**(COU 5.7) Processing: Manufacturing of EPS Foam from Imported EPS Resin beads**		
	Production Volume (lbs/year)											
	100,000	**50,000**	**25,000**	**100,000**	**50,000**	**25,000**	**100000**	**50000**	**25000**	**100000**	**50000**	**25000**
Mammalian Species												
fog/water shrew	0.6	0.3	0.1	**23.6**	**21.2**	**20.1**	0.0	0.0	0.0	0.5	0.5	0.5
rice rat/star-nosed mole	0.8	0.4	0.2	**34.4**	**31.0**	**29.4**	0.0	0.0	0.0	0.7	0.7	0.7
small mink	**2.0**	1.0	0.5	**84.3**	**75.9**	**72.1**	0.0	0.0	0.0	**1.8**	**1.8**	**1.8**
large mink	**2.2**	**1.1**	0.5	**93.1**	**83.8**	**79.6**	0.1	0.0	0.0	**2.0**	**2.0**	**1.9**
small river otter	**2.4**	**1.2**	0.6	**100.2**	**90.2**	**85.7**	0.1	0.0	0.0	**2.1**	**2.1**	**2.1**

J.3 Environmental Risk based on 10th Percentile Surface Water and Sediment Predictions

Processing: Repackaging of Import Containers

As presented in Table_Apx J-4, conservatively using the 7Q10 (represent the lowest expected weekly flow over a ten-year period) 10th percentile predictions, the RQs suggest that there is risk due to both acute and chronic exposures to HBCD through this condition of use because out of all eight modeled sub-scenarios, only two RQs for acute exposures were below one (SWC is less than the acute COC of 2.5 µg HBCD/L). Further, in regard to chronic risk, for all eight modeled sub-scenarios, SWCs predicted using the 7Q10 10th percentile predictions all exceed the chronic COC of 0.417 µg HBCD/L for more than 20 days (within a given year). The SWCs predicted using the 7Q10 10th percentile predictions also exceeded the acute COC of 2.5 µg/L for all the modeled sub-scenarios except for 1.2 and 1.6.

The PSC was used to predict chronic risk due to HBCD in the sediment environment. For RQs regarding sediment exposures, a chronic COC of 1,570 µg/kg was used (based on growth reduction observed in a California blackworm chronic HBCD exposure). Water releases for all modeled sub-scenarios for this COU are either for 29 or 300 days, thus any risk estimates equal to or greater than 1 denotes sub-scenarios where sediment organisms are chronically exposed to concentrations of HBCD that may result in toxicity. As presented in Table_Apx J-5, when using the 10th percentile predictions based on either an 11- or 128-day HBCD half-life (representing an acute or chronic HBCD exposure in benthic communities, respectively), risk estimates for acute and chronic exposures are greater than 1 for half and all of the modeled sub-scenarios, respectively. Additionally, although there are four acute risk estimates that are less than one for this condition of use using the 10th percentile predictions (more conservative than the 50th percentile predictions), the values are close to one (0.88-0.92), suggesting that conservative predictions of HBCD sediment concentrations are either greater than or close to the COC of 1,570 µg/kg, despite using the shorter HBCD half-life of 11 days.

Sensitivity Analysis based on Production Volume:

Surface Water:
Based on the 7Q10 10th percentile surface water concentration predictions presented in Table_Apx J-4, (production volume of 50,000 and 25,000 lbs/yr, respectively), out of the eight model sub-scenarios, there are six acute risk estimates greater than one (model sub-scenario 1.1, 1.3-1.5, and 1.7-1.8); the two remaining acute risk estimates (model sub-scenarios 1.2 and 1.7) are the same across all three production volumes, with both demonstrating that the predicted HBCD surface water concentrations are approximately 30% less than the acute COC. The acute risk quotients using the 7Q10 10th percentile surface water concentration predictions for the two lower production volumes are similar to those calculated using a production volume of 100,000 lbs/yr, where except for sub-scenarios 1.2 and 1.6 all the other sub-scenarios have risk estimates greater than one. In regard to the chronic RQs based on the 7Q10 10th percentile surface water concentrations, all eight chronic risk estimates are greater than one, with four model sub-scenarios having days of release greater than 20 days (model sub-scenarios 1.2, 1.4, 1.6, and 1.8) for production volumes of 100,000 and 50,000 lbs/yr. In regard to the production volume of 25,000 lbs/yr, there is one chronic risk estimate based on the 7Q10 10th percentile surface water concentrations that is less than one (model sub-scenario 1.2); this risk estimate is 0.97, suggesting that although the predicted surface water concentration is less than one, reducing the predicted production

volume by 75% (from 100,000 to 25,000 lbs/yr) only reduced the predicted chronic risk below one estimate for this sub-scenario by 3%.

For this COU, reducing the production volume resulted in one chronic risk estimate (using the 7Q10 10th percentile surface water concentrations) to decrease when reaching the production volume of 25,000 lbs/yr,

Sediment:

As presented in Table_Apx J-5, based on the 10th percentile sediment HBCD concentration predictions using the 11-d half-life of HBCD, all three production volumes resulted in risk estimates greater than one in the same four model sub-scenarios (1.3, 1.4, 1.7 and 1.8). For both production volumes of 100,000 and 50,000 lbs/yr, all eight model sub-scenarios for this COU have risk estimates greater than one, based on the 10th percentile sediment HBCD concentration predictions using the 128-d half-life of HBCD. Whereas in regard to the production volume of 25,000 lbs/yr, only the four model sub-scenarios that have risk estimates greater than one based on the 10th percentile sediment HBCD concentration predictions using the 11-d and 128-d half-life of HBCD (1.3, 1.4, 1.7 and 1.8), also have risk estimates greater than one based on the 10th percentile sediment HBCD concentration predictions using the 128-d half-life of HBCD.

Using a production volume of 100,000 lbs/yr for this COU, there are only two model sub-scenarios (1.7 and 1.8) with risk estimates greater than one (based on the 128-d half-life of HBCD), when using the 50th percentile predictions for sediment concentrations of HBCD.

In regard to the risk estimates based on the 10th percentile predictions for sediment concentrations of HBCD, the only difference between the three production volumes was that for 25,000 lbs/yr, four of the risk estimates based on the 128-d half-life of HBCD remain greater than one (whereas all eight were greater than one for the two higher production volumes).

Processing: Compounding of Polystyrene Resin to Produce XPS Masterbatch

Releases of HBCD to the aquatic environment is due to the activity of compounding polystyrene resin to produce masterbatches of XPS. The predicted SWCs, based on 7Q10 10th percentile predictions, exceed the acute COC of 2.5µg/L for five out of the 12 model sub-scenarios (2.1, 2.3-2.4, 2.7, and 2.11). Also based on 7Q10 10th percentile predictions, SWCs exceed the chronic COC of 0.42 µg/L in four out of the 12 model sub-scenarios, with there being greater than 20 days of release for four of those model sub-scenarios. Conservatively using the 7Q10 10th percentile predictions presented in Table_Apx J-2, the risk estimates suggest that there are SWCs that exceed the acute COC and chronic COC.

Interestingly, as shown in Table_Apx J-3, there are only two risk estimates that are equal to or greater than one for predicted sediment concentrations, and both were calculated using the conservative 10th percentile prediction based on the longer 128-d HBCD half-life, one of which corresponding with model sub-scenario 2.4 with 60 days of water release.

Processing: Manufacturing of XPS Foam using XPS Masterbatch

Releases of HBCD to the aquatic environment is due to the activity of manufacturing of XPS foam using XPS Masterbatch. There are acute risk estimates where the SWCs exceed the acute COC of 2.5µg/L. Based on the 7Q10 10th percentile predictions shown in Table_Apx J-6 there are eight and five SWCs that exceed the acute and chronic COC, respectively.

Similarly, with the sediment HBCD concentrations modeled using the PSC, only the 10th percentile predictions resulted in risk estimates greater than one; sediment concentrations of HBCD, based on the 11- or 128-d HBCD half-lives, exceeded the acute and chronic COCs for one and two model sub-scenarios, respectively, as shown in Table_Apx J-7.

Sensitivity Analysis based on Production Volume:

Surface Water:

Based on the 7Q10 10th percentile surface water concentration predictions presented in Table_Apx J-6, (production volume of 50,000 lbs/r), out of the 12 model sub-scenarios, there are five acute risk estimates greater than one (model sub-scenario 3.1, 3.3, 3.4, 3.7, and 3.11); there are three other acute risk estimates are more than one magnitude below the threshold of 1, suggesting the predicted surface water concentrations are close to the acute COC. In regard to the production volume of 25,000 lbs/yr, there are four acute risk estimates greater than one, where all four correspond with model sub-scenarios with acute risk estimates greater than one for the production volume of 50,000 lbs/yr (based on the 7Q10 10th percentile surface water concentration predictions), except for model sub-scenario 3.4. In regard to chronic risk estimates based on the 7Q10 10th percentile surface water concentration predictions, there are two (3.1 and 3.3) out of the twelve model sub-scenarios for this COU with risk estimates greater than one based on a production volume of 50,000 and 25,000 lbs/yr. In comparison to the originally modeled sub-scenarios using a production volume of 100,000 lbs/yr (eight acute and five chronic risk estimates greater than one, based on the 7Q10 10th percentile surface water predictions), the number of model sub-scenarios with risk estimates greater than one was approximately reduced by 50% when reducing the production volume to 50,000 lbs/yr; reducing the production volume to 25,000 lbs/yr did not result in another 50% reduction in the number of model sub-scenarios with risk estimates greater than one.

Sediment:

As presented in Table_Apx J-7, based on the 10th percentile sediment HBCD concentration predictions (using a production volume of 50,000 lbs per year), there is one risk estimate greater than one based on the 11- and 128-d half-life (model sub-scenarios 3.3), respectively. There are no risk estimates greater than one, based on the 10th percentile sediment HBCD concentration predictions for a production volume of 25,000 lbs/yr.

Sensitivity Analysis based on Percent of HBCD Removal from Direct Release:

Surface Water:

As presented in Table_Apx J-6, Based on the 7Q10 10th percentile surface water concentrations of HBCD for a production volume of 100,000 lbs/yr, there are four acute and three chronic (3.1, 3.3, and 3.4) risk estimates that are greater than one, when there is 0% removal of HBCD from the directly

released HBCD into surface water for this COU. There are two acute and chronic (3.1, and 3.3) risk estimates that are greater than one, when there is 75% removal of HBCD from the directly released HBCD into surface water for this COU with a production volume of 100,000 lbs/yr.

For a production volume of 50,000 lbs/yr (based on the 7Q10 10th percentile surface water concentrations of HBCD), out of the three model sub-scenarios with acute risk estimates greater than one with 0% removal of HBCD from directly released surface water (3.1, 3.3, and 3.4), two model sub-scenarios remain to have acute risk estimates greater than one (3.1 and 3.3) with 75% removal. In regard to the chronic risk estimates based on the 7Q10 10th percentile surface water concentrations of HBCD, for 0 and 75% removal, there are two and one risk estimates greater than one, respectively.

For the production volume of 25,000 lbs/yr (based on the 7Q10 10th percentile surface water concentrations of HBCD), only two model sub-scenarios (3.1 and 3.3) have acute and chronic risk estimates greater than one, with 0% removal, however with 75% removal, those two same sub-scenarios only have acute risk estimates greater than one.

Increasing the amount of HBCD removed from direct releases by 75% only impacted the chronic risk estimates in the lower two production volumes; every sub-scenario with an acute risk estimate greater than one for 0% removal, still had acute risk estimates greater than one for 75% removal.

Sediment:

As presented in Table_Apx J-7, based on the 7Q10 10th percentile sediment concentrations of HBCD for the production volume of 100,000 lbs/yr, there is one (3.3) and two (3.1 and 3.3) model sub-scenarios with risk estimates greater than one, based on the 11- and 128-d half-lives of HBCD. Model sub-scenario 3.1 has a risk estimate based on the 11-d half-life of 0.91, suggesting that the sediment concentration of HBCD is less than 10% less than the chronic COC; based on the more conservative 7Q10 10th percentile sediment concentrations of HBCD, risk estimates are either close or over the threshold of one for model sub-scenarios 3.1 and 3.3. Additionally, when there is 75% removal of HBCD from directly released HBCD into surface water for this COU, there are no risk estimates greater than one using either the 7Q10 10th or 50th percentile sediment concentrations of HBCD.

Based on the 7Q10 10th percentile sediment concentrations of HBCD for the production volume of 50,000 lbs/yr, only model sub-scenario 3.3 has a risk estimate greater than one for both the 11- and 128-d half-lives of HBCD. Also on the same note, when there is 75% removal of HBCD from directly released HBCD into surface water for this COU, there are no risk estimates greater than one using either the 7Q10 10th or 50th percentile sediment concentrations of HBCD.

For the production volume of 25,000 lbs/yr, there are no risk estimates greater than one for either 0 or 75% removal of HBCD from directly released HBCD into surface water for this COU. Overall, increasing the percent removal from 0 to 75%, results in risk estimates below one for all three production volumes.

Processing: Manufacturing of XPS Foam using HBCD Powder

Releases of HBCD to the aquatic environment is due to the activity of manufacturing XPS foam using HBCD powder. Based on the 7Q10 10th percentile predictions presented in Table_Apx J-6 there are four

(model sub-scenarios 4.1-4.3, and 4.5) and six (model sub-scenarios 4.1- 4.6) SWCs that exceed the acute and chronic COCs, respectively.

In regard to sediment HBCD concentrations modeled using the PSC, there is only one risk estimate greater than one, using the 10th percentile predictions based on the 128-d HBCD half-life (model sub-scenario 4.1) as shown in Table_Apx J-3.

Processing: Manufacturing of EPS Foam from Imported EPS Resin Beads

Releases of HBCD to the aquatic environment is due to the activity of the processing of EPS foam from imported EPS resin beads. Based on the 7Q10 10th percentile predictions presented in
This condition of use does not have direct releases of HBCD into surface water, therefore the targeted sensitivity analysis only considers the impact of production volume on risk estimates.

all 12 model sub-scenarios have acute risk estimates greater than one, regardless of whether there is 0 or 75% removal from direct releases, across all three production volumes. For chronic risk estimates, there were only two model sub-scenarios that have risk estimates less than one (5.4 and 5.7) for the production volume of 100,000 lbs/yr. Similarly, the conservative 10th percentile sediment HBCD concentration predictions also resulted risk estimates greater than one for all 12 model scenarios using both the 11- and 128-half-lifes. Increasing the percentage of HBCD removed from direct surface water releases did not significantly impact acute or chronic aquatic risk estimates for this condition of use.

Processing: Manufacturing of Structural Insulated Panels (SIPs) and Automotive Replacement Parts from XPS/EPS Foam

Releases of HBCD to the aquatic environment is due to the activity of manufacturing of structural insulated panels and automotive replacement parts from XPS/EPS foam. Based on the 7Q10 10th percentile predictions presented in Table 4-5, out of the twelve model sub-scenarios, there are five acute (model sub-scenarios 6.1, and 6.7-6.10) and four chronic (model scenarios 6.1, 6.4, 6.7, and 6.10) risk estimates that are greater than one.

The 10th percentile sediment HBCD concentration predictions resulted in one (6.7) and three (6.1, 6.4, and 6.7) risk estimates greater than one based on the 11- and 128- day half-lives, respectively, as shown in Table_Apx J-3.

Use: Installation of XPS/EPS Foam Insulation in Residential, Public, and Commercial Buildings, and Other Structures

Releases of HBCD to the aquatic environment is due to the activity of installation of XPS/EPS foam insulation in residential, public and commercial buildings (and other structures). There are not any risk estimates greater than one for any of the modeled scenarios for surface water or sediment HBCD concentrations.

Processing: Recycling of EPS Foam and Reuse of XPS Foam

Releases of HBCD to the aquatic environment is due to the activity of the recycling of EPS foam and reuse of XPS foam. Based on the 7Q10 10th percentile predictions presented in Table_Apx J-2 out of the 12 model sub-scenarios, there are six acute (model sub-scenario 10.1-10.3, 10.7-10.9) and two chronic (10.1, and 10.7) risk estimates that are greater than one.

The 10th percentile sediment HBCD concentration predictions resulted in two acute and chronic risk estimates greater than one on both the 11- and 128-day half-lives (10.1 and 10.7), as shown in Table_Apx J-3.

Use of Solder/Flux Pastes

Releases of HBCD to the aquatic environment is due to the activity of the use of solder or flux pastes. There are not any risk estimates greater than one for any of the modeled scenarios for surface water or sediment HBCD concentrations.

Appendix K Human Health Risk

K.1 Targeted Sensitivity Analysis

A targeted sensitivity analyses on the impact of import volumes on environmental risk estimates was performed. The conditions of use (COU) considered in the sensitivity analysis represent the COUs that resulted in the highest estimates of releases on a daily basis and include scenarios that rely on both industry data and OECD ESDs.

Manufacturing of EPS Foam from Imported EPS Resin beads
Estimation of the risk is below the benchmark MOE for all lifestages only following acute exposure from the highest exposure sub-scenario (5.7) assuming 100,000 lbs PV and 0% WWT removal. Estimation of the risk remains below the benchmark MOE for all lifestages except teenagers when assuming 75% WWT removal and both lower PVs. Reduced PV alone has essentially no effect on acute exposures and associated risk estimates. Therefore, sensitivity analysis demonstrates that differing assumptions of production volume or wastewater treatment has minimal effect on the risk estimate conclusions for the highly exposed population

Table_Apx K-1. Targeted Sensitivity Analysis Based on Production Volume for the Highly Exposed Population Following Acute Exposure

SCENARIO NAME	Production Volume (lbs / year)	WWT Removal Percentage	Young Toddler (1- <2 years)	Toddler (2- <3 years)	Small Child (3- <6 years)	Child (6 - <11 years)	Teen (11- <16 years)	Adult (16- <70 years)
5.7 Manufacturing of EPS Foam from Imported EPS Resin beads (Highest Exposure)	100,000	0%	**14**	**17**	**18**	**24**	**39**	**21**
5.7 Manufacturing of EPS Foam from Imported EPS Resin beads (Highest Exposure)	100,000	75%	**56**	**67**	**73**	**95**	157	**82**
5.7 Manufacturing of EPS Foam from Imported EPS Resin beads (Highest Exposure)	50,000	0%	**14**	**17**	**19**	**24**	**40**	**21**
5.7 Manufacturing of EPS Foam from Imported EPS Resin beads (Highest Exposure)	50,000	75%	**57**	**68**	**75**	**96**	160	**84**
5.7 Manufacturing of EPS Foam from Imported EPS Resin beads (Moderate Exposure)	25,000	0%	**14**	**17**	**19**	**24**	**40**	**21**
5.7 Manufacturing of EPS Foam from Imported EPS Resin beads (Highest Exposure)	25,000	75%	**57**	**69**	**75**	**97**	161	**85**

Note: MOEs represent risk from aggregate exposure values from fish ingestion ADR and background general population exposure.