United States
Consumer Product Safety Commission

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CPSC Staff Statement on: Class-Based Exposure Assessment of Polyhalogenated Organophosphate (PHOP) Flame Retardants Using Four Approaches

The U.S. Consumer Product Safety Commission (CPSC or Commission) contracted with ICF (Contract BPA No. 61320622A0005, Order No. 61320622F2012) to complete a class-based exposure assessment of Polyhalogenated Organophosphate (PHOP) Flame Retardants using four approaches. This statement was prepared by the CPSC staff. ICF produced the accompanying report for CPSC staff. The statement and report have not been reviewed or approved by, and may not represent the views of, the Commission.

ICF's report consists of a main report that describes background, methods, and results from this analysis. This report follows the 2024 *Guidance Document for Conducting Class-Based Exposure Assessments for Organohalogen Flame Retardants* developed by ICF for CPSC staff. The main report lists 37 supporting files in the Appendix (Report Section 7.0). These files describe interim calculations, results files across the four approaches, and the R programming code used for some analyses.

This report is a class-based exposure assessment and does not make statements with regard to potential risks to human health. Quantitative exposure assessments for chemicals in the PHOP subclass can later be combined with quantitative toxicity reference values in various ways for class-based risk assessment. Chronic Average Daily Dose (mg/kg/day) values are estimated for population groups using four different approaches: 1) mechanistic modeling, 2) empirical measurements, 3) indoor dust monitoring, and 4) reverse dosimetry from human biomonitoring data. The report and supporting files for Approach 4 are described in a companion cover memo *CPSC Staff Statement on: Exposure Assessment of Polyhalogenated Organophosphate (PHOP) Flame Retardants Using Human Biomonitoring Data.*

While all chemicals in the subclass received some quantitative estimates using mechanistic modeling for some consumer exposure scenarios, quantitative exposure estimates for other approaches were dependent on available data. EPA's Consumer Exposure Model (CEM) was the primary modeling approach used, although other mechanistic modeling approaches were also considered and compared. Estimates across approaches agreed well with each other and trends to scale-up or scale-down exposure estimates based on correlated key physical-chemical properties were explored. CPSC staff considered background exposures, aggregate exposures, and uncertainty and variability. Newly available code for Approach 3: using indoor dust monitoring data and calculating dose through multiple exposure pathways can serve as a valuable resource more generally. CPSC staff plan to consider quantitative estimates generated by all four approaches in this exposure assessment. Individually and collectively, they provide useful information characterizing chronic exposures to PHOPs.

Class-based Exposure Assessment of Polyhalogenated Organophosphate (PHOP) Flame Retardants

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1. Introduction

Exposure assessments typically focus on single-pathway and single-chemical evaluations, wherein the results can be combined to determine aggregate (i.e., exposure to a single chemical from multiple sources and pathways) or cumulative (i.e., exposure to multiple chemicals from multiple sources and pathways) exposures. When multiple chemicals need to be evaluated, conducting assessments for each individual chemical can be time consuming. In addition, chemical measurements from environmental media or biological matrices, content in consumer products, and emissions or migration from products are often not available to allow for empirical estimates. Therefore, modeling approaches that incorporate available empirical data are needed to fill data gaps for class-based exposure assessment.

A class-based exposure approach assesses multiple chemicals at one time. Considering the entire class at one time allows modeled estimates and available data from data-rich members of the class to be extrapolated to data-poor members of the class. Depending on the data available, class-based exposure estimates can be qualitative or semi-quantitative (e.g., providing exposure estimates for one chemical relative to another).

One chemical class of interest is organohalogen flame retardants (OFRs), which are used in consumer and commercial products. In 2015, the Consumer Product Safety Commission (CPSC) received a petition to ban the use of additive OFRs, as a class, from certain consumer products. The National Academies of Sciences, Engineering, and Medicine (NASEM) concluded that OFRs cannot be treated as a single class and instead identified 14 different subclasses of OFRs based on chemical structure, physicochemical properties, and predicted biological activity (NASEM, 2019).

This report applies the *Guidance Document for Conducting Class-Based Exposure Assessment of Organohalogen Flame Retardants*[1] (ICF, 2024a) to the polyhalogenated organophosphate (PHOP) subclass, which was selected based on results found during an initial scoping of data availability as described in *Organohalogen Flame Retardant Scope Document: Polyhalogenated Organophosphate Subclass* (U.S. CPSC, 2023). Specifically, our objectives were to: (i) assess exposure to PHOPs using four approaches, (ii) corroborate the calculated doses by comparing doses from different approaches, (iii) identify trends or key parameters that would allow chemicals to be ranked relative to one another, and (iv) apply the trends identified to extrapolate doses to data-poor chemicals.

[1] The document, "Guidance Document for Conducting Class-Based Exposure Assessment of Organohalogen Flame Retardants," was developed under U.S. Consumer Product Safety Commission (CPSC) contract BPA No. 61320622A00005, Call Order No. 61320622F2012.

2. Scope of Report

The *Organohalogen Flame Retardant Scope Document: Polyhalogenated Organophosphate Subclass* (U.S. CPSC, 2023) determined that the PHOP subclass has sufficient data to proceed with exposure assessment. The document also noted that CPSC staff, in coordination with the Division of Translational Toxicology (DTT) at the National Institute of Environmental Health Sciences, was conducting a comprehensive literature search (henceforth referred to as the DTT and CPSC search) to identify available health effects and exposure information. During the development of this report, title-abstract screening and full-text screening results from this search were available, but data extraction had not been completed yet. As such, our report focuses on establishing how class-based exposure assessment can occur with available data[2] to demonstrate the workflow and steps for conducting a class-based exposure assessment. Once the full DTT and CPSC search is complete, the analysis conducted in this report can be updated to incorporate additional data identified.

3. Methods

3.1. Overview of Approaches to Estimate Exposure

The four approaches used to estimate exposure are listed below and are referred to in this report as Approach 1, Approach 2, Approach 3, and Approach 4:

1. Mechanistic models: use of mechanistic models based on first principles to estimate indoor environmental concentrations and/or doses associated with consumer products used in indoor or quasi-indoor environments.

2. Empirical measurements: includes (a) use of chemical migration measurements from products to people to estimate contact (direct) consumer exposure or (b) use of chemical emissions measurements from products to indoor environments to estimate mediated (indirect) consumer exposure.

3. Indoor dust monitoring data: use of measured concentrations of indoor dust to estimate dose from multiple pathways and all potential sources, including consumer products, contributing to occurrence in dust.

[2] Available data were from the following data sources: (i) available extracted data from existing databases (e.g., Comparative Toxicogenomics Database and Multimedia Monitoring Database), (ii) a subset of references from the DTT and CPSC search that were identified as potentially relevant by CPSC staff, (iii) results from the literature survey Level 3B compiled through previous CPSC task orders (Nos. 6132062IF1001, 6132062IF1002, and 6132062IF1003 [Tasks # 12 through 14] under contract No. CPSC-D-17-0001), and (iv) an update to the DTT and CPSC search for August 2021 to February 2023. We focused on studies with reported data for PHOPs (i.e., if a study reported that a PHOP was below the limit of detection, this study was not extracted).

4. Reverse dosimetry: use of occurrence data in biological matrices and chemical-specific toxicokinetic data to estimate the dose that would be consistent with the measured biomonitoring level.

For each chemical, Approach 1 provides scenario-based estimates of consumer exposure, Approach 2 estimates pathway-specific exposures depending on the type of empirical data collected, Approach 3 provides an estimated total dose for all sources related to indoor dust, and Approach 4 estimates total dose for all sources and pathways to which a person is exposed. While all chemicals are evaluated using Approach 1, exposures are estimated for the other three approaches only when data are available.

3.2. Approach 1: Mechanistic Models

Approach 1 uses mechanistic models to estimate exposure to OFRs from consumer products in indoor or quasi-indoor (e.g., garage) environments. Exposure scenarios, wherein the source, pathway, and receptor are specified, are first developed to describe how exposure occurs. Model equations are based on well-established mechanistic processes informed by physicochemical properties, with the models requiring source inputs (physicochemical properties and consumer product/material properties), environmental inputs (room volume, air exchange rate), and population inputs (exposure factors, activity patterns). For each exposure scenario, an estimated dose can be determined and is specific to that scenario.

3.2.1. List of Exposure Scenarios

To avoid having an overwhelming number of exposure scenarios and to provide consistency across exposure assessments for different OFR subclasses, a master list of exposure scenarios was initially developed by considering product use information for all subclasses from CPSC's *Market Use Report: Characterizing OFR Chemistries, Sources, and Uses in the U.S. and International Markets, Volumes 1 (Main Report) and 2 (Appendices)* (IEc, 2022a; IEc, 2022b). This master list is the starting point of exposure scenarios for every subclass. For a specific subclass, the master list is narrowed to only relevant exposure scenarios (i.e., a subclass will never have more scenarios than the master list).

Table 1 shows the master list of 18 exposure scenarios. Each specific consumer product identified can be mapped to one of the scenarios. For example, televisions are mapped to "*Non-handheld electronics and appliances where mediated exposure is likely for children and adults*," whereas clothing is mapped to "*Textiles where contact and mediated exposure is likely for children and adults*." Each scenario is also crosswalked to the six exposure pathways of interest (see Section 3.2.2 for descriptions of the six pathways); relevant pathways for each scenario are indicated with an "x" in Table 1.

Table 1. Crosswalk of Master List of Consumer Exposure Scenarios Relevant to All OFR Subclasses.

#	Exposure Scenario Description	Example Products	Pathways [a]					
			1	2	3	4	5	6
1	Handheld electronic casings (or appliances) where contact and mediated exposure is likely for children and adults	Cell phones, gaming devices, hairdryers	x	x	x	x	x	x
2	Non-handheld electronics and appliances where mediated exposure is likely for children and adults	Large televisions, computers, remote-controlled toy cars	x	x	x	x		
3	Small hand-held hard and soft plastic items (including foam) where contact and mediated exposure is likely for children and adults	Dolls, foam blocks, hard plastic bricks, artist and craft supplies, toys	x	x	x	x	x	x
4	Small hand-held hard and soft plastic items (including foam) where incidental ingestion/swallowing exposure is likely for children	Play-based food/food serving products						x
5	Small hand-held rubber items where contact and mediated exposure is likely for children and adults	Bouncy/kick balls, dress up/Halloween masks, artist and craft supplies, toys	x	x	x	x	x	x
6	Large stationary hard and soft plastic items (including foam and rubber) where mediated exposure is likely for children and adults	Doll houses, playhouses, block-based castles, foam play forts/sofas, outdoor play structures	x	x	x	x		
7	Wearable plastic, rubber, or foam clothing and clothing accessories where contact and mediated exposure is likely for children and adults	Costume jewelry, rain gear (coats, boots, etc.), costumes	x	x	x	x	x	x
8	Textiles where contact and mediated exposure is likely for children and adults	Clothing, bedding, costumes, baby carriers and swings, car/booster seats, play pens	x	x	x	x	x	x
9	Textiles where mediated exposure is likely for children and adults	Wallpaper, tents, play tunnels, outdoor play structures	x	x	x	x		
10	Portable and stationary furnishings where contact and mediated exposure is likely for children and adults	Sofas, chairs, ottomans, car seats (foam)	x	x	x	x	x	x
11	Mattresses and mattress toppers where contact and mediated exposure is likely for children and adults	Innerspring mattresses, foam mattresses, mattress pads/toppers, waterproof mattress covers	x	x	x	x	x	x

#	Exposure Scenario Description	Example Products	Pathways [a]					
			1	2	3	4	5	6
12	Infant nap pads where contact and mediated exposure is likely for children	Nap pads	x	x	x	x	x	x
13	Foam carpet backing, carpeting, or hard surface flooring where contact and mediated exposure is likely for children and adults	Foam carpet backing, rubberized carpet backing (in carpet tiles), rubber flooring, foam or rubber floor mats	x	x	x	x	x	x
14	Prefabricated building insulation where mediated exposure is likely for children and adults	Prefabricated insulation (EPS, XPS panels)	x	x	x	x		
15	Custom site-applied building insulation where mediated exposure is likely for children and adults	Site-applied insulation (SPF)	x	x	x	x		
16	Coatings, adhesives, sealants, and elastomers for building materials where mediated exposure is likely for children and adults	Insulation (liquid applied), paint, stains, resins, floor wax	x	x	x	x		
17	Other task-based renovation, repair, or refurbishment of an existing exposure scenario		To be determined on a case-by-case basis					
18	Large stationary wooden (and other materials not covered elsewhere) structures where mediated exposure is likely for children and adults	Wood, wood-engineered products	x	x	x	x		
19	Handheld hard and soft plastic food contact materials (including rubber) where contact and mediated exposure is likely for children and adults		Excluded from further consideration; outside CPSC jurisdiction					

EPS = expanded polystyrene; XPS = extruded polystyrene; SPF = spray polyurethane foam.
[a]Pathway numbers refer to: 1 = ingestion of indoor dust; 2 = gas-phase air transfer to skin; 3 = inhalation of particle dust; 4 = inhalation of gas; 5 = dermal contact; 6 = mouthing.

3.2.2. Modeling Tool

Several exposure modeling tools are readily available to estimate exposure from specific consumer products, all with well-established documentation and/or were peer reviewed. We used EPA's Consumer Exposure Model (CEM; U.S. EPA, 2024) version 3.2, which is capable of modeling the four mediated and two contact exposure pathways of interest. In the mediated pathways, chemicals are emitted from products and partition between settled dust, airborne dust (particulates), and gas; exposure occurs through interaction with one of these media. In the contact pathways, the receptor interacts directly with the product. We list below the six pathways of interest and also provide the corresponding CEM models (e.g., A_DER1, A_DER2).

1. Ingestion of indoor dust: this mediated pathway models incidental ingestion of settled dust (floor dust, surface dust) (A_ING3).
2. Gas-phase air transfer to skin: this mediated pathway models the chemical deposition directly onto the skin from the gas phase, followed by dermal absorption (A_DER1).
3. Inhalation of particle dust: this mediated pathway models inhalation of airborne particulates, followed by absorption in the gastrointestinal tract (A_ING1).
4. Inhalation of gas: this mediated pathway models inhalation of gas, followed by lung absorption (A_INH1).
5. Dermal: this contact pathway models direct contact of the product with the skin, with chemical migration into the skin over time (A_DER2).
6. Mouthing/oral: this contact pathway models direct product-to-mouth contact, where the chemical migrates into saliva (A_ING2).

For this report, the sources considered are all articles, which are consumer product sources that are continuously present and releasing chemicals into the home (e.g., furniture, carpets, appliances). CEM contains eight individual models to estimate exposure to chemicals in articles—one emission model, one inhalation model, three ingestion models, and three dermal models—and reports acute and chronic exposures for persons of various ages by exposure pathway. The relevant processes and associated mathematical equations are described in the CEM User's Guide (U.S. EPA, 2023a).

3.2.3. Input Data for Approach 1

For the relevant CEM exposure models (E6, A_INH1, A_ING1, A_ING2, A_ING3, A_DER1, A_DER2, and A_DER3), CEM has built-in estimators or default values for many of the required input variables. When an estimator was available, we used the CEM-estimated value. For all other parameter values used, see Appendix A-1.

As part of setting up the CEM runs, we also performed a focused literature search to supplement information available on product concentration from the Market Use Report. The product concentration data used in modeling are representative of data sources identified to date and may not be fully representative. Note that product concentration is an important and scalable variable in modeling that can be adjusted to reflect the range of concentrations expected in products over time.

3.3. Approach 2: Empirical Measurements

Approach 2 uses empirical measurements (e.g., product testing emissions data, migration data) to estimate exposure to OFRs from consumer products. Typically, only one or two equations are needed to estimate exposure, and the primary input is an experimentally measured value. For this report, Approach 1 (mechanistic models) and Approach 2 (empirical measurements) are differentiated as follows:

Approach 1:

- Model equations are based on first principles with inputs from chemical, product, and environmental properties.
- Empirical measurements may be used as modeling inputs.

Approach 2:

- Uses empirical measurements to calculate dose in one step or
- First extrapolates empirical measurements to a different set of conditions using a regression model and then uses extrapolated value to calculate dose.
- Equations are not based on first principles and instead are typically based on empirical data-fitting regressions.

Four types of empirical measurements are considered in this report.

3.3.1. Migration Rates from Products into Saliva

Chemical migration rates from product to saliva can be used to estimate direct product-to-mouth contact, also referred to as mouthing. Testing is conducted using artificial saliva, which are commercially available or can be prepared on site in the laboratory. Using the measured migration rate, the dose can be estimated as (Aurisano et al., 2022):

$$AD_{ing} = \frac{R_{mgr} \times A_{contact} \times t_m}{BW} \quad \text{(Eq. 1)}$$

Where:

AD_{ing} = ingestion absorbed dose (µg/kg/day)

R_{mgr} = migration rate of chemical to saliva (µg/cm^2/min)
$A_{contact}$ = mouthing contact area (cm^2)
t_m = mouthing duration per day (min/day)
BW = body weight (kg)

3.3.2. Personal Dermal Loading (Wipe Data)

Personal dermal loading (the amount of a chemical present on a defined surface area of skin) can be measured directly by using wipes. Wipe data can be used to measure chemicals on skin surface directly, typically on hands but also on other parts of the body. Two methods used here to estimate direct dermal exposure are: (i) fraction absorbed and (ii) permeability coefficient.

In the fraction-absorbed method, dose is given by (Tay et al., 2018):

$$AD_{der} = \frac{C_{hw} \times SA \times f_{abs\_derm} \times ED \times EF}{BW \times 24} \quad \text{(Eq. 2)}$$

Where:

AD_{der} = dermally absorbed dose (µg/kg/day)
C_{hw} = surface area normalized chemical mass of chemical in handwipes (µg/cm^2)
SA = hand skin surface area exposed per event (cm^2/event)
f_{abs_derm} = absorption fraction for dermal (-)
ED = exposure duration (hr/day), assumed to be 24 hr/day
EF = exposure frequency (event/day) assumed to be 1
BW = body weight (kg)
24 = (hr/day)

In the permeability coefficient method, dose is estimated as (Liu et al., 2017):

$$AD_{der} = \frac{k_{p-l} \times C_d \times SA \times ED}{BW} \quad \text{(Eq. 3)}$$

$$k_{p-l} = \frac{k_{p-w}}{K_{l-w}} \quad \text{(Eq. 4)}$$

$$C_d = \frac{C_{hw}}{\mathrm{h}} \quad \text{(Eq. 5)}$$

Where:

AD_{der} = dermally absorbed dose (µg/kg/day)
k_{p-l} = permeability coefficient of chemical from lipid to skin (cm/hr)
C_d = chemical concentration in skin lipid (µg/cm^3)
SA = hand skin surface area (cm^2)

ED = exposure duration (hr/day), assumed to be 24 hr/day
BW = body weight (kg)
k_{p-w} = permeability coefficient from water to skin (cm/hr)
K_{l-w} = partition coefficient between skin surface lipids and water (-), approximated with the octanol-water partition coefficient, K_{ow}
C_{hw} = surface area normalized chemical mass of chemical in handwipes (mg/cm^2)
h = thickness of skin surface lipid film (cm)

3.3.3. Personal Air Concentrations

Personal inhalation exposure can be estimated using personal air monitoring devices that measure the air concentration in the personal breathing zone (i.e., bubble) near the nose and mouth. Because these are co-located with the exposed person, the concentrations measured reflect time spent indoors, outdoors, and commuting.

Personal inhalation exposure can be estimated as:

$$AD_{inh} = \frac{C \times Inh \times f_{abs\_inh}}{BW} \quad \text{(Eq. 6)}$$

Where:

AD_{inh} = inhalation absorbed dose (µg/kg/day)
C = concentration of chemical in air (µg/m^3)
Inh = inhalation rate (m^3/day)
f_{abs_inh} = absorption fraction for inhalation (-)
BW = body weight (kg)

3.3.4. Product Emission Data and/or Mass Transfer Parameters

Emission of chemicals from articles can be characterized several different ways. This section provides the equations used to calculate steady-state air concentrations for the three types of PHOP data that were extracted.

For studies reporting area-specific emission rates (i.e., emission factors, µg/m^2/hr) measured from chamber tests, a review of the time series data can confirm whether steady state is reached. Depending on the experimental setup, studies can report area-specific emission rates or other data that can be used to derive the area-specific emission rate. For example, if cumulative emissions per unit area of the source (µg/m^2) are reported at various time points, these can be used to calculate area-specific emission rates. The steady-state air concentration is then given by:

$$C = \frac{A \times E}{Q} \quad \text{(Eq. 7)}$$

$$Q = AER \times V \quad \text{(Eq. 8)}$$

Where:

C = concentration of chemical in air (µg/m^3)
A = exposed area of the source (m^2)
E = area-specific emission rate (µg/m^2/hr)
Q = ventilation flow rate (m^3/hr)
AER = air exchange rate (1/hr)
V = room volume (m^3)

For non-steady-state emissions, there are over 30 mass transfer models available for predicting semi-volatile organic compound emission rates as a function of time, with all requiring three key parameters: the initial content of the chemical in the solid material (C_0 in µg/m^3), the material/air partition coefficient (K_{ma}, dimensionless) and the solid-phase diffusion coefficient (D_m in m^2/h). The following equations provide a basic method to estimate steady-state air concentration using a mass balance approach:

$$V \times \frac{dC}{dt} = A \times h_a \times \left(\frac{C_0}{K} - C\right) - Q \times C \quad \text{(Eq. 9)}$$

At steady state:

$$C = \frac{A \times h_a \times C_0}{(A \times h_a + Q) \times K} \quad \text{(Eq. 10)}$$

Where:

V = room volume (m^3)
C = concentration of chemical in air (µg/m^3)
t = time (hr)
A = exposed area of the source (m^2)
h_a = gas-phase mass transfer coefficient (m/hr)
C_0 = concentration of chemical in the source (µg/m^3)
K = solid-air partition coefficient (dimensionless)
Q = ventilation flow rate (m^3/hr)

For studies reporting the gas-phase concentration in equilibrium with the material (y_0 in µg/m^3), the variable "y_0" effectively measures the rate of chemical flux from the article and depends on the type of material in the article and the chemical of interest. y_0 is simple to measure in lab experiments on a variety of articles without destructive analysis.

The steady-state air concentration is related to y_0 by (Liang et al., 2018):

$$y_0 = y_{ss}\left(1 + \frac{Q}{h_m \times A_0}\right) \quad \text{(Eq. 11)}$$

Where:

y_{ss} = steady-state gas-phase air concentration in the chamber (µg/m^3)
y_0 = gas-phase concentration in equilibrium with the material (µg/m^3)
Q = ventilation rate through the microchamber (m^3/hr)
h_m = mass transfer coefficient across the source (m/hr)
A_0 = total emission area (m^2)

Once the steady-state air concentration is determined, inhalation exposure due to the gas phase can be estimated as:

$$AD_{inh} = \frac{(C_g \times 10^{-3}) \times Inh \times f_{home} \times f_{abs\_inh}}{BW} \quad \text{(Eq. 12)}$$

Where:

AD_{inh} = inhalation absorbed dose (µg/kg/day)
C_g = concentration of chemical in gas phase (µg/m^3)
Inh = inhalation rate (m^3/day)
f_{home} = fraction of time spent at home (-)
f_{abs_inh} = absorption fraction for inhalation (-)
BW = body weight (kg)

3.3.5. Input Data for Approach 2

Migration rates from products into saliva, personal dermal loading (wipe data), personal air concentrations, and product emission data/mass transfer parameters were obtained through a focused literature search. Because we did not conduct a systematic literature review, the data used for Approach 3 may not be representative of the full range of data available in the literature.

All other modeling inputs are shown in Table 2.

Table 2. Input Values Used for Approach 2.

Symbol	Variable	Value	Value (Reference)
Migration Rates into Saliva Inputs			
$A_{contact}$	Mouthing contact area	10 cm^2	Professional judgment
t_m	Mouthing duration per day	37, 47.4, 70.1 min/day	Greene (2002)

Symbol	Variable	Value	Value (Reference)
Personal Dermal Loading Inputs			
SA	Hand skin surface area	211, 290, 370, 510, 720, 830, 980 cm^2	U.S. EPA (2011)
f_{abs_derm2}	Absorption fraction for dermal[a]	0.31 for TCEP 0.262 for TCIPP 0.262 for ∑TCPP[b] 0.133 for TDCIPP	Abdallah et al. (2016)
k_{p-w}	Permeability coefficient of chemical from water to skin[c]	2.60×10^{-2} cm/hr for TCEP 1.90×10^{-2} cm/hr for TCIPP 1.90×10^{-2} cm/hr for ∑TCPP[b] 6.00×10^{-3} cm/hr for TDCIPP	Abdallah et al. (2016)
K_{ow}	Octanol-water partition coefficient	Chemical-specific (-)	U.S. CPSC (2023)
h	Thickness of skin surface lipid film	1.3 cm	Cao et al. (2019)
Product Emission Data/ Mass Transfer Parameters [d]			
A	Exposed area of source	Product-specific (m^2)	Professional judgment
AER	Air exchange rate	0.45 /hr	U.S. EPA (2011)
V	Room volume	Room-specific (m^3)	U.S. EPA (2011)
h_a	Gas-phase mass transfer coefficient	1 m^2	Professional judgment
f_{home}	Fraction of time spent at home	0.89, 0.82, 0.77, 0.74, 0.74, 0.71, 0.73	U.S. EPA (2023b)
Common Inputs [d]			
BW	Body weight	7.8, 12.6, 18.6, 31.8, 56.8, 71.6, 80 kg	U.S. EPA (2011)
Inh	Inhalation rate	0.23, 0.35, 0.42, 0.5, 0.63, 0.68, 0.61 m^3/hr	U.S. EPA (2011)
f_{abs_inh}	Absorption fraction for inhalation	0.5	Professional judgment

∑TCPP = sum of trischloropropylphosphate isomers, one of which is TCIPP.
[a]Abdallah et al. (2016) reported absorption fractions in human ex vivo skin and EPISKIN—models. The dermal absorption fractions used are the average of both skin types.
[b]We assumed the dermal absorption fraction and permeability coefficient for ∑TCPP to be the same as TCIPP.
[c]Abdallah et al. (2016) reported permeability coefficients from acetone to skin for human ex vivo skin and EPISKIN—models, which were used as a surrogate for permeability coefficients from water to skin. The permeability coefficients used are the average of both skin types.
[d]When multiple values are given, these correspond to age-specific inputs for <1 year, 1–2 years, 3–5 years, 6–10 years, 11–15 years, 16–20 years, and 21+ years.

3.4. Approach 3: Indoor Dust Monitoring Data

Approach 3 uses chemical measurements of settled dust and relevant physicochemical properties to estimate exposure, where in the estimated exposure represents the aggregate exposure to all consumer products in an indoor environment. Three phases are

considered for the chemical—settled dust, airborne dust (suspended particulates), and airborne gas—and four exposure pathways are evaluated: (i) inhalation of gas + particulates, (ii) ingestion of settled dust, (iii) dermal absorption from gas phase air through the skin, and (iv) dermal absorption through dust contact with skin. The associated equations are based on those of Weschler and Nazaroff (2010) to determine chemical partitioning between the three phases at steady-state and Mitro et al. (2016)/Pelletier et al. (2017) to estimate exposure via the first three exposure pathways (see source publications for equation derivations). The fourth pathway—dermal intake through dust absorption—was not included in either Mitro et al. (2016) or Pelletier et al. (2017), with both studies noting that this pathway is expected to be minor, and the input parameters required are often not available. In this report, we have included a simplified calculation for exposure of dermal absorption through dust contact with skin for completeness.

3.4.1. Chemical Concentrations in Indoor Air

To estimate chemical concentrations in gas (vapor) and airborne particulates from measurements of chemical in the settled house dust, we assume steady-state conditions.

Gas-phase chemical concentration can be calculated as (Weschler and Nazaroff, 2010):

$$C_g = \frac{(\rho_{dust} \times 10^{12}) \times X_{dust}}{f_{om\_dust} \times K_{oa}} \quad \text{(Eq. 13)}$$

Where:

C_g = gas-phase chemical concentration (µg/m^3)
ρ_{dust} = density of settled dust particles (g/cm^3)
X_{dust} = chemical mass fraction in settled dust (-)
f_{om_dust} = organic matter fraction in settled dust (-)
K_{oa} = octanol-air partition coefficient (-)
10^{12} = (µg/g) × (cm^3/m^3)

Particulate-phase chemical concentration can then be calculated as (Weschler and Nazaroff, 2010):

$$C_p = \frac{C_g \times TSP \times f_{om\_part} \times K_{oa}}{(\rho_{part} \times 10^{12})} \quad \text{(Eq. 14)}$$

Where:

C_p = concentration of chemical attached to airborne particles (µg/m^3)
C_g = gas-phase chemical concentration (µg/m^3)

TSP = total suspended particulates (µg/m^3)
f_{om_part} = organic matter fraction in airborne particles (-)
K_{oa} = octanol-air partition coefficient (-)
ρ_{part} = density of airborne particles (g/cm^3)
10^{12} = (µg/g) × (cm^3/m^3)

Total air concentration is then estimated as:

$$C_a = C_g + C_p \quad \text{(Eq. 15)}$$

Where:

C_a = concentration of chemical in gas-phase and attached to airborne particles (µg/m^3)
C_p = concentration of chemical attached to airborne particles (µg/m^3)
C_g = gas-phase chemical concentration (µg/m^3)

3.4.2. Inhalation

Based on the equations from Mitro et al. (2016) and Pelletier et al. (2017), the inhalation absorbed dose is given by:

$$AD_{inh} = \frac{(C_a \times 10^{-3}) \times Inh \times f_{home} \times f_{abs\_inh}}{BW} \quad \text{(Eq. 16)}$$

Where:

AD_{inh} = inhalation absorbed dose (mg/kg/day)
C_a = concentration of chemical in gas phase and attached to airborne particles (µg/m^3)
Inh = inhalation rate (m^3/day)
f_{home} = fraction of time spent at home (-)
f_{abs_inh} = absorption fraction for inhalation (-)
BW = body weight (kg)
10^{-3} = (mg/µg)

3.4.3. Ingestion

The ingestion absorbed dose is given by (Mitro et al., 2016; Pelletier et al. 2017):

$$AD_{ing} = \frac{X_{dust} \times Ing \times f_{home} \times f_{abs\_ing}}{BW} \quad \text{(Eq. 17)}$$

Where:

AD_{ing} = ingestion absorbed dose (mg/kg/day)
X_{dust} = chemical mass fraction in settled dust (-)
Ing = dust ingestion rate (mg/day)
f_{home} = fraction of time spent at home (-)
f_{abs_ing} = absorption fraction for ingestion (-)
BW = body weight (kg)

The dust ingestion rate in the equation above reflects ingestion of settled dust by (i) mouthing of dust objects such as plush toys and (ii) first getting dust on the hands and then transferring by hand-to-mouth contact.

3.4.4. Dermal Absorption of Dust

This pathway was not included in Mitro et al. (2016) or Pelletier et al. (2017) primarily due to the difficulty of quantification and its large interpersonal variability. Dermal absorption of dust is a two-step process in which the person first contacts the settled dust, most often (but not exclusively) with their hands, followed by chemical leaching from the dust into the biofilm (sweat, sebum) on the skin surface, and subsequent absorption. Given that children play on the floor, in addition to hands, other skin surfaces (bottoms of feet, arms, legs) may also have contact with dust. This approach focuses first on hands, but it could be expanded to other body parts in the future for some population groups.

Unlike dermal absorption from gas phase air through the skin (see Section 3.4.5), this process is relatively slow because even after the dust adheres to the skin, the chemical is initially particle bound. The chemical needs to dissolve into the film on the skin (e.g., containing sweat and sebum in a thin surface) surface before it is absorbed. On a daily basis, this delay is not significant, but if hand-to-mouth contact occurs, then some dust will be ingested, and, therefore, will become unavailable for dermal absorption. Since hand-to-mouth contact is relatively frequent (several contacts per hour), it may be assumed that the hand-to-mouth removal occurs before any dermal absorption. In addition, hand washing will remove nearly all the dust, so frequent hand washing will greatly reduce the absorbed dose from this pathway.

To avoid double counting of dust that is ingested via hand-to-mouth versus dust that stays on the hand for dermal absorption, we first calculate the rate of dust ingested from mouthing hands and the rate of dust getting on the hands. The rate of dust mass ingested from the hands is:

$$Ing_{hands} = Ing \times f_{ing\_htm} \quad \text{(Eq. 18)}$$

Where:

Ing_{hands} = dust ingestion rate due to hand-to-mouth transfer (mg/day)
Ing = dust ingestion rate (mg/day)
f_{ing_htm} = fraction of ingested dust due to hand-to-mouth transfer (-)

The remainder of the ingested dust (that is, a fraction 1-f_{ing_htm}) comes from the direct mouthing of dusty objects, such as plush toys, fabric, and so on. The rate of dust getting on the hands is estimated as:

$$Dust_{hands} = \frac{Ing_{hands}}{f_{hand\_ing}} \quad \text{(Eq. 19)}$$

Where:

$Dust_{hands}$ = rate of dust adhering to hands (mg/day)
Ing_{hands} = dust ingestion rate due to hand-to-mouth transfer (mg/day)
f_{hand_ing} = fraction of dust on hands that enters the mouth

The value for the fraction f_{hand_ing} is discussed in Section 3.4.6 below. A reasonable estimate is that it represents the area of one thumb, expressed as a fraction of the total skin area on both hands.

The amount of dust picked up on the hands and available for dermal absorption is then given as:

$$Dust_{hands\_adj} = Dust_{hands} - Ing_{hands} \quad \text{(Eq. 20)}$$

Where:

$Dust_{hands\_adj}$ = rate of dust adhering to hands available for dermal absorption(mg/day)
$Dust_{hands}$ = rate of dust adhering to hands (mg/day)
Ing_{hands} = dust ingestion rate due to hand-to-mouth

The dermal absorbed dose from dust absorption is then given by:

$$AD_{der} = \frac{Dust_{hands\_adj} \times X_{dust} \times f_{abs\_derm}}{BW} \quad \text{(Eq. 21)}$$

Where:

AD_{der} = dermally absorbed dose (mg/kg/day)
$Dust_{hands\_adj}$ = rate of dust adhering to hands available for dermal absorption(mg/day)

X_{dust} = chemical mass fraction in settled dust (-)
f_{abs_derm} = absorption fraction for dermal (-)
BW = body weight (kg)

3.4.5. Dermal Deposition from Gas Phase

Based on the equations from Mitro et al. (2016) and Pelletier et al. (2017), the dermal absorbed dose from gas-phase deposition is given by:

$$AD_{der} = \frac{(C_g \times 10^{-3}) \times (k_{p-g} \times 10^{-2} \times 24) \times BSA \times f_{home}}{BW} \quad \text{(Eq. 22)}$$

Where:

AD_{der} = dermally absorbed dose (mg/kg/day)
C_g = gas-phase chemical concentration (µg/m^3)
k_{p-g} = indoor air transdermal permeability coefficient (cm/h)
BSA = human body surface area (m^2)
f_{home} = fraction of time spent at home (-)
BW = body weight (kg)
10^{-3} = (mg/µg)
10^{-2} = (m/cm)
24 = (hr/day)

The transdermal permeability coefficient is calculated with the following equations (further details and original sources cited in Pelletier et al., 2017):

$$k_{p\_cw} = 10\text{^}(0.7 \times \log K_{ow} - 0.0722 \times MW^{\frac{2}{3}} - 5.252) \times 3600 \quad \text{(Eq. 23)}$$

$$B = \frac{k_{p\_cw} \times MW^{0.5}}{2.6} \quad \text{(Eq. 24)}$$

$$k_{p\_w} = \frac{k_{p\_cw}}{1+B} \quad \text{(Eq. 25)}$$

$$k_{p\_b} = \frac{k_{p\_w}}{K_{aw}} \quad \text{(Eq. 26)}$$

$$k_{p\_g} = \frac{1}{\frac{1}{V_d} + \frac{1}{k_{p\_b}}} \quad \text{(Eq. 27)}$$

Where:

k_{p_cw} = water phase permeability coefficient through stratum corneum (cm/h)
K_{ow} = octanol-water partition coefficient (-)
MW = molecular weight of chemical (g/mol)

B = ratio of stratum corneum to viable epidermis permeabilities (-)
k_{p_w} = water phase permeability through stratum corneum and viable epidermis (cm/h)
k_{p_b} = gas phase permeability coefficient through skin surface (cm/h)
K_{aw} = air-water partition coefficient (-)
k_{p_g} = transdermal permeability coefficient (cm/h)
V_d = air-to-skin deposition velocity (cm/h)

If K_{aw} is not known, it can be calculated using other input parameters:

$$K_{aw} = \frac{K_{ow}}{K_{oa}} = \frac{H}{R \times T} \quad \text{(Eq. 28)}$$

Where:

K_{aw} = air-water partition coefficient (-)
K_{ow} = octanol-water partition coefficient (-)
K_{oa} = octanol-air partition coefficient (-)
H = Henry's law constant (Pa m^3/mol)
R = universal gas constant = 8.314 Pa m^3 / (mol K)
T = temperature (K)

3.4.6. Input Data for Approach 3

Dust monitoring data were obtained through a focused literature search. The data used for Approach 3 are representative of identified data sources to date and may not represent the full range of data available in the literature.

All other modeling inputs are shown in Table 3.

Table 3. Input Values Used for Approach 3.

Symbol	Variable	Value	Value (Reference)
Chemical-Specific Inputs			
MW	Molecular weight of chemical	g/mol	U.S. CPSC (2023)
K_{ow}	Octanol-water partition coefficient	-	U.S. CPSC (2023)
K_{oa}	Octanol-air partition coefficient	-	U.S. CPSC (2023)
H	Henry's law constant	Pa m^3/mol	U.S. CPSC (2023)
Dust Inputs			
TSP	Total suspended particulates	20 µg/m^3	Weschler and Nazaroff (2010)
f_{om_dust}	Organic matter fraction in settled dust	0.2	Weschler and Nazaroff (2010)
ρ_{dust}	Density of settled dust particles	2 g/cm3	Weschler and Nazaroff (2010)

Symbol	Variable	Value	Value (Reference)
f_{om_part}	Organic matter fraction in airborne dust	0.4	Weschler and Nazaroff (2010)
ρ_{part}	Density of airborne dust particles	1 g/cm3	Weschler and Nazaroff (2010)
Exposure Inputs [a]			
BW	Body weight	7.8, 12.6, 18.6, 31.8, 56.8, 71.6, 80 kg	U.S. EPA (2011)
Inh	Inhalation rate	0.23, 0.35, 0.42, 0.5, 0.63, 0.68, 0.61 m^3/hr	U.S. EPA (2011)
Ing	Dust ingestion rate	30, 40, 30, 30, 20, 20, 20 mg/day	U.S. EPA (2017)
BSA	Human body surface area	0.199, 0.285, 0.38, 0.54, 0.795, 0.92, 0.98 m^2	U.S. EPA (2011)
f_{home}	Fraction of time spent at home	0.89, 0.82, 0.77, 0.74, 0.74, 0.71, 0.73	U.S. EPA (2023b)
f_{abs_inh}	Absorption fraction for inhalation	0.5	Professional judgment
f_{abs_ing}	Absorption fraction for ingestion	0.8 for $logK_{ow} < 5$; Regression equation[b] for $5 \leq logK_{ow} \leq 8$; 0.3 for $logK_{ow} > 8$	Fang and Stapleton (2014)
f_{abs_derm}	Absorption fraction for dermal	0.23[c]	Abdallah et al. (2016)
f_{ing_htm}	Fraction of ingested dust due to hand-to-mouth transfer	0.75	Professional judgment
$f_{hand_{ing}}$	Fraction of dust on hands that enters the mouth	0.05[d]	Professional judgment
V_d	Air-to-skin deposition velocity	600 cm/h	Mitro et al. (2016)

[a]When multiple values are given, these correspond to age-specific inputs for <1 year, 1–2 years, 3–5 years, 6–10 years, 11–15 years, 16–20 years, and 21+ years.
[b]Fang and Stapleton (2014) reported bioaccessibility fractions for various chemicals at different $logK_{ow}$. We fitted the data between $5 \leq logK_{ow} \leq 8$ and obtained a regression equation of: fraction = $-0.176 logK_{ow} + 1.7918$.
[c]Abdallah et al. (2016) reported absorption fractions for TCEP, TCIPP, and TDCIPP (see Table 2). The average of 0.23 was used for all chemicals.
[d]Fraction of dust on hands that enters the mouth is assumed to be 0.05 because typical behavior (e.g., thumb sucking) involves one finger.

3.5. Approach 4: Reverse Dosimetry

Approach 4 estimates exposure to OFRs based on reported chemical measurements in human biological matrices (i.e., biomonitoring data). Measurements may be available from a variety of matrices, including urine, blood, breast milk, hair, nails, sweat, saliva,[3] and teeth. However, measurements in urine (for rapidly eliminated chemicals) and blood

[3] Note that measurements of saliva in this context would need to be appropriately separated from any mouthing incidents, so the saliva reflects internal dose rather than recent exposure via mouthing.

(typically for chemicals eliminated more slowly, with an elimination half-life of >8 hours) are most common and have the best-developed methods for reverse dosimetry and the best data for appropriately parameterizing the equations. The biomonitoring-based estimates in the present report are drawn from *Exposure Assessment of Polyhalogenated Organophosphate (PHOP) Flame Retardants Using Human Biomonitoring Data*, prepared under Task Order No. 61320622F10004 of Contract No. CPSC-D-17-00001 (UC, 2023). UC (2023) describes the methods and equations used to calculate daily intake of PHOPs from human biomonitoring data using Approach 4. The authors applied and extended methods and equations outlined in an earlier report, *Guidance Document for Use of Human Biomonitoring Data for Exposure Assessment*, which was prepared under Task Order No. 61320620F1013 of Contract No. CPSC-D-17-00001 (UC, 2021). Because these reports provide extensive step-by-step directions for obtaining data and conducting the analysis, this report summarizes the key equations and identifies toxicokinetic parameters and focuses on issues specific to class-based assessments.

3.5.1. Key Conversion Equations

UC (2021, 2023) provided the equations for conducting reverse dosimetry calculations based on biomarker measurements in a variety of biological matrices. The key equations for conducting reverse dosimetry with urinary biomonitoring data are repeated here for context. All of these equations are based on a steady-state assumption. Equation 29 provides the conversion approach for biomarkers in urine for data normalized based on specific gravity.

$$DI = \frac{C * UFR}{BW * F_{ue}} \quad \text{(Eq. 29)}$$

Where:

DI = daily intake of the parent compound (mg/kg-day)
C = biomarker concentration in urine (mg biomarker/L)
UFR = 24-hour urinary flow rate (L/day)
BW = body weight (kg)
F_{ue} = fractional urinary excretion (mg biomarker excreted/mg parent compound intake) (If the F_{ue} is based on molar percent, such as percent of a radioactive label, the DI needs to be further adjusted based on the ratio of the molecular weight of the parent to the molecular weight of the biomarker.)

As discussed in a previous publication (UC 2021, 2023), variability in the population distribution may be overestimated when the half-life is short relative to the exposure frequency. This overestimation is of concern because exposure estimates often focus on the high end of the population distribution (e.g., the 95th percentile). The intraclass

correlation coefficient (ICC) provides an approach for quantifying the relative contribution of intra-individual variability and inter-individual variability and for calculating a better estimate of the overall population variability. The ICC is defined as the ratio of the logged variance between subjects and the total logged variance (Pleil and Sobus, 2013; Casas et al., 2018):

$$ICC = \frac{\sigma_\alpha^2}{\sigma_\alpha^2+\sigma_\varepsilon^2} \quad \text{(Eq. 30)}$$

Where:

σ_α^2 = between subject logged variance
σ_ε^2 = within subject logged variance

To better characterize the population variability, the method of Pleil and Sobus (2016) was used to estimate the central tendency for an individual from a single spot sample concentration, information on the intraclass correlation coefficient (ICC), and population summary statistics (geometric mean and geometric standard deviation), using the following equation:

$$GM_i = \left(\frac{X_i}{GM}\right)^{ICC^y} * GM \quad \text{(Eq. 31)}$$

Where:

GM_i = predicted geometric mean for any single measurement (µg/L)
X_i = single-spot measurement concentration (µg/L)
GM = geometric mean for the population distribution (µg/L)
ICC = intraclass correlation coefficient (unitless)
y = slope factor (1/2: See Pleil and Sobus, 2016; unitless)

The GM_i was then used in daily intake calculations instead of the individual's reported exposure concentration, according to the following equation:

$$DI = GM_i * \left(\frac{UFR}{BW*F_{ue}}\right) \quad \text{(Eq. 32)}$$

Where:

DI = daily intake (µg/kg-day)
GM_i = predicted geometric mean for any single-spot measurement, after correcting for ICC in Equation 31 (µg/L)
UFR = urinary flow rate (L/day)
BW = individual body weight (kg) from NHANES
F_{ue} = fractional urinary excretion (unitless)

3.5.2. Identification of Physiological and Chemical-specific Toxicokinetic Parameters

Physiological data were individual-level UFR and BW for each NHANES subject. UC (2023) provided full detail on calculation of UFR as recommended by NHANES analytical guidelines.

As described in UC (2021), the chemical-specific toxicokinetic parameters needed for reverse dosimetry calculations depend on the matrix in which the biomarker is evaluated. The key parameter for urinary biomarkers is the F_{ue} (see Equation 29). When data are available on multiple chemicals in a class, it may be possible to extrapolate from chemicals with available toxicokinetic data to others without such data. The present work used multiple animal data sources on toxicokinetics of PHOP chemicals to estimate F_{ue} values and supported extrapolation from animal data to human data using toxicokinetic data on low molecular weight phthalates (which have similarly short half-lives and are also excreted in urine). Based on the phthalate data, a factor of 1 was used to the best estimate for extrapolating from rat to human F_{ue} for all of the PHOPs, with in vitro metabolism data used for a bounding analysis. (The in vitro data were not used for the primary calculation because they were of low quality.) While rat F_{ue} data were availble for key metabolites of TDCIPP (BDCIPP) and TCEP (BCEP), such data were available only for total excretion of TCIPP (parent and all metabolites). The F_{ue} based on the TCIPP metabolite available in NHANES (BCIPP) was derived from the total TCIPP-based F_{ue} and the ratio of the F_{ue} for the key metabolite to that for total excretion for the other two PHOPs. For additional details in general and specific to the present work, refer to UC (2021) and UC (2023), respectively.

3.5.3. Input Data for Approach 4

The present work used urine biomonitoring data from NHANES (cycles from 2011–2012, 2013–2014, 2015–2016, 2017–2018, 2017–2020; high-level data are presented here, and the full presentation is in UC (2023)) and both urine and blood biomonitoring data from published literature (see UC (2023)).

All other modeling inputs are shown in Table 4.

Table 4. Input Values Used for Approach 4.

Symbol	Variable	Value	Value (Reference)
F_{ue}	Fractional urinary excretion	0.23, BDCPP (TDCPP) 0.13, BCEP (TCEP) 0.23, BCPP (TCPP) 0.58, BCIPP & BCIPHIPP (TCIPP) 0.35, BCIPHIPP (TCIPP)	Lynn et al. (1981); Nomeir et al. (1981) Burka et al. (1991) Minegishi et al. (1988); adjusted based on Lynn et al. (1981) and Burka et al. (1991)

Symbol	Variable	Value	Value (Reference)
UFR	Urinary flow rate (also referred to as urine volume)	Calculated on an individual basis for each subject in NHANES, per NHANES guidelines (L/day)	e.g., https://wwwn.cdc.gov/Nchs/Nhanes/2011-2012/UCFLOW_G.htm#Analytic_Notes
BW	Body weight	Individual body weight from NHANES (kg)	e.g., https://wwwn.cdc.gov/Nchs/Nhanes/2011-2012/BMX_G.htm
ICC	Intraclass correlation coefficient	0.54, BDCPP (TDCPP) 0.45, BCEP (TCEP) 0.48, BCPP (TCPP)	Average of many published values (UC, 2023)

4. Results and Discussion

4.1. Exposures Estimated from Mechanistic Models (Approach 1)

4.1.1. Construction of Exposure Scenarios

Commercial and consumer products where PHOPs are, have been, or may potentially be used were first identified using five data sources: (i) Interstate Chemicals Clearinghouse's High Priority Chemicals Data System (HPCDS); (ii) EPA's Chemical Data Reporting (CDR) database; (iii) literature sources; (iv) patent data from PubChem; and (v) UL's Prospector database. Data from sources (i) through (iv) were already downloaded and made available in CPSC's Market Use Report: Characterizing OFR Chemistries, Sources, and Uses in the U.S. and International Markets, Volumes 1 (Main Report) and 2 (Appendices) (IEc, 2022a; IEc, 2022b).

Review of the five data sources identified 27 PHOPs with a reported consumer product use that could be mapped to at least one of the 18 pre-defined exposure scenarios (these include potential product uses that were extrapolated based on material-product relationships, in which we erred on the side of overinclusion to be conservative). A 28th chemical (CASRN 76649-15-5) did not have any product uses reported; however, given that it is an isomer of TCIPP and included in commercial mixtures with TCIPP at approximately 10% (U.S. EPA, 2015), we assigned this chemical to the same exposure scenarios as TCIPP. In addition, of the 28 chemicals with use data, two were duplicates of others (115-96-8 is the same as 29716-44-7; 26248-87-3 is the same as 1067-98-7), resulting in a final count of 26 out of 40 PHOPs with reported uses. Table 5 shows the breakdown of chemical-scenario combinations identified for a total of 379 combinations across 26 chemicals. All scenarios had at least one chemical mapped to it, and 13

chemicals were mapped to all scenarios. Fourteen of the 40 PHOPs did not have any uses reported; therefore, no exposures were calculated for these chemicals.

For modeling purposes, we assumed that all PHOPs were found at the same concentration in a specific product, and we did not consider co-occurrence of multiple PHOPs in a product (i.e., we did not estimate total exposure across PHOPs). Because the predefined exposure scenarios can be broad categories that capture more than one consumer product (e.g., small hand-held hard and soft plastic items [including foam] can include plastic toys, foam blocks, etc.), we selected one representative product for each scenario and based our CEM input parameters on the representative product. Table 6 lists examples of products that were identified from the five data sources, the representative product selected, and key CEM input parameters used for each scenario. In some cases, only generic products were identified from the five data sources (e.g., solid wood), and we used professional judgment to assign a representative product. For the full list of CEM input parameters used, see Appendix A-1.

After review of the parameterized scenarios, we identified one instance in which a scenario was expanded into two sub-scenarios and another instance in which two scenarios were combined:

- Scenario # 8 (*Textiles where contact and mediated exposure is likely for children and adults*) was broken out into the following two sub-scenarios: (i) # 8C for clothing only and (ii) # 8F for non-clothing articles. This was done to reflect the difference in duration of article contact, wherein clothing has a much longer duration than non-clothing articles.
- Scenarios # 14 (*Prefabricated building insulation where mediated exposure is likely for children and adults*) and # 15 (*Custom site-applied building insulation where mediated exposure is likely for children and adults*) were combined together because the CEM runs did not differentiate between prefabricated insulation and site-applied (e.g., spray) insulation. Spray foam insulation is a special scenario in which empirical data was available and was further considered under Approach 2.

This resulted in a final count of 384 chemical-scenario combinations for modeling.

Table 5. Chemical - scenario Combinations with Product Use Data .

CASRN	Chemical	Scenario #																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
78-43-3	Tris(2,3-dichloropropyl)phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
115-96-8[a]	Tris(2-chloroethyl) phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	-	x	x	x	17
29716-44-7[a]	Tris(chloroethyl) phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	X	x	x	x	18
115-98-0	Bis(2-chloroethyl) vinylphosphonate	x	x	x	X	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
126-72-7	Tris(2,3-dibromopropyl) phosphate	-	-	x	x	-	-	-	x	-	x	x	x	-	-	-	-	-	-	6
140-08-9	Tris(2-chloroethyl) phosphite	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
1067-98-7[b]	Tris(3-chloropropyl)phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
26248-87-3[b]	Tris(chloropropyl)phosphate	x	x	x	x	-	x	x	x	x	x	x	x	-	-	-	-	-	-	11
2788-11-6	Tris(2,4dibromophenyl) phosphate	x	x	x	x	x	x	x	x	x	-	-	-	-	x	-	x	-	x	12
4351-70-6	Phosphonic acid, P-[1-[[(2-chloroethoxy)(2-chloroethyl)phosphinyl]oxy]ethyl]-, 1-[bis(2-chloroethoxy)phosphinyl]ethyl 2-chloroethyl ester	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	-	x	17
5324-12-9	2,3-Dibromopropylphosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
5412-25-9	Bis(2,3-dibromopropyl) hydrogen phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
6145-73-9	Tris(2-chloropropyl) phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	-	x	17
6294-34-4	Bis(2-chloroethyl) 2-chloroethylphosphonate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
6749-73-1	Tris(1,3-dichloropropan-2-yl) phosphite	x	x	x	x	x	x	-	-	-	x	x	x	x	-	-	x	-	-	11
7046-64-2	Tris(2,4,6-tribromophenyl) phosphate	x	x	x	x	x	x	x	x	x	-	-	-	-	-	-	x	x	x	12
13674-84-5	Tris(2-chloroisopropyl)phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
76649-15-5[c]	(2-Chloro-1-methylethyl) bis(2-chloropropyl) phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18

CASRN	Chemical	Scenario #																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
13674-87-8	Tris(1,3-dichloro-2-propyl) phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
19186-97-1	Tris(tribromoneopentyl)phosphate	x	x	x	x	x	x	x	-	-	-	-	-	-	-	-	-	-	-	7
27568-90-7	Ethanol, 2bromo, phosphate (3:1)	x	x	x	x	x	x	-	x	x	x	x	x	x	x	x	x	x	x	17
33125-86-9	Phosphoric acid, 1,2-ethanediyl tetrakis(2-chloroethyl) ester	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
35656-01-0	Tris(2bromo4methylphenyl) phosphate	x	x	x	x	x	x	x	x	x	x	x	-	-	x	x	x	x	x	16
38051-10-4	Phosphoric acid, 2,2-bis(chloromethyl)-1,3-propanediyl tetrakis(2-chloroethyl) ester	-	-	x	x	-	x	-	x	x	x	x	x	-	-	-	-	-	-	8
66108-37-0	2,2-Bis(bromomethyl)-3-chloropropyl bis[2-chloro-1-(chloromethyl)ethyl] phosphate	x	x	x	x	x	x	-	x	x	-	-	-	-	-	-	x	-	-	9
76025-08-6	Bis(2-chloro-1-methylethyl) 2-chloropropyl phosphate	-	-	-	-	-	-	-	-	-	x	x	x	-	x	-	-	x	x	6
84282-27-9	2Bromoethyl 5bromopentyl 2chloroethyl phosphate	x	x	x	x	x	x	-	-	-	-	-	-	-	-	-	x	-	-	7
40120-74-9	Tris(1,3-dichloropropyl)phosphate	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
26604-51-3	Tris(dichloropropyl) phosphate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
34432-82-1	Bis(2,3-dibromopropyl) hydrogen phosphate–ammonia (1/1)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
36711-31-6	Bis(2,3-dibromopropyl) phosphate, magnesium salt	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
49690-63-3	Tris(dibromophenyl) phosphate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
53461-82-8	Diethylene glycol bis[bis(2-chloroethyl)phosphate]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
61090-89-9	2,4,8,10-Tetraoxa-3,9-diphosphaspiro[5.5]undecane, 3,9-bis[3-bromo-2,2-bis(bromomethyl)propoxy]-, 3,9-dioxide	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

CASRN	Chemical	Scenario # 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total
64864-08-0	Sodium bis(2,3-dibromopropyl) phosphate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
66519-18-4	potassium bis(2,3-dibromopropyl) phosphate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
72236-72-7	Bis(1,3-dichloropropan-2-yl) hydrogen phosphate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
98923-48-9	4-Bromo-2-chlorobutyl 3-bromo-2,2-dimethylpropyl phosphate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
125997-20-8	Phosphoric acid, mixed 3-bromo-2,2-dimethylpropyl and 2-bromoethyl and 2-chloroethyl esters	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
1047637-37-5	2,2-Bis(chloromethyl)-1,3-propanediyl tetrakis(1-chloro-2-propanyl) bis(phosphate)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
1373346-90-7	dimethyl {[(4,6-dichloro-1,3,5-triazin-2-yl)oxy]methyl}phosphonate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
34621-99-3	Tetrakis(1-chloropropan-2-yl) ethane-1,2-diyl bis(phosphate)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0

- = no product uses were identified.
[a] 115-96-8 is the same chemical as 29716-44-7.
[b] 26248-87-3 is the same chemical as 1067-98-7.
[c] 76649-15-5 did not have any product uses reported; however, given it is an isomer of 13674-84-5 and included in commercial mixtures with 13674-84-5 at approximately 10%, the same exposure scenarios were assigned.

Table 6. Key Parameters Used in CEM Runs.

#	Scenario	Examples of Products Identified	Representative Product	Use Environment	Surface Area of Product (m^2)	Duration of Contact [a] (min)
1	Handheld electronic casings (or appliances) where contact and mediated exposure is likely for children and adults	Smartphones; hard polymer casings of electronic products; heat sealers; electrical and electronic devices	Tablet	Living room	0.12	120
2	Non-handheld electronics and appliances where mediated exposure is likely for children and adults	Televisions; hard polymer casings of electronic products; electrical and electronic devices	Television	Living room	2.3	0
3	Small hand-held hard and soft plastic items (including foam) where contact and mediated exposure is likely for children and adults	Soft/hard plastic toys; baby products; arts/crafts variety packs	Toy block	Living room	0.035	120
4	Small hand-held hard and soft plastic items (including foam) where incidental ingestion/swallowing exposure is likely for children and adults	Soft/hard plastic toys; baby products; arts/crafts variety packs	Toy food	Living room	0.005	60
5	Small hand-held rubber items where contact and mediated exposure is likely for children and adults	Rubber toys; arts/crafts variety packs	Rubber ball	Living room	0.02	30
6	Large stationary hard and soft plastic items (including foam and rubber) where mediated exposure is likely for children and adults	Plastic and rubber products not covered elsewhere; baby carriers; highchairs	Indoor playhouse	Living room	8.5	0
7	Wearable plastic, rubber, or foam clothing and clothing accessories where contact and mediated exposure is likely for children and adults	Role play – housekeeping/gardening/DIY toys textiles	Plastic raincoat	Bedroom	1.2	60
8C	Textiles where contact and mediated exposure is likely for children and adults	Clothing	Clothing	Bedroom	1.2	960
8F	Textiles where contact and mediated exposure is likely for children and adults	Car seats; baby carriers; nursing pillows	Car seat	Automobile	1	60

#	Scenario	Examples of Products Identified	Representative Product	Use Environment	Surface Area of Product (m^2)	Duration of Contact [a] (min)
9	Textiles where mediated exposure is likely for children and adults	Curtains; camping tents; wallpaper	Curtains	Bedroom	2.8	0
10	Portable and stationary furnishings where contact and mediated exposure is likely for children and adults	Upholstered furniture; car seats	Sofa chair	Living room	5	120
11	Mattresses and mattress toppers where contact and mediated exposure is likely for children and adults	Mattresses	Adult and children's mattress	Bedroom	3	480
12	Infant nap pads where contact and mediated exposure is likely for children	Nap mats	Nap mat	Bedroom	1	90
13	Foam carpet backing, carpeting, or hard surface flooring where contact and mediated exposure is likely for children and adults	Carpets; hard/laminate flooring	Flooring	Whole house	200	180
14/15	Prefabricated and custom site-applied building insulation where mediated exposure is likely for children and adults	Insulating foam; expanded polystyrene (EPS); extruded polystyrene (XPS)	Insulation	Whole house	100	0
16	Coatings, adhesives, sealants, and elastomers for building materials where mediated exposure is likely for children and adults	Adhesives and sealants; latex paint	Coating	Whole house	50	0
17	Other task-based renovation, repair, or refurbishment of an existing exposure scenario	Blockboard; particleboard; fiberboard; construction materials	Furniture chest	Garage	3.5	0
18	Large stationary wooden (and other materials not covered elsewhere) structures where mediated exposure is likely for children and adults	Solid wood (varnished); multilayer solid wood; wood and engineered wood products	Large bookcase	Living room	18	0

[a]Duration of article contact was estimated using professional judgment.

4.1.2. Doses by Individual Scenario

Chronic average daily dose (CADD) for all scenarios, as estimated by CEM, are available in Appendix A-2 by chemical. Because all scenarios are consumer articles that are present in the house for long durations, only CADDs are presented. All model runs were conducted using a chemical weight fraction of 0.1% (equal to 1,000 ppm or 1 mg/g). The 0.1% value was selected to differentiate between intentional addition of OFRs versus impurities during production (Stapleton et al., 2011). We used the same weight fraction for all chemical-product combinations because (i) weight fraction data were not available for most chemical-product combinations modeled, (ii) for chemicals with reported weight fractions, the values could vary widely, and (iii) a sensitivity analysis showed that doses varied linearly with weight fraction, and therefore, the results at 0.1% could be scaled as needed in future analyses that consider variability in OFR concentration in products over time (see Section 4.1.5). Specifically, as an example of the varying weight fractions reported, of the studies identified in our focused literature review, TDCIPP concentrations in furniture foam varied as follows: 0.11%–4.35% for arithmetic means (Harrad et al., 2023; Stapleton et al., 2012), 0.0013%–0.0024% for medians (Harrad et al., 2023), and 1.99% for geometric mean (Hammel et al., 2017).

Using TDCIPP as an example chemical, Table 7 provides the total dermal, ingestion, and inhalation doses for adults and 3-5 year olds by scenario. For a breakdown by the individual dermal/ingestion pathways (or breakdown of inhalation by gas and particulate phase), see Appendix A-2.

Table 7. Chronic Average Daily Doses (mg/kg/day) of TDCIPP for the 18 Consumer Exposure Scenarios for Adults and 3-5 Year Olds as Estimated by CEM.

#	Scenario	Receptor	Dermal	Ingestion	Inhalation
1	Handheld electronic casings (or appliances) where contact and mediated exposure is likely for children and adults	Adult	9.15E-04	2.59E-08	1.31E-06
		3–5 yrs	1.47E-03	3.66E-02	3.87E-06
2	Non-handheld electronics and appliances where mediated exposure is likely for children and adults	Adult	8.32E-09	4.11E-07	2.50E-05
		3–5 yrs	1.34E-08	5.88E-06	7.41E-05
3	Small hand-held hard and soft plastic items (including foam) where contact and mediated exposure is likely for children and adults	Adult	9.14E-04	1.09E-08	3.83E-07
		3–5 yrs	1.47E-03	3.66E-02	1.13E-06
4	Small hand-held hard and soft plastic items (including foam) where incidental ingestion/swallowing exposure is likely for children	Adult	6.30E-04	5.59E-09	5.64E-08
		3–5 yrs	1.01E-03	3.66E-02	1.67E-07
5	Small hand-held rubber items where contact and mediated exposure is likely for children and adults	Adult	4.40E-04	8.24E-09	2.20E-07
		3–5 yrs	7.07E-04	3.66E-02	6.50E-07

#	Scenario	Receptor	Dermal	Ingestion	Inhalation
6	Large stationary hard and soft plastic items (including foam and rubber) where mediated exposure is likely for children and adults	Adult	3.07E-08	1.50E-06	9.25E-05
		3–5 yrs	4.94E-08	2.16E-05	2.74E-04
7	Wearable plastic, rubber, or foam clothing and clothing accessories where contact and mediated exposure is likely for children and adults	Adult	2.54E-02	2.03E-07	1.36E-05
		3–5 yrs	4.22E-02	3.66E-02	4.03E-05
8C	Textiles where contact and mediated exposure is likely for children and adults (e.g., clothing)	Adult	1.25E-01	2.03E-07	1.36E-05
		3–5 yrs	2.07E-01	3.66E-02	4.03E-05
8F	Textiles where contact and mediated exposure is likely for children and adults (e.g., car seats)	Adult	7.00E-03	9.65E-08	6.21E-06
		3–5 yrs	1.16E-02	3.66E-02	1.84E-05
9	Textiles where mediated exposure is likely for children and adults	Adult	1.05E-08	4.68E-07	3.17E-05
		3–5 yrs	1.69E-08	6.70E-06	9.40E-05
10	Portable and stationary furnishings where contact and mediated exposure is likely for children and adults	Adult	9.49E-03	8.87E-07	5.44E-05
		3–5 yrs	1.58E-02	3.66E-02	1.61E-04
11	Mattresses and mattress toppers where contact and mediated exposure is likely for children and adults	Adult	8.20E-02	5.01E-07	3.40E-05
		3–5 yrs	1.36E-01	3.66E-02	1.01E-04
12	Infant nap pads where contact and mediated exposure is likely for children	Adult	3.14E-02	1.70E-07	1.13E-05
		3–5 yrs	5.21E-02	3.66E-02	3.36E-05
13	Foam carpet backing, carpeting, or hard surface flooring where contact and mediated exposure is likely for children and adults	Adult	5.26E-03	8.52E-05	2.79E-03
		3–5 yrs	8.45E-03	3.78E-02	8.25E-03
14/ 15	Building insulation where mediated exposure is likely for children and adults	Adult	2.31E-07	4.27E-05	1.39E-03
		3–5 yrs	3.72E-07	6.12E-04	4.12E-03
16	Coatings, adhesives, sealants, and elastomers for building materials where mediated exposure is likely for children and adults	Adult	2.31E-07	2.13E-05	6.96E-04
		3–5 yrs	3.72E-07	3.05E-04	2.06E-03
17	Other task-based renovation, repair, or refurbishment of an existing exposure scenario	Adult	1.19E-08	7.02E-07	3.58E-05
		3–5 yrs	1.91E-08	1.01E-05	1.06E-04
18	Large stationary wooden (and other materials not covered elsewhere) structures where mediated exposure is likely for children and adults	Adult	6.51E-08	3.18E-06	1.96E-04
		3–5 yrs	1.05E-07	4.56E-05	5.80E-04
Aggregate across all scenarios		Adult	2.88E-01	1.58E-04	5.39E-03
		3–5 yrs	4.78E-01	4.04E-01	1.60E-02

4.1.3. Aggregate Consumer Exposures

For the purposes of comparing exposures across the four different approaches, we determined an aggregate consumer exposure value across all scenarios using two methods. In the first method, which we refer to as "unadjusted," we summed the doses by pathway across all scenarios for each chemical-age group combination (see last row in Table 7). This represents the maximum possible dose but is unrealistic because it is unlikely that a person would be exposed to every scenario. It also identified model defaults that could be refined to better represent the range of population exposures.

In the second method, which we refer to as "adjusted," we incorporated several adjustment factors to determine a reasonable population exposure. A review of the doses identified mouthing (A_ING2) and direct dermal contact (A_DER2) as two pathways in which the inputs required a closer examination. For mouthing, we compared the mouthing exposures estimated by CEM with those calculated from empirical measurements (Approach 2, see Section 4.2.1). For the PHOP class, there was a clear difference in the migration rates into saliva and mouthing durations between the two approaches. The ratio of the migration rate into saliva used in CEM to empirical measurements was dependent on the chemical and could be categorized into three tiers. For Tier 1 chemicals, the ratio was approximately a factor of 900 higher, whereas for Tiers 2 and 3, the ratio was higher by 2,250 and 9,000, respectively (see Appendix A-3 for further details on the derivation of the adjustment factors and the chemicals that fall under each tier). For mouthing durations, a comparison of the durations used in the CEM runs with empirical mouthing durations from an observational study (Greene 2002) showed that the CEM values were approximately a factor of 2 higher. Combining these factors results in an overall mouthing adjustment factor of 1,800, 4,500, and 18,000 for Tier 1, 2, and 3 chemicals, respectively.

For direct dermal contact, we used professional judgment to estimate an adjustment factor that would take into account the following: (i) the CEM-modeled scenarios used default surface areas of "whole body," "half body," "quarter body," etc., whereas the actual surface area in contact with the article could potentially be lower; (ii) the article may not be continuously in contact with skin, and therefore, actual duration of article contact could potentially be lower; and (iii) the CEM-modeled doses do not incorporate a loss mechanism such as handwashing or showering. It is possible to adjust chemical- and product-specific defaults to better reflect these additional considerations. However, in the interim, adjustment factors of 5, 5, and 10 were applied to reflect the difference between modeled and actual exposed surface skin area, the difference between modeled and actual duration of article contact, and the lack of loss mechanism (e.g., handwashing, showering), respectively. Taken together, an overall adjustment factor of 250 was applied to the A_DER2 results to determine a reasonable population estimate. The total dermal,

ingestion, and inhalation doses after the adjustments for mouthing and direct dermal contact are shown in Table 8 by scenario for TDCIPP.

Table 8. Chronic Average Daily Doses (mg/kg/day) of TDCIPP for the 18 Consumer Exposure Scenarios for Adults and 3 - 5 Year Olds as Estimated by CEM with Adjustment Factors for Mouthing and Direct Dermal Contact.

#	Scenario	Receptor	Dermal	Ingestion	Inhalation
1	Handheld electronic casings (or appliances) where contact and mediated exposure is likely for children and adults	Adult	4.87E-06	2.59E-08	1.31E-06
		3–5 yrs	7.81E-06	8.49E-06	3.87E-06
2	Non-handheld electronics and appliances where mediated exposure is likely for children and adults	Adult	8.32E-09	4.11E-07	2.50E-05
		3–5 yrs	1.34E-08	5.88E-06	7.41E-05
3	Small hand-held hard and soft plastic items (including foam) where contact and mediated exposure is likely for children and adults	Adult	4.16E-06	1.09E-08	3.83E-07
		3–5 yrs	6.67E-06	8.28E-06	1.13E-06
4	Small hand-held hard and soft plastic items (including foam) where incidental ingestion/swallowing exposure is likely for children	Adult	2.77E-06	5.59E-09	5.64E-08
		3–5 yrs	4.44E-06	8.20E-06	1.67E-07
5	Small hand-held rubber items where contact and mediated exposure is likely for children and adults	Adult	2.12E-06	8.24E-09	2.20E-07
		3–5 yrs	3.41E-06	8.24E-06	6.50E-07
6	Large stationary hard and soft plastic items (including foam and rubber) where mediated exposure is likely for children and adults	Adult	3.07E-08	1.50E-06	9.25E-05
		3–5 yrs	4.94E-08	2.16E-05	2.74E-04
7	Wearable plastic, rubber, or foam clothing and clothing accessories where contact and mediated exposure is likely for children and adults	Adult	4.71E-04	2.03E-07	1.36E-05
		3–5 yrs	7.83E-04	1.10E-05	4.03E-05
8C	Textiles where contact and mediated exposure is likely for children and adults (e.g., clothing)	Adult	9.56E-04	2.03E-07	1.36E-05
		3–5 yrs	1.59E-03	1.10E-05	4.03E-05
8F	Textiles where contact and mediated exposure is likely for children and adults (e.g., car seats)	Adult	7.64E-04	9.65E-08	6.21E-06
		3–5 yrs	1.27E-03	9.33E-06	1.84E-05
9	Textiles where mediated exposure is likely for children and adults	Adult	1.05E-08	4.68E-07	3.17E-05
		3–5 yrs	1.69E-08	6.70E-06	9.40E-05
10	Portable and stationary furnishings where contact and mediated exposure is likely for children and adults	Adult	4.52E-04	8.87E-07	5.44E-05
		3–5 yrs	7.52E-04	2.08E-05	1.61E-04
11	Mattresses and mattress toppers where contact and mediated exposure is likely for children and adults	Adult	1.37E-03	5.01E-07	3.40E-05
		3–5 yrs	2.28E-03	1.53E-05	1.01E-04
12	Infant nap pads where contact and mediated exposure is likely for children	Adult	4.39E-04	1.70E-07	1.13E-05
		3–5 yrs	7.29E-04	1.06E-05	3.36E-05

#	Scenario	Receptor	Dermal	Ingestion	Inhalation
13	Foam carpet backing, carpeting, or hard surface flooring where contact and mediated exposure is likely for children and adults	Adult	4.12E-03	8.52E-05	2.79E-03
		3–5 yrs	6.62E-03	1.23E-03	8.25E-03
14/ 15	Building insulation where mediated exposure is likely for children and adults	Adult	2.31E-07	4.27E-05	1.39E-03
		3–5 yrs	3.72E-07	6.12E-04	4.12E-03
16	Coatings, adhesives, sealants, and elastomers for building materials where mediated exposure is likely for children and adults	Adult	2.31E-07	2.13E-05	6.96E-04
		3–5 yrs	3.72E-07	3.05E-04	2.06E-03
17	Other task-based renovation, repair, or refurbishment of an existing exposure scenario	Adult	1.19E-08	7.02E-07	3.58E-05
		3–5 yrs	1.91E-08	1.01E-05	1.06E-04
18	Large stationary wooden (and other materials not covered elsewhere) structures where mediated exposure is likely for children and adults	Adult	6.51E-08	3.18E-06	1.96E-04
		3–5 yrs	1.05E-07	4.56E-05	5.80E-04
Aggregate across all scenarios		Adult	8.59E-03	1.58E-04	5.39E-03
		3–5 yrs	1.40E-02	2.35E-03	1.60E-02

In addition to the adjustment factors noted above, we also incorporated two scenario probabilities (see Table 9). The first is the probability that the consumer product is present in a household, and the second reflects the probability that the product contains an OFR in the same subclass (i.e., in this case, the probability it contains a PHOP). Because these probabilities were based on professional judgment, we used only high-medium-low (corresponding to 0.9, 0.5, and 0.1, respectively) for the first probability and higher-lower (corresponding to 0.5 and 0.1, respectively) for the second probability. Given there are 14 subclasses of OFRs and also FRs that are not OFRs, the "higher" for the second probability was set to 0.5 to reflect the diversity of potential flame retardant formulations in consumer products. The product of the two probabilities then gives the probability of the consumer product being in a household and containing a PHOP.

Table 9. Probability of Household Occurrence and Probability That a Product Contains an OFR in the Same Subclass, Based on Professional Judgment.

#	Scenario	Representative Product [a]	Probability of Household Occurrence	Probability That It Contains PHOP
1	Handheld electronic casings (or appliances) where contact and mediated exposure is likely for children and adults	Tablet	High	Lower
2	Non-handheld electronics and appliances where mediated exposure is likely for children and adults	Television	High	Lower

#	Scenario	Representative Product [a]	Probability of Household Occurrence	Probability That It Contains PHOP
3	Small hand-held hard and soft plastic items (including foam) where contact and mediated exposure is likely for children and adults	Toy block	High	Higher
4	Small hand-held hard and soft plastic items (including foam) where incidental ingestion/swallowing exposure is likely for children	Toy food	Low	Higher
5	Small hand-held rubber items where contact and mediated exposure is likely for children and adults	Rubber ball	Low	Lower
6	Large stationary hard and soft plastic items (including foam and rubber) where mediated exposure is likely for children and adults	Indoor playhouse	Low	Lower
7	Wearable plastic, rubber, or foam clothing and clothing accessories where contact and mediated exposure is likely for children and adults	Plastic raincoat	Medium	Lower
8C	Textiles where contact and mediated exposure is likely for children and adults	Clothing	High	Higher
8F	Textiles where contact and mediated exposure is likely for children and adults	Car seat	Medium	Higher
9	Textiles where mediated exposure is likely for children and adults	Curtains	High	Higher
10	Portable and stationary furnishings where contact and mediated exposure is likely for children and adults	Sofa chair	High	Higher
11	Mattresses and mattress toppers where contact and mediated exposure is likely for children and adults	Adult and children's mattress	High	Higher
12	Infant nap pads where contact and mediated exposure is likely for children	Nap mat	Low	Higher
13	Foam carpet backing, carpeting, or hard surface flooring where contact and mediated exposure is likely for children and adults	Flooring	High	Higher
14/15	Prefabricated and custom site-applied building insulation where mediated exposure is likely for children and adults	Insulation	High	Higher
16	Coatings, adhesives, sealants, and elastomers for building materials where mediated exposure is likely for children and adults	Coating	High	Lower
17	Other task-based renovation, repair, or refurbishment of an existing exposure scenario	Furniture chest	Low	Lower
18	Large stationary wooden (and other materials not covered elsewhere) structures where mediated exposure is likely for children and adults	Large bookcase	Medium	Lower

Using the doses adjusted for mouthing and direct dermal exposures, we calculated the aggregate consumer exposure by pathway for 100,000 simulated people (for each age group), with each person having randomly selected combinations of scenarios as determined by the two probabilities. Table 10 presents the mean (a) ingestion, (b) inhalation, (c) dermal, and (d) total exposures for adults and 3–5 year olds from the 100,000 runs for TDCIPP and compares them to the unadjusted aggregate consumer exposure estimated using the first method (the maximum possible dose) and the aggregate consumer exposure after mouthing and direct dermal contact adjustments. Table 10 also shows the aggregate doses if a fraction absorbed/bioaccessibility value <1 was used for the inhalation and ingestion pathways. CEM applies an absorption fraction for dermal but assumes that for the inhalation and ingestion pathways, all of the chemical enters the body. For TDCIPP, we assumed an inhalation fraction absorbed value of 0.5 based on professional judgment, and from Fang and Stapleton (2014), we used an ingestion fraction absorbed value of 0.8. Inclusion of the mouthing and direct dermal adjustment factors, the probability of the consumer product being in a household and containing a PHOP, and ingestion and inhalation absorption fractions resulted in doses that were 81%–99.8% lower than the unadjusted values. The combination of these adjustments brings aggregate consumer exposures closer to what would be expected compared to aggregate exposures from reverse dosimetry from biomonitoring data and toxicokinetics. For comparison purposes, the doses in Table 10 for TDCIPP are shown in Figure 1 along with the corresponding doses for TCEP and TCIPP.

Table 10. Comparison of Aggregate Consumer Exposures after Incorporation of Several Adjustments for Adults and 3–5 Year Olds for TCEP, TCIPP, and TDCIPP.

Age Group	Unadjusted Dose (mg/kg/day)			Adjusted for Mouthing/Dermal (mg/kg/day)			Adjusted for Mouthing/Dermal and Probabilities (mg/kg/day)			Adjusted for Mouthing/Dermal, Probabilities, and Absorption Fractions (mg/kg/day)		
	Dermal	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	Ingestion	Inhalation
TCEP												
Adult	6.42E-01	4.59E-03	4.23E-01	7.01E-02	4.59E-03	4.23E-01	3.13E-02	1.83E-03	1.68E-01	3.13E-02	1.46E-03	8.39E-02
3–5 yrs	1.06E+00	4.68E-01	1.25E+00	1.13E-01	6.61E-02	1.25E+00	5.03E-02	2.62E-02	4.97E-01	5.03E-02	2.10E-02	2.49E-01
TCIPP												
Adult	4.98E-01	2.15E-03	1.58E-01	3.93E-02	2.15E-03	1.58E-01	1.74E-02	8.53E-04	6.26E-02	1.74E-02	6.83E-04	3.13E-02
3–5 yrs	8.26E-01	4.33E-01	4.68E-01	6.32E-02	3.10E-02	4.68E-01	2.80E-02	1.23E-02	1.85E-01	2.80E-02	9.83E-03	9.27E-02
TDCIPP												
Adult	2.88E-01	1.58E-04	5.39E-03	8.59E-03	1.58E-04	5.39E-03	3.34E-03	6.05E-05	2.01E-03	3.34E-03	4.84E-05	1.01E-03
3–5 yrs	4.78E-01	4.04E-01	1.60E-02	1.40E-02	2.35E-03	1.60E-02	5.44E-03	8.90E-04	5.97E-03	5.44E-03	7.12E-04	2.98E-03

[a]Each aggregate dose builds off of the previous dose. For example, the "Adjusted for Mouthing/Dermal, Probabilities, and Absorption Fractions" doses apply the absorption fractions to the mean doses calculated from the 100,000 simulated runs. The simulated runs used the individual scenario doses with adjustment factors for mouthing and direct dermal contact.

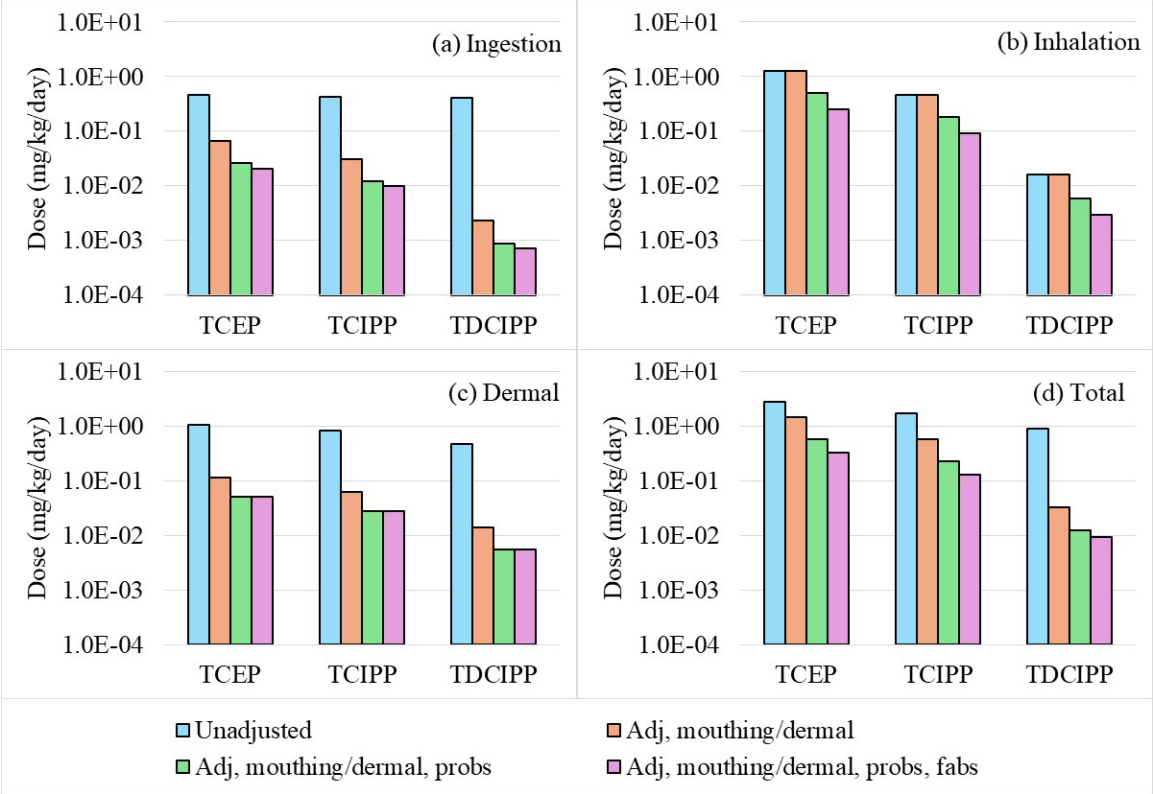

Figure 1. Mean Aggregate Consumer Exposures for (a) Ingestion, (b) Inhalation, (c) Dermal, and (d) Total Pathways for 3 –5 Year Olds.

4.1.4. Aggregate Total Exposures

Aggregate total exposures can be estimated by combining aggregate consumer exposures with background exposures from other sources. Background exposures from non-consumer products were estimated using monitoring data from recent review papers that contained a large number of samples for TCEP, TCIPP, and TDCIPP. Priority was given for data from the United States or other similar developed nations, reflecting similar chemical use consumption patterns. Relevant pathways include dietary ingestion, drinking water ingestion, soil ingestion, and inhalation of outdoor air.

Table 11 presents central tendency estimates of dietary, drinking water, soil, and ambient air concentrations along with the aggregate background total for TCEP, TCIPP, and TDCIPP for adults and 3–5 year olds. Central tendency data were extracted in the following priority order: geometric mean, median, arithmetic mean. Aggregate consumer exposures (adjusted with the adjustment factors and probabilities discussed in the previous section and including absorption fractions for the ingestion and inhalation pathways) and the resulting aggregate total exposures are also presented. In all instances, aggregate consumer exposures were always orders of magnitude higher than aggregate background exposures; this was true for all age groups for these three chemicals (data not shown), and therefore, the aggregate total exposure was always driven by the aggregate

consumer exposure. In addition to Table 11, these values are also plotted in Section 4.5, Comparison of Estimated Exposures from Different Approaches.

Table 11 Aggregate Background, Aggregate Consumer, and Aggregate Total Exposures (mg/kg/day) for Adults and 3 –5 Year Olds for TCEP, TCIPP, and TDCIPP.

Age Group	Dietary	Drinking Water	Soil	Ambient Air	Aggregate Background	Aggregate Consumer [a]	Aggregate Total
TCEP							
Adult	3.05E-06	3.94E-07	4.57E-09	5.21E-08	3.50E-06	1.17E-01	1.17E-01
3–5 yrs	1.04E-05	4.09E-07	5.80E-08	1.39E-07	1.10E-05	3.20E-01	3.20E-01
TCIPP							
Adult	4.25E-06	1.61E-06	6.76E-09	7.70E-08	5.94E-06	4.94E-02	4.94E-01
3–5 yrs	1.51E-05	1.67E-06	8.56E-08	2.05E-07	1.70E-05	1.31E-01	1.31E-01
TDCIPP							
Adult	3.29E-06	3.27E-08	1.99E-09	2.62E-08	3.36E-06	4.39E-03	4.40E-03
3–5 yrs	1.02E-05	3.39E-08	2.53E-08	6.99E-08	1.04E-05	9.14E-03	9.15E-03

[a] Aggregate consumer exposures presented are the "Adjusted for Mouthing/Dermal, Probabilities, and Absorption Fractions" doses in Table 10.

4.1.5. Uncertainties and Limitations

Product uses for each chemical were identified using five data sources: HPCDS, CDR, literature sources, patent data, and UL's Prospector database. While some sources provided the exact consumer product, other s reported only broad categories. For example, sources reported "television" versus "electrical and electronic products ."

When broad categories were reported, we mapped the product to all potentially applicable scenarios. In this example, "electrical and electronic products" was mapped to both #01 (*Handheld electronic casings [or appliances] where contact and mediated exposure is likely for children and adults*) and #02 (*Non-handheld electronics and appliances where mediated exposure is likely for children and adults*), which may lead to an overinclusion of scenarios. Similarly, our review of patent data identified primarily material uses, which we extrapolated to potential product uses based on material-product relationships; this likely also led to an overinclusion of scenarios.

Our workflow addressed the uncertainty in uses by assuming a conservative approach and including all potentially relevant uses. However, this list can be adjusted in the following ways: (i) we could use additional product formulation data should results become available and (ii) our review of patent data was primarily at the title-abstract level, with full-text review performed only for chemicals with no identified uses after title-abstract screening. Prioritization of patents (e.g., leveraging the Cooperative Patent

Classification system as was done in a recent white paper on PFAS [RTI, 2023]), followed by full-text review would provide a potentially more relevant list of uses.

Given the large number of chemical-product combinations, we developed 18 broad exposure scenarios to model, and for each scenario, we selected a representative product to base our input values for article surface area and duration of contact. This workflow allowed us to obtain screening-level estimates of exposure for a large number of products. For example, tablets, cell phones, and heat sealers would all fall under scenario "#01, *Handheld electronic casings (or appliances) where contact and mediated exposure is likely for children and adults*," and share the same estimated doses. However, there is (i) product-to-product variability for many of the input parameters, including weight fraction, surface area, and duration of article contact, that our use of a representative product does not capture and (ii) uncertainty in the input values used for our CEM runs due to the limited data available in the literature for the various input parameters.

In the absence of available information, we used professional judgment or CEM defaults/estimators as inputs. This resulted in lower to medium confidence in the exposure estimates depending on the scenario. A sensitivity analysis to vary key parameters would provide a range of doses and, therefore, a characterization of variance and can be conducted for future assessments.

A pathway-specific comparison of results between Approach 1 and Approach 2 also informed initial adjustments for Approach 1 and how a follow-up sensitivity analysis could be conducted to better characterize within-scenario variability, especially for pathways that potentially lead to higher exposures. An adjustment factor of at least 800 was used for mouthing scenarios specific to children, with the adjustment factor dependent on the chemical, and an adjustment factor of 250 was used for direct dermal scenarios.

For this report, we did not perform scenario-specific sensitivity analyses. Instead, we conducted general sensitivity analyses with TDCIPP as the example chemical for weight fraction, surface area, and duration to determine whether doses could be scaled for these parameters. Using one scenario with contact and mediated exposure (#03, *Small hand-held hard and soft plastic items [including foam] where contact and mediated exposure is likely for children and adults*) and one scenario for mediated exposure only (#09, *Textiles where mediated exposure is likely for children and adults)*, our analyses showed that in general, for scenarios with only mediated exposures, doses for all pathways can be scaled linearly on a 1:1 basis with weight fraction and surface area for the range of values tested (we did not perform a sensitivity analysis for duration of article contact because this is always set as 0 since there are no contact exposures). For scenarios with both

contact and mediated exposures, doses can be scaled linearly on 1:1 basis with weight fraction for all pathways except ingestion for age groups with mouthing behavior. The results for surface area and duration of article contact varied depending on pathway (see Figure 2).

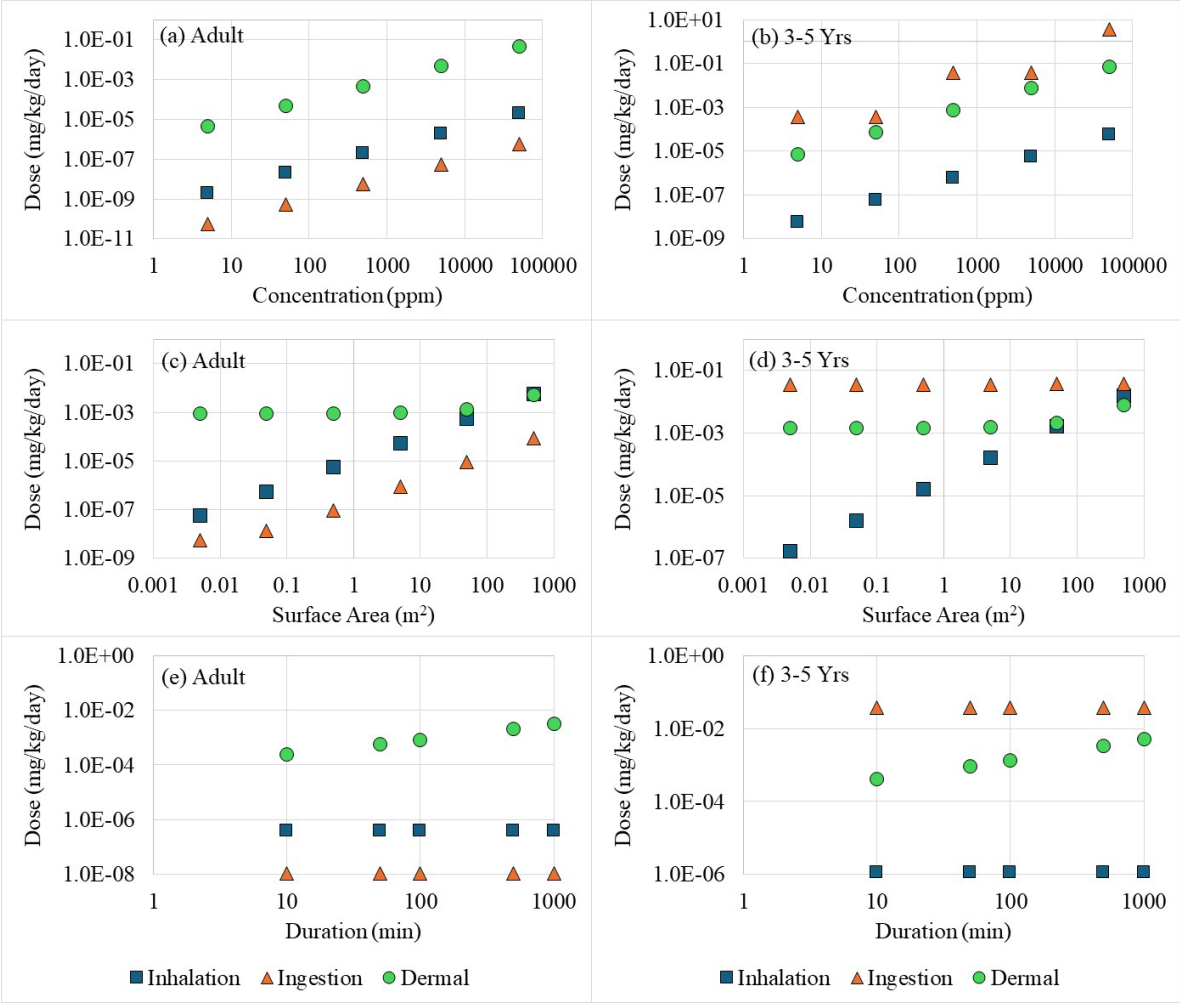

Figure 2. Effect of Initial Concentration (panels a, b), Surface Area (panels c, d), and Duration of Article Contact (panels e, f) on Doses Modeled for Adults and 3 –5 Year Olds with Contact and Mediated Exposure to Small Hand - held Hard and Soft Plastic Items

To compare exposures estimated using the four different approaches, we determined an aggregate consumer exposure value across all scenarios for each chemical. As part of this determination, we applied professional judgment to estimate (i) observed differences in the reported magnitude of results between Approach 1 and Approach 2, (ii) the probability of the consumer product occurring in a household, and (iii) the probability of the product containing an OFR in the same subclass (i.e., in this case, the probability it contains a PHOP). Because we were not able to validate the two probabilities with external data, such as consumer surveys or product testing data, there is lower confidence in the probability values used. The uncertainty in these probabilities is

reflected in the use of only a high-medium-low or higher-lower scale as any finer resolution may implicitly suggest higher confidence in the values. The second probability was also purposefully designed to be for an OFR in the same subclass, rather than a specific OFR, due to the absence of available data (i.e., the probability values are already highly uncertain, and therefore, we should not create separate probability values by chemical). While a source for the first probability was not identified in this report, these values can likely be derived by economists and, once available, would help refine our aggregate consumer estimates. In addition to the uncertainties in the probability values, we also note that the higher aggregate consumer exposures are likely driven by a small number of individual scenarios with higher exposures. Excluding or refining these individual scenarios and re-running the aggregate analysis may provide insight in how the use of the probabilities reduces total exposure.

Absorption fractions for inhalation and ingestion were also applied to the aggregate estimates. In the absence of chemical-specific absorption fractions, we applied the same inhalation absorption fraction of 0.5, which was selected based on professional judgment, to all chemicals. However, separate absorption fractions should be applied for the gaseous and particulate fractions, wherein the latter is chemical dependent (i.e., if the chemical is particle bound). The ingestion absorption fraction was based on a relationship between bioaccessibility and the octanol-water partition coefficient using empirical data from Fang and Stapleton (2014) for several flame retardants. However, only three of the PHOPs were included in the chemicals measured. Future experimental data for additional chemicals would help refine the adjusted aggregate consumer exposures.

4.2. Exposures Estimated from Empirical Measurements (Approach 2)

Exposures were estimated from measured (i) migration rates from products into saliva, (ii) personal dermal loading (wipe) data, (iii) personal air concentrations, and (iv) product emission data and/or mass transfer parameters. In general, the number of data sets available was limited, and therefore, pooled central tendency values and corresponding doses calculated may not be representative of the full range of data available in the literature. Product emission data were also used for the spray polyurethane foam insulation scenario, in which we briefly summarize studies that reported modeled and/or measured exposures during or after spray foam application.

4.2.1. Migration Rates from Products into Saliva

There were no studies identified that reported PHOP migration rates from product to saliva. However, the CEM User Guide Appendix (U.S. EPA, 2023c), which compiles measured migration rate data from over 20 studies for primarily phthalates and plastic

materials, lists four studies (Ghanem, 2015a; Ghanem, 2015b; EC, 2008; Babich, 2006) with data for TCIPP and TDCIPP migrating into artificial saliva and potential surrogates for saliva (e.g., artificial sweat, distilled water, citric acid) under various experimental conditions (e.g., unaged, UV aged, thermally aged at 25°C). Note that the CEM tool itself does not estimate migration rates from products into saliva, offering instead default migration rates for four chemical concentration ranges.

Since experimental data were available for only two chemicals, we used the regression-based model from Aurisano et al. (2022) to estimate migration rates for all PHOPs and assessed how close the estimated values of TCIPP and TDCIPP were to the measured data from the four studies. Briefly, Aurisano et al. (2022) developed a regression model using available data in the literature from 60 chemicals, including polybrominated diphenyl ethers (an OFR subclass), and from 5 materials. The inputs to the regression model included initial chemical concentration, octanol-water partition coefficient, and diffusion coefficient, the final one depending on the material type. While Aurisano et al. (2022) also presented a mechanistic material-saliva model adapted from a previously developed mechanistic model for chemicals in food packaging, we chose to use their regression model because the focus of Approach 2 is to use empirical measurements to calculate dose in 1–2 steps. Here, the regression-based model is used to extrapolate empirical measurements to a different set of conditions before calculating dose.

4.2.1.1. Comparison of Measured and Modeled Migration Rates

Table 12 shows the study-reported and modeled migration rates as estimated by the Aurisano et al. (2022) regression-based model for polyurethane-based materials. When a study evaluated migration into more than one artificial biological fluid, only saliva (if available) measured rates are presented in Table 12. The two studies by Ghanem (2015a and 2015b) also reported data for thermally aged foam at 60°C and 90°C that are not included in the CEM User Guide Appendix but are included below. Because the model inputs are only initial chemical concentration and material type (in addition to physicochemical properties), the same modeled migration rate is given for a product regardless of the experimental conditions. For example, the unaged and UV-aged CM Ether foam in Ghanem (2015a) had measured migration rates of 66.1 and 23.6 μg/cm^2/hr, respectively, but a modeled migration rate of 68.5 μg/cm^2/hr for both.

With the exception of one data point, the modeled rates were the same as (defined as within 5%) or higher than the measured rates, indicating that doses calculated from the modeled rates would be conservative. Specifically, when only artificial saliva is considered, the modeled rates were on average higher than the measured rates by a factor of 3. In general, measured migration rates for TCIPP were higher than TDCIPP, even after taking into account initial concentration.

Table 12 Comparison of Measured and Modeled Migration Rates.

Study [a]	Chemical	Product	Biological Fluid	Migration Rate (µg/cm²/hr)		
				Measured	Modeled	Modeled /Measured
EC (2008)	TCIPP	Polyurethane foam, 10% (no pressure applied)	Artificial sweat	2.78	79.6	28.6
EC (2008)	TCIPP	Polyurethane foam, 10% (pressure applied)	Artificial sweat	4.6	79.6	17.3
EC (2008)	TCIPP	Polyurethane foam, 10% (maximum possible)	Artificial sweat	130	79.6	0.61
Ghanem (2015a)	TCIPP	Unaged foam (CMHR), 5.2%	Artificial saliva	45.1	43.5	0.96
Ghanem (2015a)	TCIPP	UV-aged foam (CMHR), 5.2%	Artificial saliva	9.2	43.5	4.73
Ghanem (2015a)	TCIPP	Thermally aged at 25°C foam (CMHR), 5.2%	Artificial saliva	38.1	43.5	1.14
Ghanem (2015a)	TCIPP	Thermally aged at 60°C foam (CMHR), 5.2%	Artificial saliva	18.5	43.5	2.35
Ghanem (2015a)	TCIPP	Thermally aged at 90°C foam (CMHR), 5.2%	Artificial saliva	12.7	43.5	3.43
Ghanem (2015a)	TCIPP	Unaged foam (CM Ether), 8.5%	Artificial saliva	66.1	68.5	1.04
Ghanem (2015a)	TCIPP	UV-aged foam (CM Ether), 8.5%	Artificial saliva	23.6	68.5	2.90
Ghanem (2015a)	TCIPP	Thermally aged at 25°C foam (CM Ether), 8.5%	Artificial saliva	58.6	68.5	1.17
Ghanem (2015a)	TCIPP	Thermally aged at 60°C foam (CM Ether), 8.5%	Artificial saliva	41.6	68.5	1.65
Ghanem (2015a)	TCIPP	Thermally aged at 90°C foam (CM Ether), 8.5%	Artificial saliva	48.2	68.5	1.42
Babich (2006)	TDCIPP	Upholstery furniture foam, 5.1%	Artificial sweat	0.025	22.5	900
Ghanem (2015b)	TDCIPP	Unaged foam, 6.5%	Artificial saliva	2.2	28.1	12.8
Ghanem (2015b)	TDCIPP	UV-aged foam, 6.5%	Artificial saliva	10.7	28.1	2.63
Ghanem (2015b)	TDCIPP	Thermally aged at 25°C foam, 6.5%	Artificial saliva	3.0	28.1	9.37
Ghanem (2015b)	TDCIPP	Thermally aged at 60°C foam, 6.5%	Artificial saliva	7.9	28.1	3.56
Ghanem (2015b)	TDCIPP	Thermally aged at 90°C foam, 6.5%	Artificial saliva	12.1	28.1	2.32

[a]Migration rates for Ghanem (2015a, 2015b) are reported in the CEM User Guide Appendix (U.S. EPA, 2023c). The original papers reported the measured percentage of flame retardant transferred to filter paper from foam samples, determined by the head-over-heels test simulating oral exposure.

4.2.1.2. Estimation of Mouthing Exposure

Daily mouthing exposure for all PHOPs with product use data (i.e., 26 PHOPs) was calculated for the <1 year old, 1–2 year old, and 3–5 year old age groups using migration rates into saliva estimated from the Aurisano et al. (2022) regression-based model. Two types of materials, polypropylene homopolymer and polyurethane-based materials, were run to reflect plastic and foam products. Consistent with the initial concentrations used in Approach 1, we also used an initial concentration of 1,000 ppm (equal to 0.1% or 1 mg/g).

Estimated migration rates for polyurethane-based materials were approximately one order of magnitude higher than for polypropylene homopolymer, ranging from 0.050 to 2.4 μg/cm^2/hr for the former and 0.0064 to 0.30 μg/cm^2/hr for the latter across chemicals. Because the comparison of modeled-to-measured migration rates (Table 12) showed that modeled rates were higher than the measured rates, we adjusted the modeled rates of all 26 PHOPs by a factor of 3. In the absence of measured data for polypropylene materials, the adjustment factor of 3 was used for both polypropylene and polyurethane-based materials. Using daily mouthing durations of 70.1, 47.4, and 37 min for the <1 year old, 1–2 year old, and 3–5 year old age groups (Greene, 2002), respectively, from a CPSC observational mouthing study and assuming a surface area mouthed of 10 cm^2, mouthing exposures were calculated and presented in Table 13 for polyurethane and polypropylene.

Table 13. Comparison of Doses for Children Mouthing Polyurethane and Polypropylene Materials.

CASRN	Chemical	Dose – Polyurethane (mg/kg/day)			Dose – Polypropylene (mg/kg/day)		
		<1 yr	1–2 yrs	3–5 yrs	<1 yr	1–2 yrs	3–5 yrs
78-43-3	Tris(2,3-dichloropropyl)phosphate	2.94E-04	1.23E-04	6.51E-05	3.70E-05	1.55E-05	8.20E-06
115-96-8	Tris(2-chloroethyl) phosphate	8.45E-04	3.54E-04	1.87E-04	1.06E-04	4.45E-05	2.35E-05
115-98-0	Bis(2-chloroethyl) vinylphosphonate	1.20E-03	5.00E-04	2.65E-04	1.51E-04	6.30E-05	3.33E-05
126-72-7	Tris(2,3-dibromopropyl) phosphate	1.15E-04	4.80E-05	2.54E-05	1.45E-05	6.05E-06	3.20E-06
140-08-9	Tris(2-chloroethyl) phosphite	9.51E-04	3.98E-04	2.10E-04	1.20E-04	5.01E-05	2.65E-05
1067-98-7	Tris(3-chloropropyl)phosphate	5.81E-04	2.43E-04	1.29E-04	7.32E-05	3.06E-05	1.62E-05
2788-11-6	Tris(2,4-dibromophenyl) phosphate	5.21E-05	2.18E-05	1.15E-05	6.57E-06	2.75E-06	1.45E-06
4351-70-6	Phosphonic acid, P-[1-[[(2-chloroethoxy)(2-chloroethyl)phosphinyl]oxy]ethyl]-, 1-[bis(2-chloroethoxy)phosphinyl]ethyl 2-chloroethyl ester	1.85E-04	7.73E-05	4.09E-05	2.33E-05	9.74E-06	5.15E-06
5324-12-9	2,3-Dibromopropylphosphate	9.01E-04	3.77E-04	1.99E-04	1.14E-04	4.75E-05	2.51E-05
5412-25-9	Bis(2,3-dibromopropyl) hydrogen phosphate	2.58E-04	1.08E-04	5.70E-05	3.25E-05	1.36E-05	7.18E-06
6145-73-9	Tris(2-chloropropyl) phosphate	5.39E-04	2.25E-04	1.19E-04	6.78E-05	2.84E-05	1.50E-05
6294-34-4	Bis(2-chloroethyl) 2-chloroethylphosphonate	8.94E-04	3.74E-04	1.98E-04	1.13E-04	4.72E-05	2.49E-05
6749-73-1	Tris(1,3-dichloropropan-2-yl) phosphite	3.29E-04	1.38E-04	7.29E-05	4.15E-05	1.74E-05	9.18E-06
7046-64-2	Tris(2,4,6-tribromophenyl) phosphate	2.52E-05	1.05E-05	5.57E-06	3.17E-06	1.33E-06	7.01E-07
13674-84-5	Tris(2-chloroisopropyl)phosphate	5.65E-04	2.36E-04	1.25E-04	7.11E-05	2.98E-05	1.57E-05
76649-15-5	(2-Chloro-1-methylethyl) bis(2-chloropropyl) phosphate	5.43E-04	2.27E-04	1.20E-04	6.84E-05	2.86E-05	1.51E-05
13674-87-8	Tris(1,3-dichloro-2-propyl) phosphate	2.99E-04	1.25E-04	6.61E-05	3.76E-05	1.57E-05	8.33E-06
19186-97-1	Tris(tribromoneopentyl)phosphate	3.42E-05	1.43E-05	7.56E-06	4.30E-06	1.80E-06	9.52E-07

CASRN	Chemical	Dose – Polyurethane (mg/kg/day)			Dose – Polypropylene (mg/kg/day)		
		<1 yr	1–2 yrs	3–5 yrs	<1 yr	1–2 yrs	3–5 yrs
27568-90-7	Ethanol, 2-bromo-, phosphate (3:1)	3.80E-04	1.59E-04	8.42E-05	4.79E-05	2.00E-05	1.06E-05
33125-86-9	Phosphoric acid, 1,2-ethanediyl tetrakis(2-chloroethyl) ester	3.04E-04	1.27E-04	6.73E-05	3.83E-05	1.60E-05	8.48E-06
35656-01-0	Tris(2-bromo-4-methylphenyl) phosphate	1.22E-04	5.10E-05	2.69E-05	1.53E-05	6.42E-06	3.39E-06
38051-10-4	Phosphoric acid, 2,2-bis(chloromethyl)-1,3-propanediyl tetrakis(2-chloroethyl) ester	1.85E-04	7.75E-05	4.10E-05	2.33E-05	9.76E-06	5.16E-06
66108-37-0	2,2-Bis(bromomethyl)-3-chloropropyl bis[2-chloro-1-(chloromethyl)ethyl] phosphate	1.68E-04	7.03E-05	3.72E-05	2.12E-05	8.85E-06	4.68E-06
76025-08-6	Bis(2-chloro-1-methylethyl) 2-chloropropyl phosphate	5.48E-04	2.29E-04	1.21E-04	6.90E-05	2.89E-05	1.53E-05
84282-27-9	2-Bromoethyl 5-bromopentyl 2-chloroethyl phosphate	3.50E-04	1.46E-04	7.74E-05	4.40E-05	1.84E-05	9.75E-06
40120-74-9	Tris(1,3-dichloropropyl)phosphate	2.93E-04	1.22E-04	6.48E-05	3.69E-05	1.54E-05	8.16E-06

4.2.2. Personal Dermal Loading (Wipe Data)

Thirty-one data sets from nine studies were identified with reported median concentrations of TCEP (n = 10), TCIPP (n = 5), TDCIPP (n = 9), and the sum of trischloropropylphosphate isomers (∑TCPP; n = 7) in handwipes. All data sets were converted to units of mass per surface area sampled using the study-reported sampling area (e.g., palm, back of hand) and recommended age-specific body weights and surface area-to-body weight ratios (U.S. EPA, 2011). Each data set was mapped to the closest age group, and a pooled central tendency concentration was calculated for each chemical-age group combination using study-reported medians and sample size. Note that the method of calculating a pooled central tendency value for handwipe data differed from the method used for indoor dust (Approach 3); the latter would have excluded one-third of the data sets.

Average daily dose from direct dermal exposure was calculated using two methods: (i) the fraction absorbed method and (ii) the permeability coefficient method. Figure 3 presents the range of estimated doses across all age groups by chemical, with age-group specific doses and pooled medians available in Table 14. In general, doses calculated using the fraction absorbed method were within two orders of magnitude for the four chemicals, whereas doses calculated using the permeability coefficient method spanned four orders of magnitude. Consistent with the results found in Liu et al. (2017), higher doses were calculated using the permeability coefficient method compared to the fraction absorbed method for all chemicals.

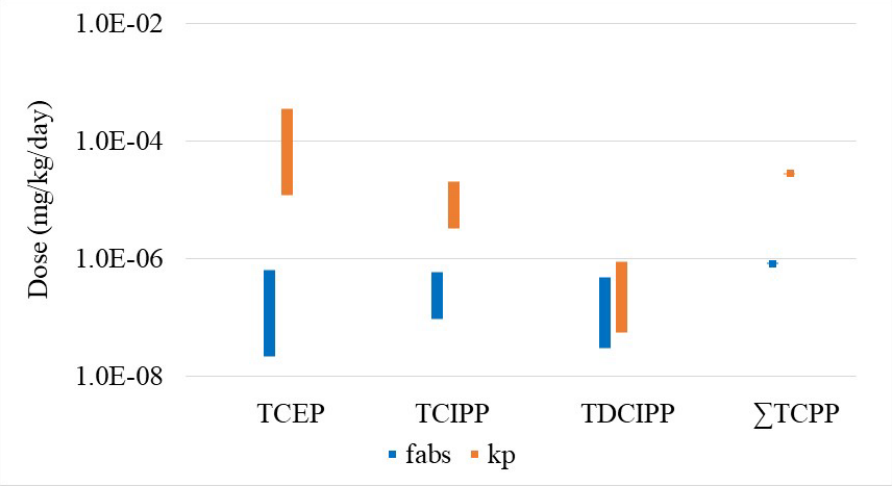

Figure 3. Range of Estimated Direct Dermal Exposures Across Age Groups, by Chemical, Based on Measured Handwipe Data and Using the Fraction Absorbed and Permeability Coefficient Methods.

Table 14. Pooled Medians and Direct Dermal Dose by Age Group and Chemical Using the Fraction Absorbed and Permeability Coefficient Methods.

Chemical	Age Group	Pooled Median (pg/cm ^{2})	Dose (mg/kg/day)	
			Fraction Absorbed	Permeability Coefficient
TCEP	1–2 years	86.3 (n = 1)	6.16E-07	3.46E-04
TCEP	3–5 years	3.42 (n = 1)	2.11E-08	1.19E-05
TCEP	≥21 years	110 (n = 8)	4.18E-07	2.35E-04
TCIPP	1–2 years	15.5 (n = 1)	9.36E-08	3.21E-06
TCIPP	3–5 years	53.6 (n = 2)	2.79E-07	9.57E-06
TCIPP	≥21 years	180 (n = 2)	5.77E-07	1.98E-05
∑TCPP	≥21 years	256 (n = 7)	8.21E-07	2.82E-05
TDCIPP	1–2 years	9.66 (n = 1)	2.96E-08	5.51E-08
TDCIPP	3–5 years	129 (n = 2)	3.41E-07	6.36E-07
TDCIPP	≥21 years	288 (n = 6)	4.66E-07	8.74E-07

4.2.3. Personal Air Concentrations

There were 12 extracted data sets from three studies reporting personal air concentrations for the general population. Across the three studies, concentrations were reported for (i) combined inhalable and respirable fractions, (ii) separate inhalable and respirable fractions, and (iii) respirable fraction only. Due to the limited number of data sets available, we used data from both fractions to calculate a pooled central tendency value for each chemical using study-reported medians and sample size. Note that the method of calculating a pooled central tendency value for personal air concentrations differed from the method used for indoor dust (Approach 3) due to the limited number of data sets available.

Figure 4 presents the estimated inhalation exposure by age group and chemical corresponding to pooled median concentrations of 4.9, 140, 3.9, and 28 ng/m^3 for TCEP,

TCIPP, TDCIPP, and ∑TCPP, respectively. TCEP and TDCIPP doses ranged from 3.6×10^{-7} to 1.7×10^{-6} mg/kg/day, whereas doses for TCIPP and ∑TCPP ranged from 2.6×10^{-6} to 5.0×10^{-5} mg/kg/day.

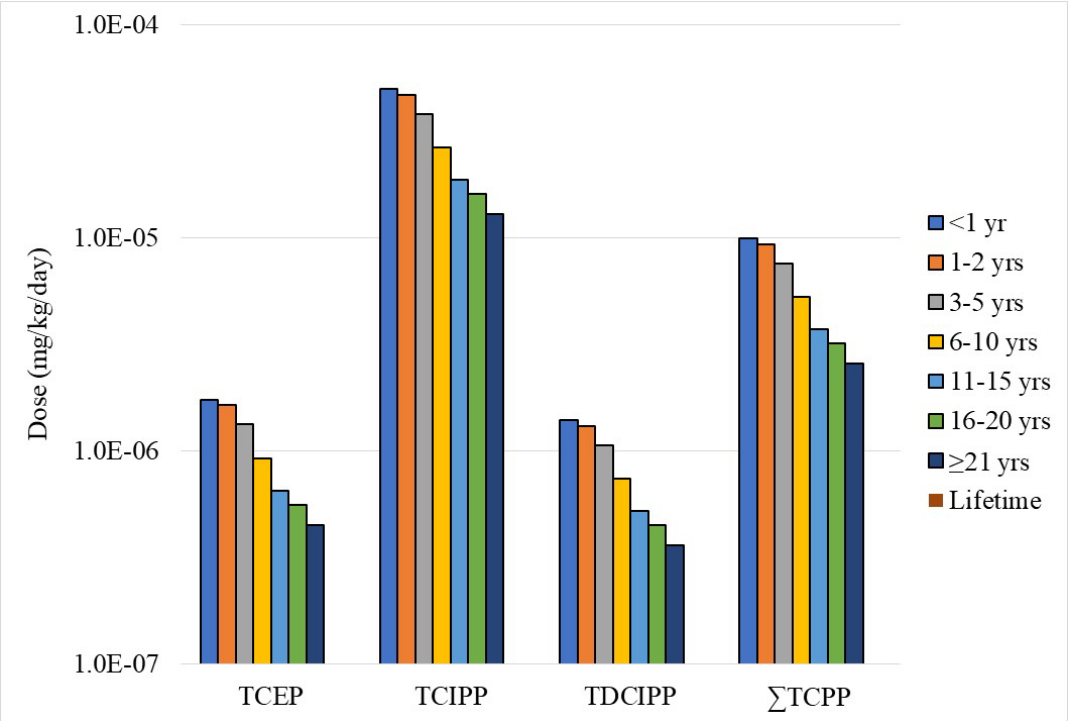

Figure 4. Estimated Inhalation Exposure by Chemical and Age Group Based on Personal Air Monitoring Data.

4.2.4. Product Emission Data and/or Mass Transfer Parameters

Product emission data and/or mass transfer parameters from seven studies were extracted for six products. Three types of data were available: (i) steady-state, area-specific emission rates (or emission factors in µg/m^2/hr); (ii) the initial content of the chemical in the solid material (C_0 in µg/m^3), the material/air partition coefficient (K_{ma}, dimensionless), and the solid-phase diffusion coefficient (D_m in m^2/h); and (iii) the gas-phase concentration in equilibrium with the material (y_0 in µg/m^3). Individual steady-state concentrations were first estimated for each data set before calculating a pooled value for each chemical-product combination.

Figure 5 shows the estimated pooled steady-state air concentrations for a whole house, which ranged from 0.15 to 302 ng/m^3, depending on the product. TCEP had data for only one product, polyisocyanurate (PIR) foam, and TDCIPP had data for two products, polyester curtains and PIR foam. TCIPP was emitted from five products, with mattresses having the lowest emissions, resulting in a steady-state air concentration of 0.15 ng/m^3, and upholstered furniture having the highest emissions with a steady-state air concentration of 302 ng/m^3. All estimated steady-state air concentrations had an

adjustment factor of 4 applied to correct for sink effects (i.e., chemical mass settling in dust or sticking to surfaces). In addition, for PIR insulating boards, we also applied an adjustment factor of 10 to account for the fact that these boards will be behind a wall and are not exposed sources. Corresponding inhalation exposures from product emissions for each chemical-product combination are shown in Figure 6.

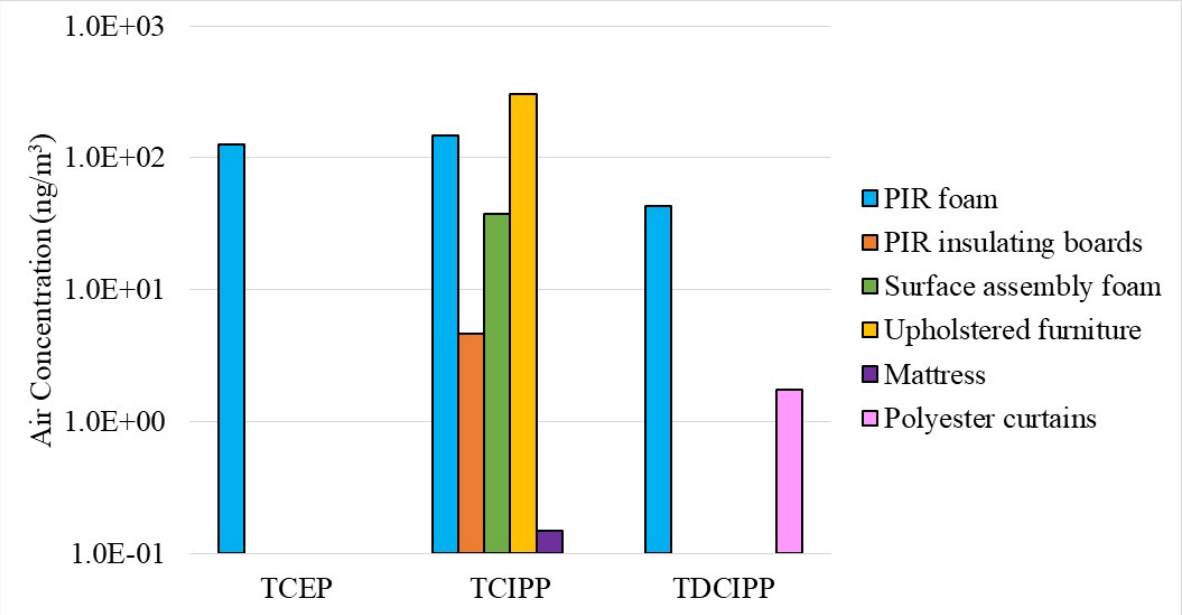

Figure 5. Estimated Steady-state Air Concentrations from Product Emissions Calculated from Product Emission Data and/or Mass Transfer Parameters.

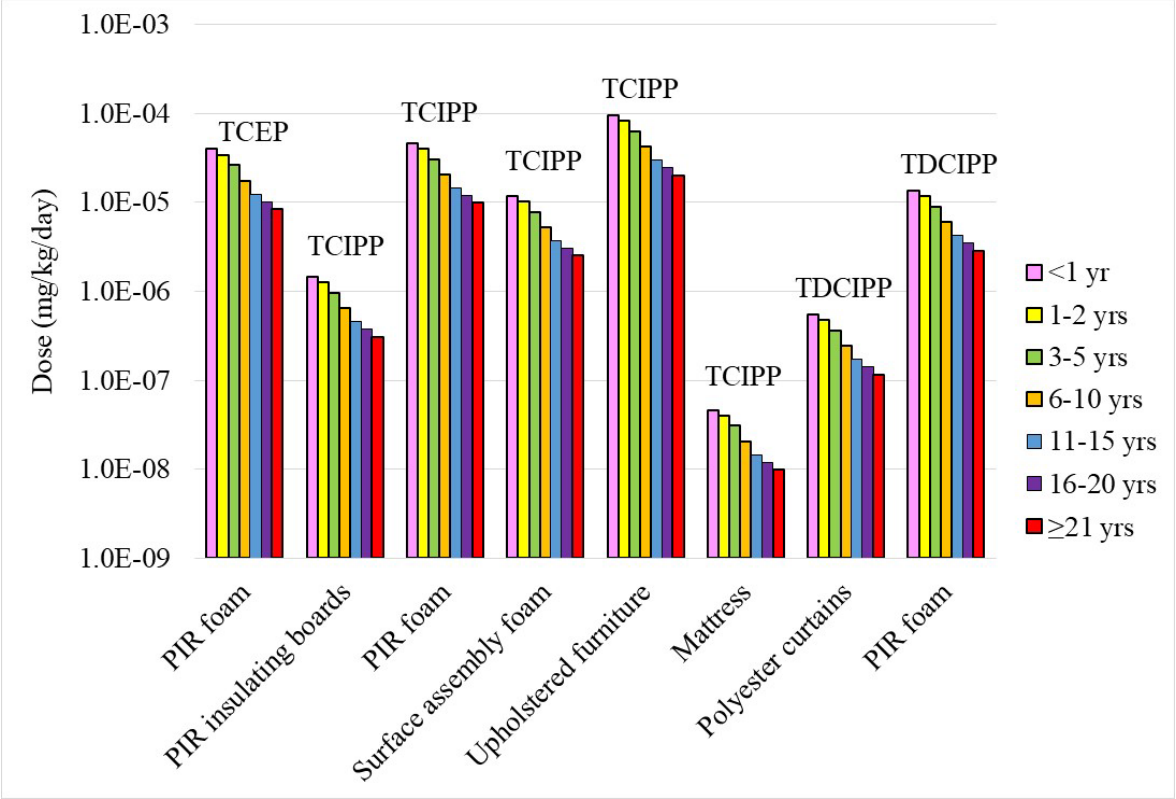

Figure 6. Estimated Inhalation Exposure by Product, Chemical, and Age Group Based on Product Emission Data and/or Mass Transfer Parameters.

4.2.5. Spray Polyurethane Foam Data and/or Parameters

Spray polyurethane foam (SPF) insulation is a special use scenario that has available empirical data. Due to the complex nature of the spray application in typically unoccupied areas of a building (e.g., attic, crawlspace) and subsequent longer-term fate and transport within the building, a single-zone model, such as CEM, would not be the best fit for this product. A multi-zone model, such as EPA's Indoor Environmental Concentrations in Buildings with Conditioned and Unconditioned Zones (IECCU) or NIST's CONTAM, can characterize both shorter-term and longer-term emissions and subsequent fate and transport within a building across multiple rooms or zones.

Spray application exposures are expected to be orders of magnitude higher than typical residential exposures and consumers are advised to leave the home for the entire day of spray-foam application. In a recent study that collected handwipe, personal air, and biomonitoring data for spray foam application workers pre- and post-shift (Estill et al., 2019), the range of personal-breathing zone TCIPP air concentrations for workers over an 8-hour shift ranged from 2.62 to 519 µg/m^3. For comparison, the upper range of personal breathing zone air concentrations and estimated air concentrations from empirical emission ranges were 0.1 to 0.5 µg/m^3 with more typical values reported in nanograms per m^3 (see Section 4.2.3).

While these short-term elevated values were not used in this exposure assessment because they are for worker, rather than consumer, populations, they could be considered in the future for uniquely exposed population groups. These levels are notable as they are one to two orders of magnitude higher than air concentrations used to calculate doses in Table 15.

To evaluate consumer exposures to SPF, a CPSC-sponsored NIST study used microchambers to characterize emissions of TCIPP and other chemicals from SPF. Differences in testing conditions (flow rate, temperature, age of material, and condition of material) were explored. Emissions from TCIPP remained relatively constant over the time period of testing (300 hours). There was also little difference between newer foam (after application) and aged foam (years old) indicating potential for long-term emissions into residences (Poppendieck et al., 2017).

In a follow-up study, a more in-depth comparison of modeled estimates of TCIPP and measured reports of TCIPP in NIST's Net-Zero house, where SPF was the only possible source of TCIPP in the home, showed good agreement between the two. Both the model and measured data showed higher concentrations in the basement (where the foam is located) compared to the living area. The study also quantified changes in air concentration of TCIPP based on temperature and airflow variability with the building (Poppendieck et al., 2021).

For this PHOP exposure assessment, a range of rounded values based on both measured and modeled TCIPP emissions reported in Poppendieck et al. (2021) were considered for estimating inhalation exposure (Table 15). In basements or unoccupied spaces, a range of 2.5 to 5 µg/m^3 of TCIPP in air was considered, and a value of 3 µg/m^3 was used. In living spaces, a range of 0.75 to 1.5 µg/m^3 was considered, and a value of 1 µg/m^3 was used. For this scenario, we assumed 22 hours per day were spent in the home (2 hours of zero exposure), with 0.5 hours spent in the basement and 21.5 hours spent in the living area. Using these concentrations and time spent in the basement and living area gave an estimated inhalation exposure of 8.77×10^{-5} and 2.60×10^{-4} mg/kg/day for adults and 3-5 year olds, respectively.

For ingestion, specifically dust ingestion, dust concentrations can be estimated when air concentrations are available and steady-state conditions are assumed, as described in Approach 3 (Section 3.4). The use of Approach 3 to estimate dust concentrations is supported by a recent study that conducted field measurements and modeling of TCIPP and other chemicals in indoor air and on indoor surfaces after SPF application (Tian et al., 2018). Tian et al. (2018) quantified deposition of TCIPP attached to particles onto indoor surfaces such as carpet and drywall. The total suspended particle concentration in the

air, the types of indoor surfaces, and the types of flooring (carpet or hard surface) all influenced reported levels of particles deposited to surfaces. Applying Approach 3 for this PHOP assessment, and assuming a combined TCIPP gas-phase and particulate-phase air concentration of 1 µg/m^3 in the living space and 3 µg/m^3 in the basement, results in a concentration of 63 and 189 µg/g in dust and corresponding ingestion exposure of 1.21×10^{-5} and 7.79×10^{-5} mg/kg/day for adults and 3-5 year olds, respectively.

Finally, for dermal exposures, a recent study used hand wipe data to demonstrate transfer of TCIPP to skin after direct contact with one-component SPF, another kind of SPF used to fill gaps in smaller spaces. We calculated dermal doses for all hand wipe data and report the largest values in Table 15. For each age group, there was a factor of 5 difference between highest and lowest reported doses. The dose for adults was 3.29×10^{-7} mg/kg/day and the dose for 3-5 year-olds was 5.34×10^{-7} mg/kg/day (Brandsma et al., 2021).

Table 15. Chronic Average Daily Doses (mg/kg/day) of TCIPP for Spray Polyurethane Foam Scenario Based on Available Empirical and Modeled Data.

Scenario	Receptor	Dermal	Ingestion	Inhalation	Total
Large-scale spray polyurethane foam in unoccupied areas of residence as insulation (ingestion, inhalation) and small-scale application to fill in gaps and cracks (dermal)	Adult	3.29E-07	1.21E-5	8.77E-05	1.00E-04
	3–5 yrs	5.34E-07	7.79E-5	2.60E-04	3.39E-04

4.2.6. Uncertainties and Limitations

In general, doses estimated from empirical measurements were based on limited data; as such, there is uncertainty on whether the data we used represent the full range of data available in the literature.

Migration rates from products into saliva were available for only TCIPP and TDCIPP from two studies, with an additional two studies reporting migration rates into artificial sweat for the same two chemicals. In the absence of data, we used a regression model developed by Aurisano et al. (2022) to estimate migration rates into saliva for all PHOPs and applied an adjustment factor to correct for the difference observed between measured and modeled rates. The authors noted the model was well suited for chemical-material combinations included in the training data set, for which PHOP chemicals were not a part. Despite the potential lack of applicability to PHOPs, we chose to use this regression model as the estimated migration rates were, in general, higher than the measured rates for the four studies with reported TCIPP and TDCIPP data, leading to conservative estimates of exposure. More experimental data for other PHOPs are needed to validate the use of this model or to use directly in the exposure calculations.

To estimate migration rates into saliva for all PHOPs, a required input to the Aurisano model is initial concentration in the product. As previously discussed in Section 4.1.5, there are limited data available in the literature for initial product concentrations, and, when available, values could vary depending on the study. Similar to Approach 1, we used an initial concentration of 1,000 ppm (equal to 0.1% or 1 mg/g), and we confirmed using TCIPP in (polyurethane) foam material that migration rates scaled linearly with initial concentration between 0.1% and 10%, albeit not on a 1:1 basis. Once product concentration data become available, the estimated migration rates and corresponding doses can be adjusted accordingly.

Personal dermal loading (wipe data) were available for TCEP, TCIPP, TDCIPP, and ∑TCPP, but the number of data sets per chemical-age group was generally low. With the exception of the TCEP, ∑TCPP, and TDCIPP adults, the pooled central tendency values for the other chemical-age groups were based on only 1–2 data sets. When calculating doses, we assumed that the hands were the only surface area exposed, leading to a likely underestimation of exposure. In a study that looked at halogenated flame retardants and polychlorinated biphenyls, Cao et al. (2019) showed that when skin wipe samples were taken from four typical skin locations (i.e., forearm, foot, face, and hand), the chemical concentrations in hands accounted for approximately 40%, on average, of total chemical concentrations across the four locations. This suggests that estimated dermal exposures may increase by a factor of 2 to account for dermal surface area on other body parts.

Personal air monitoring data had a similarly limited number of data sets available. As previously mentioned, because of the lack of data, we combined data on inhalable and respirable fractions and used a fraction absorbed value of 0.5 for all chemicals. The inhalable and respirable fractions may need to be treated differently to reflect their different penetration into the lungs, and chemical-specific absorption fractions should be used once the data are available.

Product emission data/mass transfer parameters were available for only a small subset of products, with TCEP and TDCIPP emissions available for only one product. Additional testing with more products and with replicates would provide more data points to help characterize variance. Similar to personal air data, chemical-specific absorption fractions should be used once the data are available. The data sets we focused on for our analysis were for steady-state emissions as characterized by emission versus time plots. Future analyses can consider non-steady-state emissions (e.g., emissions of new products right after removal from packaging) to reflect the variable emissions that would occur for chronic exposures.

For handwipe, personal air, and product emissions data, pooled central tendency values were calculated by averaging the study-report medians (for handwipe and personal air) or study-report point values. There are different choices available for calculating a central tendency value, and choosing a different option (e.g., geometric mean) may result in different values. Exposure factors such as body weight and inhalation rate were set to single values for each age group but could be varied in future analyses to obtain a distribution of exposures.

4.3. Exposures Estimated from Indoor Dust Monitoring Data (Approach 3)

Concentrations of PHOPs in settled dust were available from 30 studies across 6 PHOPs (and also ∑TCPP) for a total of 182 data sets. Data sets that reported (i) dust loadings instead of dust concentration, (ii) only single point values, (iii) two or fewer percentiles, or (iv) percentiles in an inconsistent order (e.g., the reported median was lower than the 25th percentile) were excluded. Each data set was assumed to have a normal distribution and fitted in log space (lognormal) to determine the geometric mean (GM) and geometric standard deviation (GSD).

Based on the indoor environment sampled and the description of potential OFR sources in the vicinity of the sampling site, data sets were grouped into four bins: (i) residential general population, (ii) residential elevated source, (iii) commercial general population, and (iv) commercial elevated source. A pooled GM was then calculated in log space, not regular space, for each bin-chemical combination, with the number of samples as the weighting factor. Two additional bins (vehicles and schools) were initially considered; however, a comparison of the pooled GMs by chemical found that the inclusion of schools in the residential general population bin—and, similarly, the inclusion of vehicles in the commercial general population bin—had only a small impact (20%–30%) compared to the base group and was considered to be within study-to-study variability.

4.3.1. Comparison of Pooled Dust GMs to Mitro et al. (2016)

Table 16 presents the pooled dust GMs by bin, along with the number of data sets used to calculate the pooled GM for six PHOPs and ∑TCPP. Because the data were from a focused search, the pooled GMs may not be representative of the full range of data available in the literature. For comparison, the pooled GMs for TCEP, TCIPP, and TDCIPP calculated by Mitro et al. (2016) are also shown in the table. Mitro et al. (2016) conducted a systematic literature review of indoor dust data from the United States between 2000 and 2015. They noted that their included studies tended to focus on samples collected around research universities and, therefore, may not be nationally representative.

The pooled dust GMs for TCEP, TCIPP, and TDCIPP calculated in this report were lower than the pooled GMs reported by Mitro et al. (2016) by a factor of 4–16. The difference in values is due to the data sets used to calculate the pooled values. Mitro et al. (2016) used only data sets from the United States, whereas our analysis did not have any geographic restrictions. For all three chemicals, Figure 7 shows (i) the histogram of individual GMs used in this report to calculate a pooled GM, (ii) the pooled GMs from Mitro et al. (2016), and (iii) the pooled GM calculated in this report. As seen in the figure, more than half of the data sets used had GMs lower than the pooled GM of Mitro et al. (2016). In addition, for all three chemicals, there were at least two data sets with large sample sizes, *n*, that reported low GMs. For example, TCEP had two data sets that reported GMs of 157 ng/g (n = 341) and 2.3 ng/g (n = 100).

Table 16. Pooled Dust Geometric Means by Bin.

	Residential (ng/g)			Commercial (ng/g)			Total (ng/g)		
Chemical	Gen Pop	Elevated	Combined	Gen Pop	Elevated	Combined	Gen Pop	Elevated	Combined
TCEP	203 (n = 40)	1,121 (n = 2)	207 (n = 42)	1,321 (n = 10)	1,983 (n = 3)	1,358 (n = 13)	249 (n = 50)	1,448 (n = 5)	257 (n = 55)
TCEP (Mitro et al., 2016)	†	†	†	†	†	†	†	†	1,068
TCIPP	241 (n = 36)	1,416 (n = 2)	245 (n = 38)	14,112 (n = 8)	3,297 (n = 3)	12,482 (n = 11)	351 (n = 44)	2,068 (n = 5)	363 (n = 49)
TCIPP (Mitro et al., 2016)	†	†	†	†	†	†	†	†	3,309
TDCIPP	178 (n = 44)	562 (n = 2)	179 (n = 46)	1,217 (n = 10)	1,269 (n = 3)	1,221 (n = 13)	211 (n = 54)	810 (n = 5)	215 (n = 59)
TDCIPP (Mitro et al., 2016)	†	†	2,406	†	†	6,005	†	†	3,181
TDBPP	0.69 (n = 2)	-	0.69 (n = 2)	5.41 (n = 1)	-	5.41 (n = 1)	0.95 (n = 3)	-	0.95 (n = 3)
BDCIPP	1.04 (n = 5)	-	1.04 (n = 5)	84.5 (n = 1)	300 (n = 2)	132 (n = 3)	1.75 (n = 6)	300 (n = 2)	2.40 (n = 8)
V6	11.3 (n = 3)	-	11.3 (n = 3)	83.7 (n = 2)	-	83.7 (n = 2)	27.5 (n = 5)	-	27.5 (n = 5)
∑TCPP	3,235 (n = 2)	-	3,235 (n = 2)	9,357 (n = 1)	-	9,357 (n = 1)	3,684 (n = 3)	-	3,684 (n = 3)

n = number of data sets used to calculate the pooled GM.
† = Mitro et al. (2016) did not have this bin and/or did not provide a pooled GM for this bin.
- = No data available to estimate a pooled GM.

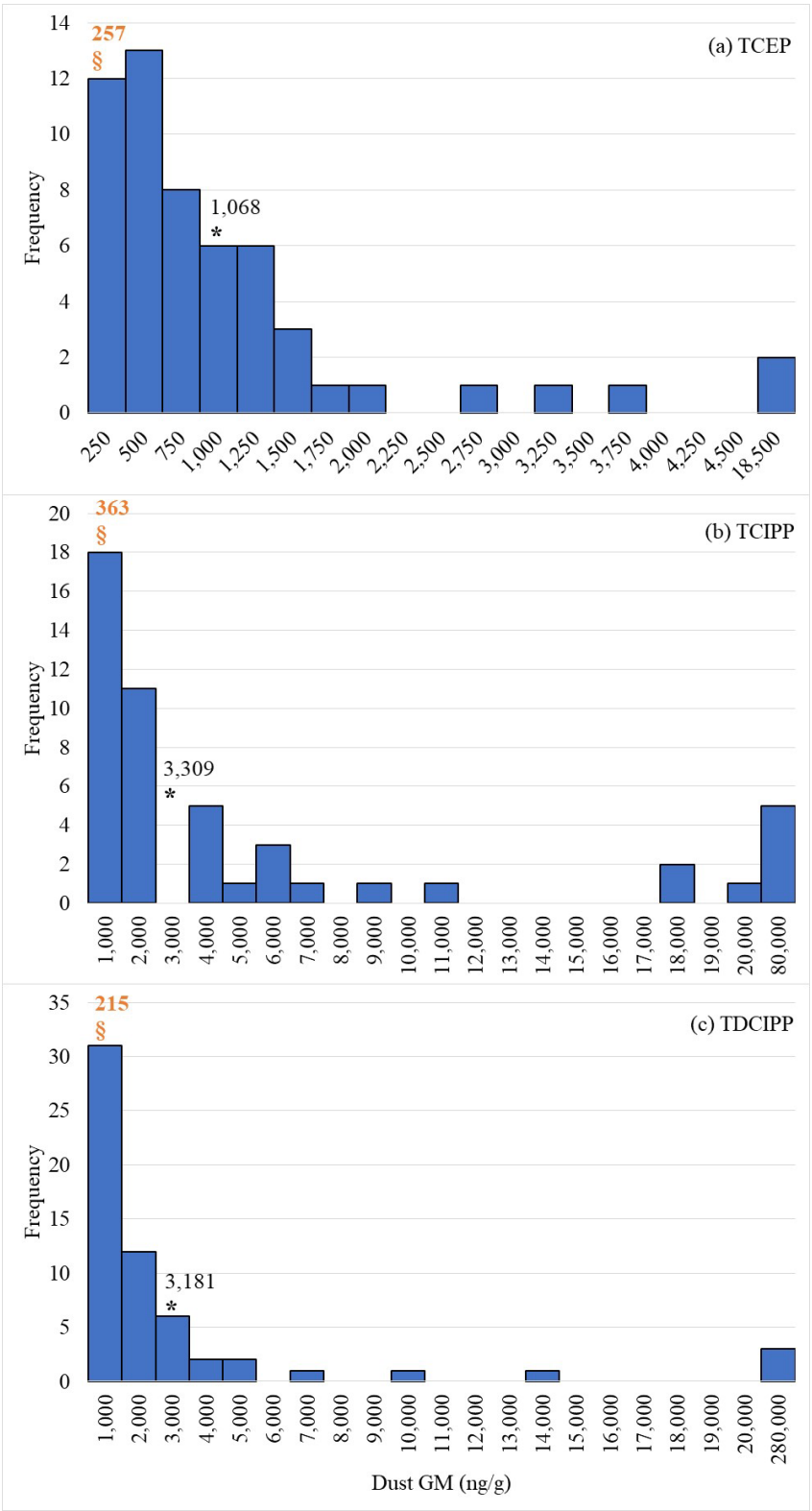

Figure 7. Frequency of Individual Dust Geometric Means Used to Estimate Pooled Geometric Means for (a) TCEP, (b) TCIPP, and (c) TDCIPP.

For each chemical, the pooled GM calculated in this report is shown above its bin with § followed by the value. Pooled GMs calculated by Mitro et al. (2016) are shown above its bin with * and the value.

4.3.2. Comparison of Measured to Modeled Air Concentrations

Prior to estimating exposure, chemical concentrations in gas (vapor) and airborne particulates were first estimated from measurements of chemical in the settled house dust. Given that the authors did not report the identities of all isomers in ∑TCPP, other than identifying TCIPP as one of the isomers, we assumed the physicochemical properties of ∑TCPP were the same as TCIPP. Figure 8 shows the comparison of measured versus modeled air concentrations from eight studies that reported both dust and indoor air measurements. No clear trend by chemical was observed, and in general, the modeled air concentrations were both equally under- and overpredicted, suggesting the model was adequate in predicting air concentrations.

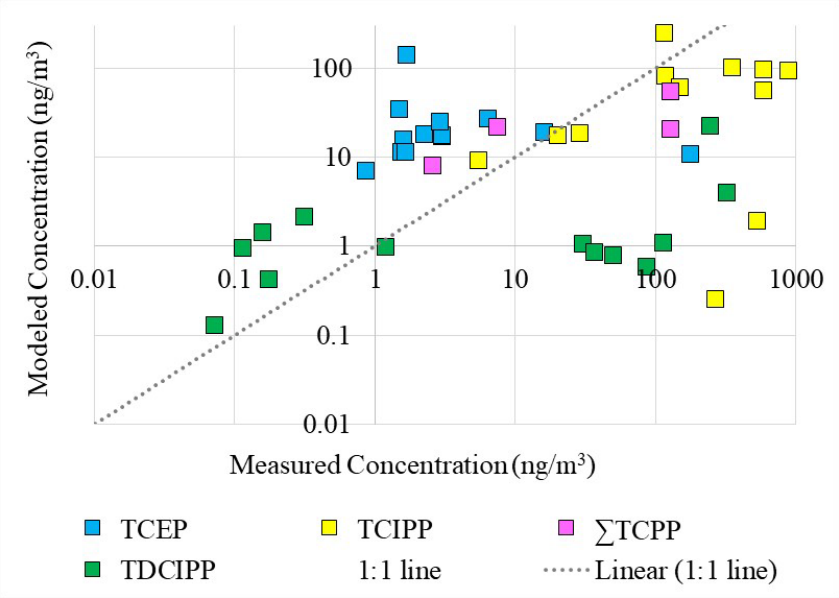

Figure 8. Estimated Total Exposure for Residential General Population by Chemical and Age Group Based on Indoor Dust Measurements .

4.3.3. Estimation of Daily Exposures

Using the pooled GM dust concentrations, daily exposures were estimated for (i) inhalation of gas + particulates, (ii) ingestion of settled dust, (iii) dermal absorption from gas phase air through the skin, and (iv) dermal absorption through dust contact with skin (see Appendix C-1). Figure 9 shows the total exposure for residential general population by age group and chemical. TCEP, TCIPP, TDCIPP, and ∑TCPP had higher doses, ranging from 2.7×10^{-7} to 1.5×10^{-4} mg/kg/day, whereas doses for TDBPP, BDCIPP, and V6 ranged from 6.8×10^{-10} to 2.0×10^{-7} mg/kg/day. Comparisons across the different bins showed that the lowest doses were found in residential general population, and with the exception of TCIPP, bins with potential OFR sources (i.e., elevated source) had higher doses than the bins without any sources identified (Figure 10 shows the 3–5 year olds as an example).

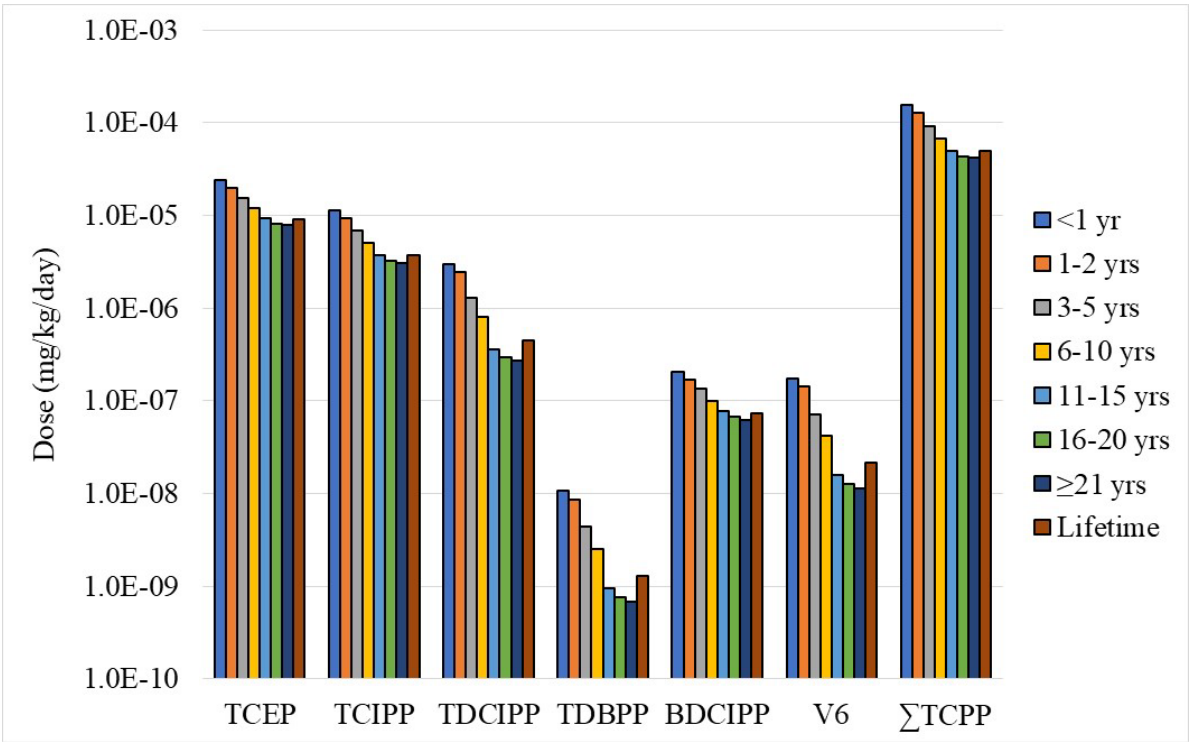

Figure 9. Estimated Total Exposure for Residential General Population by Chemical and Age Group Based on Indoor Dust Measurements.

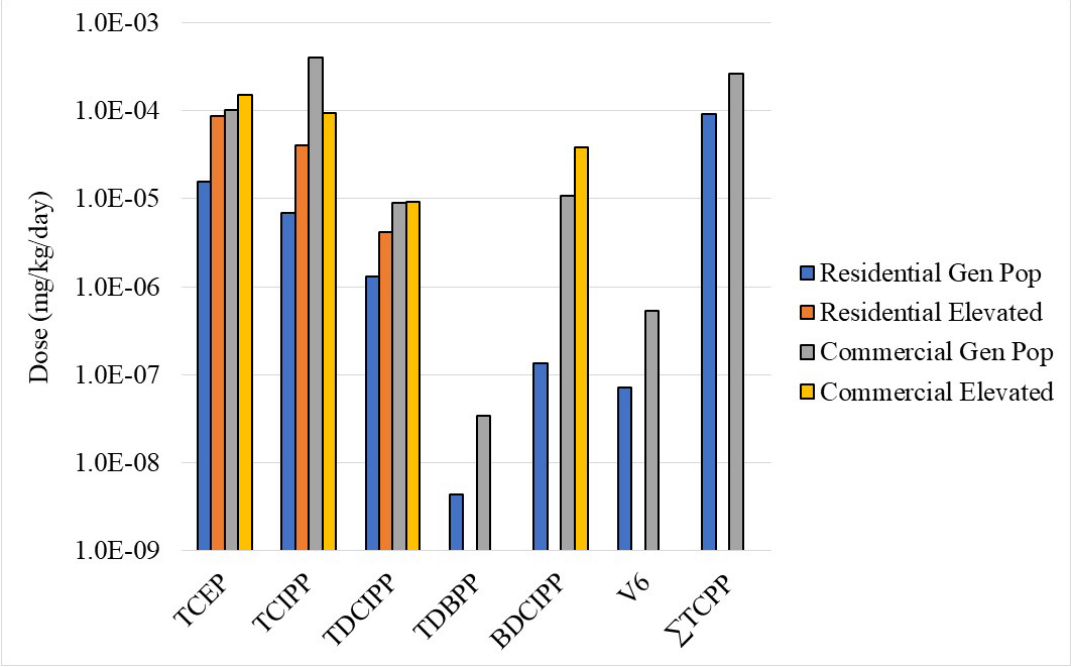

Figure 10. Estimated Total Exposure for the 3 –5 Year Olds by Chemical and Bin Based on Indoor Dust Measurements.

When the four different pathways are compared, Figure 11 shows that in general, the vapor-to-skin pathway was the dominant pathway for TCEP, TCIPP, BDCIPP, and ∑TCPP. These four chemicals have lower molecular weight, logKow, and logKoa and higher vapor pressure compared to the other three chemicals (TDBPP, V6, TDCIPP), in which dermal dust absorption was the dominant pathway.

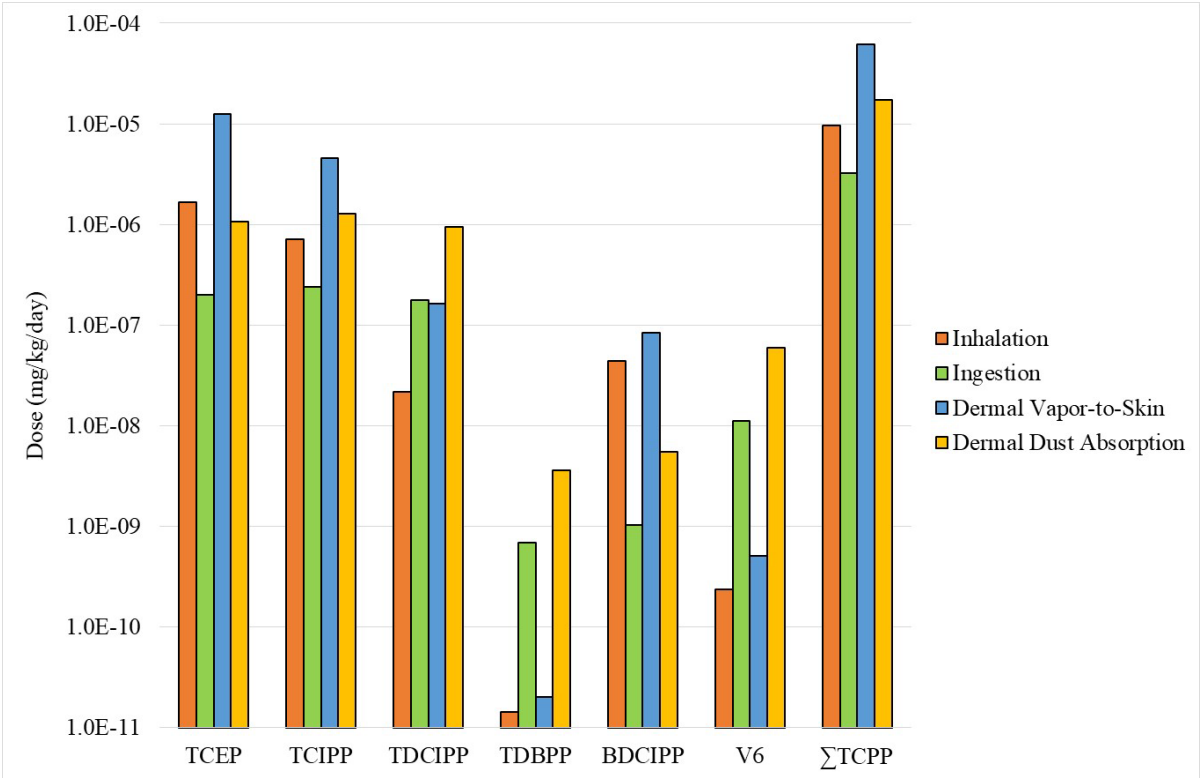

Figure 11 Estimated Exposure for Residential General Population 3–5 Year Olds by Chemical and Pathway Based on Indoor Dust Measurements .

4.3.4. Comparison of Estimated Dose from Dust Data with Estimated Intake from Reverse Dosimetry

Of the studies extracted, one also reported human biomonitoring data. Hou et al. (2021) measured OFR concentrations in whole blood, urine, air, and dust. Biomonitoring data were obtained from elderly adults aged 60–69, and air and dust samples were collected from the participants' residences. Table 17 shows the total daily exposures (or intakes for human biomonitoring) estimated from dust and urine data for TCEP, TCIPP, TDCIPP, and BDCIPP. Dust estimates were calculated with Approach 3, and urine estimates were calculated by UC (2023) using the reverse dosimetry approach (Approach 4) and the study-reported geometric mean. A comparison of the doses shows that doses estimated from the dust monitoring data are lower than the intakes calculated from biomonitoring data, which is expected, given that the biomonitoring data encompass all sources and pathways to which a person is exposed.

Table 17. Comparison of Doses for Adults Calculated from Indoor Dust and Human Biomonitoring Data for Hou et al. (2021).

Chemical	Dose (mg/kg/day)	
	Dust	Urine[a]
TCEP	3.48E-05	1.69E-04
TCIPP	8.28E-06	9.66E-06
TDCIPP // BDCIPP[b]	3.35E-07 // 6.37E-08	6.19E-06

[a]UC (2023) calculated daily intakes for urine using two methods for calculating distributional parameters for intake. Method 1 was considered more robust than method 2 (see UC (2023) for details); therefore, method 1 values are used here.
[b]Hou et al. (2021) reported separate dust concentrations for the metabolites of TCEP, TCIPP, and TDCIPP (i.e., BCEP, BCIPP, and BDCIPP, respectively). Only dust concentrations of BDCIPP were extracted, and doses subsequently calculated, because only BDCIPP is an OFR in the PHOP subclass (BCEP and BDCIPP are not one of the 42 PHOPs).

4.3.5. Uncertainties and Limitations

The modeling equations used in Approach 3 are widely accepted and have been used in the literature to analyze dust data for different populations (Mitro et al., 2016; Pelletier et al., 2017). Our approach also included an additional pathway, dermal absorption through dust contact with skin, which Mitro et al. (2016) and Pelletier et al. (2017) noted as having a minor contribution. However, as seen in Figure 11, dermal absorption through dust was minor for only some chemicals, whereas for TDBPP, V6, and TDCIPP, this pathway had the greatest contribution to total exposure. To calculate exposure for this pathway, we used professional judgment to estimate two parameters, the fraction of ingested dust due to hand-to-mouth transfer and the fraction of dust on hands that enters the mouth. These were set at 0.75 and 0.05, respectively, which we estimate to have an uncertainty factor of 2.

Concentrations of PHOPs in settled dust were obtained through a focused literature search. Because we did not conduct a systematic literature review, there is uncertainty in whether the data we used represent the full range of data available in the literature, especially for TDBPP, BDCIPP, V6, and ∑TCPP, which had only 3, 8, 5, and 3 data sets, respectively. In some instances, this resulted in only one data set for a bin (i.e., the pooled GM for the bin was equal to the GM for the data set) or a pooled GM calculated from only two data sets. For TCEP, TCIPP, and TDCIPP, all three chemicals had at least 49 data sets. In general, the majority of data sets for all chemicals were for the residential general population bin; as such, doses estimated for this bin had the greatest confidence compared to other bins.

Schools and vehicles were initially considered as two additional bins; however, given the limited number of data sets available, we ended up combining them with residential general population and commercial general population, respectively. Once a systematic literature review has been conducted with additional data identified, the analysis to determine whether schools and vehicles should be separate bins should be conducted again.

As was previously discussed in Section 4.1.5, the inhalation absorption fraction used was 0.5 for all chemicals, and we also calculated inhalation exposure using the combined concentration of PHOPs in the gaseous and particulate phases. Separate absorption fractions could be applied for the gaseous and particulate fractions, wherein the latter is chemical dependent (i.e., if the chemical is particle bound). For example, the absorption fraction for the particulate phase could be set at or closer to 1, the value used for the oral route. Exposure factors such as body weight, dust ingestion rate, and inhalation rate were set to single values for each age group but could be varied in future analyses to obtain a probabilistic distribution of exposures. The estimated variability from the combination of these parameters is estimated to be a factor of approximately 2–3, both lower and higher than central tendency values reported here. Dust ingestion rates, in particular, are a sensitive parameter we plan to vary in the future.

4.4. Exposures Estimated from Reverse Dosimetry (Approach 4)

Application of Approach 4, to calculate PHOP daily intakes from human biomonitoring data, was performed under a different project (Contract No. CPSC-D-17-00001, Task Order No. 61320622F10004). Briefly, daily intakes were estimated for TCEP, TCIPP, and TDCIPP using (i) urine biomonitoring data from the National Health and Nutrition Examination Survey (NHANES; presented in summarized form here and in full in UC (2023)) and (ii) peer-reviewed data from the literature (presented in summarized form here and in full in UC (2023)). Key equations are presented and briefly described in Section 3.5 and are discussed in full elsewhere (UC, 2021, 2023).

Table 18 presents the daily intakes calculated from the (i) averages of the geometric mean across four NHANES cycles (2011–2012, 2013–2014, 2015–2016, 2017–2018) and (ii) upper estimate (maximum estimated 95th percentile across all cycles) by age group. Data for only four age groups were available. For comparison, the central tendency (averages of the geometric means) and upper estimate (maximum value of 95th percentile) daily intakes calculated from peer-reviewed literature are shown in Table 19. Generally, the central tendency intakes estimated from the peer-reviewed literature are close to those estimated from NHANES. One exception is the teen/young adult category for TDCIPP from the peer-reviewed literature, which is approximately an order of magnitude lower than the most comparable group from NHANES (12-17 years).

For each chemical, the ranges shown reflect the variability with age; daily intakes for all chemicals were highest in the youngest age group. This age trend is clearest for NHANES data but does appear to be largely present in the peer-reviewed literature as well. The peer-reviewed literature indicates this trend may generally hold true for infants, a population not covered by NHANES. However, a lack of data on TCEP in infants precludes this conclusion for all three PHOPs. Further, adults have higher estimated intakes of TDCIPP than teens/young adults. Given that the teen/young adult age category represents a single study, is at the higher end of that age bracket, and overlaps with the age range for adults, this is not necessarily inconsistent with the broader trend. No clear time trends were observed (data not presented here). A discussion on the uncertainties and limitations of this approach is available in UC (2023).

Table 18. Central Tendency and Upper Estimate of Daily Intakes Estimated from NHANES Urine Biomonitoring Data.[a,b]

	Dose (mg/kg/day)		
Age Group	TCEP	TCIPP	TDCIPP
3–5 yrs[c]	2.33E-04 (1.35E-03)	5.58E-05 (4.08E-04)	6.01E-04 (2.42E-03)
6–11 yrs	1.07E-04 (7.54E-04)	2.22E-05 (1.66E-04)	2.07E-04 (1.70E-03)
12–17 yrs	7.06E-05 (4.73E-04)	1.30E-05 (5.36E-05)	1.02E-04 (4.62E-04)
18+ yrs	4.44E-05 (2.32E-04)	1.02E-05 (5.86E-05)	5.86E-05 (2.91E-04)

[a]Central tendency defined as the average of the geometric mean and upper estimate defined as the maximum 95th percentile across four NHANES cycles (2011–2012, 2013–2014, 2015–2016, 2017–2018).
[b]UC (2023) calculated daily intakes for urine using two methods for calculating distributional parameters for intake. Method 1 was considered more robust than method 2 (see UC (2023) for details); therefore, method 1 values are used here.
[c]Only two NHANES cycles (2015–2016, 2017–2018) had data for 3–5 year olds.

Table 19. Central Tendency and Upper Estimate of Daily Intakes Estimated from Peer-Reviewed Literature Urine Biomonitoring Data. [a,b]

Population	Dose (mg/kg/day)				
	TCEP (BCEP)	TCIPP (BCIPHIPP)	TCIPP (BCIPP & BCIPHIPP)	TCIPP (BCIPP)	TDCIPP (BDCIPP)
Infants (birth–18 months)		1.37E-04 (1.61E-03)	5.70E-04 (3.86E-02)	8.34E-04 (9.50E-02)	5.79E-04 (2.43E-02)
Children (2 months–13 years)	6.37E-04 (6.51E-03)	1.27E-04 (1.58E-03)	1.03E-04 (1.19E-03)	4.98E-05 (1.11E-03)	3.82E-04 (6.03E-02)
Teen/Young Adult (22 years)		1.95E-05 (2.04E-04)			1.19E-05 (1.44E-04)
Adults (18-90 years)	4.87E-05 (4.85E-04)	8.25E-06 (3.37E-05)		4.80E-06 (7.14E-05)	7.31E-05 (2.99E-04)

[a]Central tendency defined as the average of the geometric mean and upper estimate defined as the maximum 95th percentile across all data sets.
[b]UC (2023) calculated daily intakes for urine using two methods for calculating distributional parameters for intake. Method 1 was considered more robust than method 2 (see UC (2023) for details); therefore, method 1 values are used here.

4.5. Comparison of Estimated Exposures from Different Approaches

To corroborate the calculated doses, we compared the estimated doses from the four approaches to help identify when an approach may be over- or underpredicting exposure. For example, doses calculated using human biomonitoring and toxicokinetic data should be higher than doses calculated using indoor dust data because the biomonitoring results reflect both indoor dust and sources that do not result in indoor dust exposure. Both methods consider exposure from multiple sources (no source attribution), but one is direct and the other is indirect.

Figure 12 presents the doses estimated from each individual approach for TCEP, TCIPP, and TDCIPP by age group. For Approach 4, the doses shown are those calculated from NHANES data. In addition to plotting the daily intakes calculated from the average of the geometric mean across four NHANES cycles, Figure 12 also shows the dose calculated from the upper estimate (i.e., defined as the maximum 95th percentile value across the four cycles of NHANES data), which vary by age group. Aggregate background doses from dietary ingestion, drinking water ingestion, soil ingestion, and inhalation of outdoor air are also presented.

With the exception of the aggregate consumer exposures calculated from Approach 1, the doses estimated from other data types were generally below the upper estimate dose calculated from biomonitoring data. The aggregate consumer exposures were

several orders of magnitude higher, likely due to the uncertainties discussed in Section 4.1.5 and the possible overinclusion of sources. For TCIPP, only doses corresponding to upholstered furniture are shown in Figure 12. PIR foam also had TCIPP doses in the same order of magnitude as upholstered furniture (see Section 4.2.4), whereas the other products with TCIPP had lower doses. Similarly, only doses for PIR foam are shown in Figure 12 for TDCIPP, with lower doses estimated for polyester curtains.

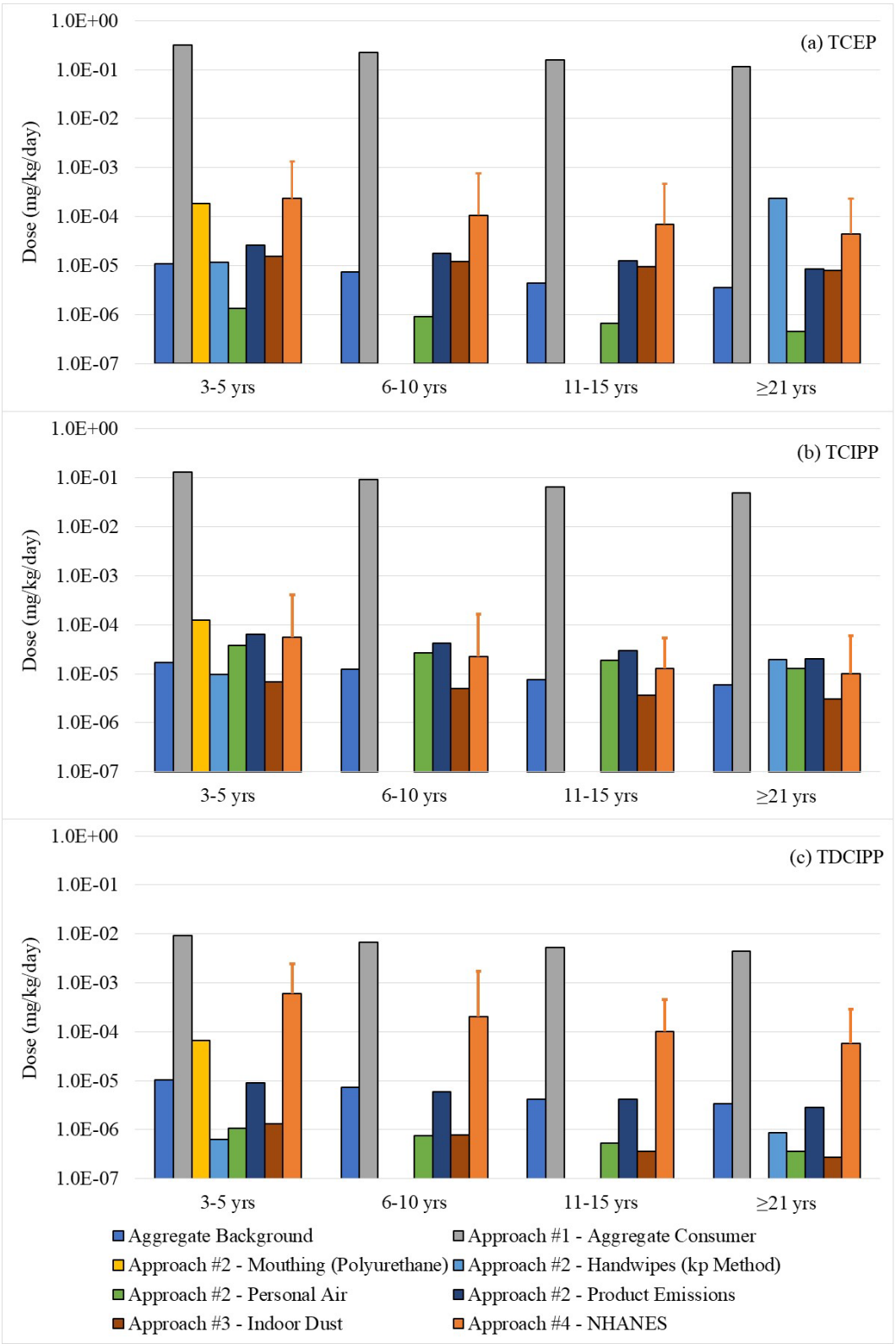

Figure 12 Comparison of Doses Calculated from Individual Approaches for (a) TCEP, (b) TCIPP, and (c) TDCIPP.

Error bar represents the upper estimate, defined as the dose calculated from the maximum 95th percentile across the four NHANES cycles.

Using the central tendency doses estimated from NHANES data as the basis for comparison, background exposures contributed 2%–8% for TCEP and TDCIPP for the four age groups evaluated. Total doses calculated using indoor dust data contributed 7%–18% for TCEP and was <1% for TDCIPP. For TCIPP, because the doses calculated from biomonitoring data were lower than those of TCEP and TDCIPP (see Table 18), this resulted in higher contributions for each approach/pathway, with background exposure contributing 31%–58% and indoor dust contributing 12%–30%. The relative contributions from Approach 2 varied depending on the data type and age group, although they were generally low for TDCIPP.

4.6. Extrapolation to Data - Poor Chemicals

In the Sections 4.1 to 4.4, we estimated exposure to PHOPs using four approaches. Aggregate consumer exposures were estimated using a mechanistic model for all chemicals with product use data. Similarly, mouthing exposure was estimated using a regression-based model for all chemicals with product use data. For all other data types/approaches considered (i.e., personal dermal loading, personal air concentrations, product emissions data, and indoor dust monitoring data), exposures were estimated for only a few chemicals due to data availability. In this section, we first identify trends that would allow chemicals to be ranked relative to one another; then, for each data type, we apply the trends identified to extrapolate doses to data-poor chemicals, if possible.

4.6.1. Identification of Trends or Relative Rankings

We used the CEM results adjusted for mouthing and direct dermal contact and included inhalation and ingestion absorption fractions for the 3–5-year-old age group for the exposure scenario "*Small hand-held hard and soft plastic items (including foam) where contact and mediated exposure is likely for children and adults*" to determine trends. In addition to the results for the 26 chemicals already modeled in Approach 1 (i.e., those with product use information that could be mapped to a scenario), we also included CEM runs for all of the other chemicals to obtain a more comprehensive data set. With the exception of the physicochemical properties, all other CEM inputs (e.g., product properties, environmental inputs, population inputs) remained the same across chemicals. The differences in dose are therefore due solely to differences in the chemicals and not any other factor.

Six physicochemical properties were considered: molecular weight (MW), Henry's law constant (H), octanol-air coefficient (Koa), octanol-water coefficient (Kow), vapor pressure (VP), and water solubility (Sol). A correlation analysis of the parameters in log space showed that most of these properties are correlated with each other (Figure 13), with most of the correlations over 0.5, indicating substantial relationships between the parameters. The largest correlations are −0.88 between ln(MW) and ln(VP) and −0.88

between logKow and ln(Sol), which are both expected. For example, we expect higher solubilities to give lower logKow values because the chemical favors being in the water over octanol.

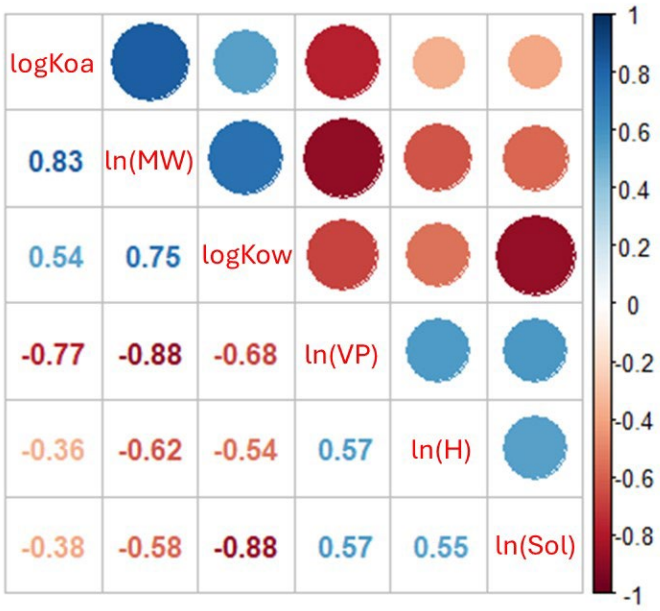

Figure 13 Correlation of PHOP Physicochemical Properties .

We then examined the correlations between the physicochemical properties with exposure from total inhalation, total dermal, total ingestion, and total across all pathways. For simplicity, this section will refer to these pathways as inhalation, dermal, ingestion, and total, respectively. For ingestion, only the results from the A_ING1 (ingestion after inhalation) and A_ING3 (incidental dust ingestion) models were included. Because the A_ING2 (mouthing) model uses a migration rate into saliva that is independent of the chemical, the A_ING2 results were the same for all chemicals within a tier (see Section 4.1.3 for discussion of the three tiers based on the mouthing adjustment factor) and therefore not included.

We found that the logs of each exposure variable were more strongly correlated with the chemical properties (also in log space) than were the exposure variables themselves. As seen in Table 20, the strongest correlation for ln(dermal) is with ln(MW) at −0.680. While the next highest correlation is with logKow (−0.545), the correlation between ln(MW) and logKow is even stronger at 0.746. Pearson correlations tend to be multiplicative, which means that correlation (dermal, logKow) is expected to be the product of correlation (dermal, MW) and correlation (MW, logKow). In this example, the expected −0.680 ×0.746 = -0.507 accounts for 93% of the value of −0.545 observed between dermal and logKow. Any additional (direct) correlation between dermal and logKow is therefore small. Similarly, the strongest relationship with ln(ingestion) and ln(inhalation)

was with logKoa and ln(VP), respectively. The ln(total) values were most strongly correlated to ln(MW), which was due to ln(total) being primarily dominated by the dermal pathway.

Table 20. Summary of Correlations of Exposure with Physicochemical Properties.

	Ln(Dermal)	ln(Ingestion)	ln(Inhalation)	ln(Total)
ln(MW)	**-0.680**	0.501	−0.805	**-0.752**
ln(H)	0.498	−0.072	0.676	0.562
logKoa	−0.378	**0.699**	−0.632	−0.462
logKow	−0.545	0.115	−0.704	−0.613
ln(VP)	0.374	−0.610	**0.893**	0.465
ln(Sol)	0.521	−0.062	0.578	0.574

Based on this analysis, we used the following parameters for extrapolating exposures to chemicals with no data:

- Use ln(MW) for predicting dermal and total dose
- Use logKoa for predicting ingestion
- Use ln(VP) for predicting inhalation

While not shown here, this correlations analysis was also repeated for two additional cases: (i) all chemicals except four PHOPs that have a brominated phenyl group and (ii) only chemicals with product use data (i.e., only chemicals modeled under Approach 1). Under a different project (Contract BPA No. 6132062 2A0005, Call Order No. 6132062 2F2011), the PHOP chemicals were evaluated under five profiles (physicochemical, mechanistic effect, PBTK, metabolite, and adverse effect) to determine their potential health effects as a subclass. For all five profiles, four PHOPs (CASRNs 7046-64-2, 2788-11-6, 49690-63-3, and 35656-01-0) were identified as outliers, meaning they were distinctly different from the other PHOPs. The details of the profiles analysis are available in ICF (2024b). In both cases, the final parameter used for extrapolation was unchanged, although the strength of the correlations differed.

Figure 14 shows these three relationships plotted for (a) dermal, (b) ingestion, and (c) inhalation, with total exposure following a similar pattern as dermal. For dermal, the relationship of increasing dermal exposure with decreasing molecular weight is true for the range of molecular weights with some outliers having lower exposure. For ingestion, the trend is less clear, with scatter in the data points before the data level off. For inhalation, the increase in inhalation exposure with increasing vapor pressure occurs

between ln(VP) of −20 and −11, which corresponds to vapor pressures of 2.1×10^{-9} to 1.7×10^{-5} mm Hg. Below or above that range, inhalation does not depend on vapor pressure.

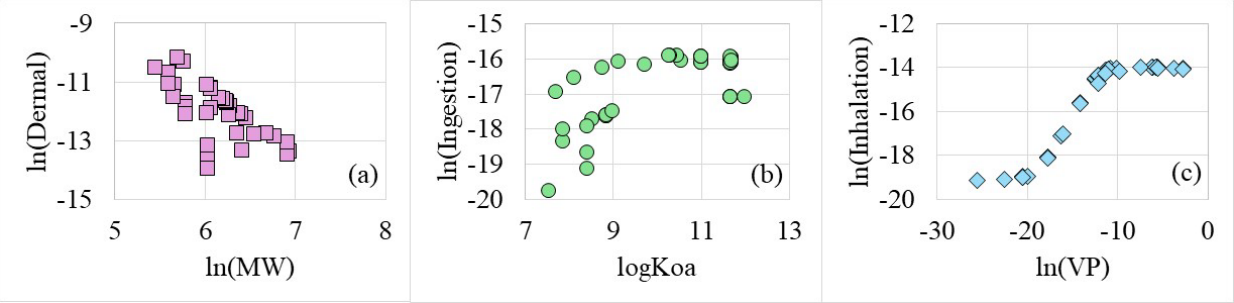

Figure 14. Relationships between Physicochemical Properties and (a) Dermal, (b) Ingestion, and (c) Inhalation Exposures for 3 –5 Year Olds with Contact and Mediated Exposure to Small Hand-held Hard and Soft Plastic Items (Including Foam) .

4.6.2. Estimated Exposures

Only chemicals with product uses identified in Approach 1were included for extrapolation. While the results for ∑TCPP were included in Approaches 2 and 3 by using the same chemical-specific and physiochemical properties as TCIPP, these results were not used for extrapolation purposes because we did not have the actual properties.

Doses could be extrapolated to other chemicals for only the indoor dust monitoring data. For indoor dust data, doses were calculated for six chemicals and ∑TCPP. Of these six chemicals with calculated doses, one was BDCIPP, which has no product use data and is a urinary metabolite of TDCIPP. Using the doses corresponding to the 3–5 year olds in the residential general population bin, the remaining five chemicals had total doses (across all pathways) ranging from 4.36×10^{-9} to 1.55×10^{-5} mg/kg/day. With these doses, we first confirmed that our data followed the trend between total dose and molecular weight. Because these doses were calculated using different pooled dust GMs for each chemical, we also normalized the dose against the dust GM. Figure 15 shows the ln of (a) dose and (b) normalized dose as a function of ln(MW). Using the (un-normalized) dose takes into account the tendency of the chemical to be found in dust, whereas the normalized dose provides the trend if all chemicals were found at the same concentration in dust. Both panels in the figure show a clear decreasing trend between TCEP and V6, although the rate of decrease between TDCIPP and V6 differs depending on the panel.

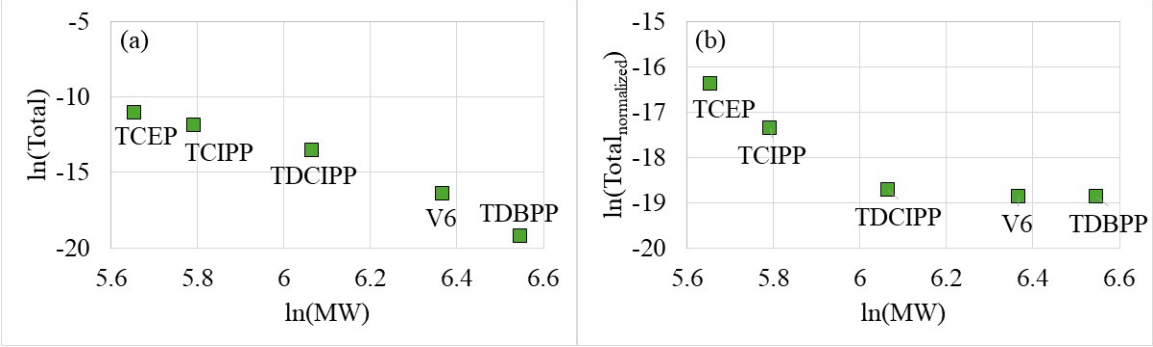

Figure 15. Relationship between Molecular Weight and Total Dose Calculated from Indoor Dust Monitoring Data for the Residential General Population 3–5 Year Olds for (a) Un-normalized Dose and (b) Normalized Dose .

Using these results, we can extrapolate doses for other PHOPs relative to the five chemicals with data. For example, for residential general population 3–5 year olds, the three PHOPs (i.e., CASRNs 115-98-0, 6294-34-4, and 140-08-9) with molecular weight less than 285.48 g/mol (i.e., the molecular weight of TCEP) are expected to have total doses on the same order of magnitude or greater than the TCEP dose of 1.55×10^{-5} mg/kg/day. Because we are extrapolating beyond our lowest data point, there is uncertainty in whether the dose would continue to increase or stay the same. For the one PHOP with a molecular weight between that of TCEP and TCIPP (i.e., CASRN 5324-12-9), the total dose is expected to be between 1.55×10^{-5} and 6.82×10^{-6} mg/kg/day. There were four PHOPs with the same molecular weight as TCIPP (i.e., 1067-98-7, 76649-15-5, 6145-73-9, and 76025-08-6) and therefore expected to have total doses similar to 6.82×10^{-6} mg/kg/day. Total doses for the other PHOPs are extrapolated in a similar fashion using the total doses of TDCIPP, V6, and TDBPP to define the extrapolation boundaries. Additional dust monitoring data for other chemicals are needed to validate our extrapolated results.

We attempted to perform a similar analysis for handwipe, personal air, and product emissions data using data from the 3–5 year olds, but the results were inconclusive because there were only three chemicals (TCEP, TCIPP, and TDCIPP) and, therefore, three data points, available. In all cases, we were unable to confirm that our data followed the general trends identified in Section 4.6.1. For handwipe data, doses were calculated in Section 4.2.2 using the fraction absorbed and permeability coefficient methods. Using the permeability coefficient method, both un-normalized and normalized doses showed a decreasing trend with molecular weight, although it is unclear whether this trend would hold up if more data points were available. However, when using doses calculated from the fraction absorbed method, the un-normalized doses showed an increasing trend, whereas the normalized dose showed no trend (i.e., minimal change dose). For personal air monitoring data, only the un-normalized dose was considered because the equations to calculate inhalation exposure did not have any chemical-specific inputs other than

chemical concentration in air. No trend was observed when the inhalation exposures were plotted against vapor pressure. Similarly, for product emissions data, only the un-normalized dose was considered. However, because the inhalation exposures for TCIPP varied over several orders of magnitude, depending on the product, any potential trend identified was considered highly uncertain. Additional experimental measurements or modeled data on other PHOPs are needed to be able to extrapolate doses for these data types. It may be possible that after the DTT and CPSC search is complete, data on other PHOPs will become available and this analysis can then be updated.

4.7. Compilation of Exposures for PHOPs with Product Use Data

Table 21 and Table 22 present the doses estimated from the four approaches for the 26 PHOPs with product use data. In Table 21, chemicals with modeled values are marked with #, whereas chemicals with extrapolated values (representing a semi-quantitative dose) are marked with o. The modeled and extrapolated values are then presented in Table 22. Doses were extrapolated for Approach 3 following the approach noted in Section 4.6.2 and for product emissions under Approach 2. For product emissions, we assumed based on professional judgment that chemicals with a vapor pressure lower than the vapor pressure of TDCIPP will have inhalation doses lower than that of TDCIPP. In addition to the four approaches, we also include background exposure in the tables. For chemical 76649-15-5, the isomer of TCIPP that was assigned the same exposure scenarios, we assume its background exposure would be less than that of TCIPP because it is included in commercial mixtures with TCIPP at approximately 10%. For chemicals for which uses were determined solely from patent data, we assumed their background exposures would be lower than those for TCEP, TCIPP, and TDCIPP, which all have existing uses (from non-patent sources). Given that the highest background exposure of TCEP, TCIPP, and TDCIPP is 1.7×10^{-5} mg/kg/day, we assigned a background exposure value of $<1.0\times10^{-5}$ mg/kg/day to the chemicals with only patent data.

Table 21. Summary of Data Availability for PHOP s with Product Use Data .

CASRN	Background	Approach #1 – CEM	Approach #2 – Mouthing	Approach #2 – Handwipes	Approach #2 – Personal Air	Approach #2 – Emissions	Approach #3 – Indoor Dust	Approach #4 - NHANES
78-43-3	o	#	#	-	-	o	o	-
115-96-8	#	#	#	#	#	#	#	#
115-98-0	o	#	#	-	-	-	o	-
126-72-7	-	#	#	-	-	o	#	-
140-08-9	o	#	#	-	-	-	o	-
1067-98-7	-	#	#	-	-	-	o	-
2788-11-6	o	#	#	-	-	o	o	-
4351-70-6	o	#	#	-	-	o	o	-
5324-12-9	o	#	#	-	-	o	o	-
5412-25-9	o	#	#	-	-	o	o	-
6145-73-9	o	#	#	-	-	-	o	-
6294-34-4	o	#	#	-	-	-	o	-
6749-73-1	o	#	#	-	-	-	o	-
7046-64-2	o	#	#	-	-	o	o	-
13674-84-5	#	#	#	#	#	#	#	#
76649-15-5[a]	o	#	#	-	-	-	o	-
13674-87-8	#	#	#	#	#	#	#	#
19186-97-1	-	#	#	-	-	o	o	-
27568-90-7	o	#	#	-	-	-	o	-
33125-86-9	o	#	#	-	-	-	o	-
35656-01-0	o	#	#	-	-	o	o	-

CASRN	Background	Approach #1 – CEM	Approach #2 – Mouthing	Approach #2 – Handwipes	Approach #2 – Personal Air	Approach #2 – Emissions	Approach #3 – Indoor Dust	Approach #4 - NHANES
38051-10-4	-	#	#	-	-	o	#	-
66108-37-0	o	#	#	-	-	-	o	-
76025-08-6	-	#	#	-	-	-	o	-
84282-27-9	o	#	#	-	-	-	o	-
40120-74-9	-	#	#	-	-	-	o	-

- = no quantitative or semi-quantitative doses estimated.

[a]76649-15-5 did not have any product uses reported; however, given it is an isomer of 13674-84-5 and included in commercial mixtures with 13674-84-5 at approximately 10%, the same exposure scenarios were assigned.

Table 22. Summary of Doses (mg/kg/day) for 3–5 Year Olds for PHOPs with Product Use Data.

CASRN	Background	Approach #1 – CEM	Approach #2 – Mouthing [a]	Approach #2 – Handwipes [b]	Approach #2 – Personal Air	Approach #2 – Emissions	Approach #3 – Indoor Dust	Approach #4 - NHANES
78-43-3	<1.0E-05 [c]	1.35E-02	6.51E-05	-	-	<8.97E-06	~1.30E-06	-
115-96-8	1.10E-05	3.20E-01	1.87E-04	1.19E-05	1.33E-06	2.62E-05	1.55E-05	2.33E-04
115-98-0	<1.0E-05	1.32E-01	2.65E-04	-	-	-	~ or >1.55E-05	-
126-72-7	-	4.02E-04	2.54E-05	-	-	<8.97E-06	4.36E-09	-
140-08-9	<1.0E-05	4.59E-02	2.10E-04	-	-	-	~ or >1.55E-05	-
1067-98-7	-	1.11E-01	1.29E-04	-	-	-	~6.82E-06	-
2788-11-6	<1.0E-05	1.60E-04	1.15E-05	-	-	<8.97E-06	~ or <4.36E-09	-
4351-70-6	<1.0E-05	4.67E-03	4.09E-05	-	-	<8.97E-06	4.36E-09 to 7.16E-08	-
5324-12-9	<1.0E-05	5.29E-03	1.99E-04	-	-	<8.97E-06	6.82E-06 to 1.55E-05	-
5412-25-9	<1.0E-05	1.82E-02	5.70E-05	-	-	<8.97E-06	7.16E-08 to 1.30E-06	-
6145-73-9	<1.0E-05	1.26E-01	1.19E-04	-	-	-	~6.82E-06	-
6294-34-4	<1.0E-05	1.47E-01	1.98E-04	-	-	-	~ or >1.55E-05	-
6749-73-1	<1.0E-05	1.02E-02	7.29E-05	-	-	-	1.30E-06 to 6.82E-06	-
7046-64-2	<1.0E-05	5.30E-05	5.57E-06	-	-	<8.97E-06	~ or <4.36E-09	-
13674-84-5	1.70E-05	1.31E-01	1.25E-04	9.57E-06	3.80E-05 (3.39E-04) [d]	6.31E-05 [e]	6.82E-06	5.58E-05
76649-15-5 [f]	<1.70E-05	1.24E-01	1.20E-04	-	-	-	~6.82E-06	-
13674-87-8	1.04E-05	9.14E-03	6.61E-05	6.36E-07	1.07E-06	8.97E-06 [g]	1.30E-06	6.01E-04
19186-97-1	-	3.77E-06	7.56E-06	-	-	<8.97E-06	~ or <4.36E-09	-

CASRN	Background	Approach #1 – CEM	Approach #2 – Mouthing [a]	Approach #2 – Handwipes [b]	Approach #2 – Personal Air	Approach #2 – Emissions	Approach #3 – Indoor Dust	Approach #4 - NHANES
27568-90-7	<1.0E-05	2.62E-01	8.42E-05	-	-	-	1.30E-06 to 6.82E-06	-
33125-86-9	<1.0E-05	8.94E-02	6.73E-05	-	-	-	7.16E-08 to 1.30E-06	-
35656-01-0	<1.0E-05	4.69E-04	2.69E-05	-	-	<8.97E-06	4.36E-09 to 7.16E-08	-
38051-10-4	-	6.79E-04	4.10E-05	-	-	<8.97E-06	7.16E-08	-
66108-37-0	<1.0E-05	2.30E-03	3.72E-05	-	-	-	~7.16E-08	-
76025-08-6	-	3.31E-02	1.21E-04	-	-	-	~6.82E-06	-
84282-27-9	<1.0E-05	8.96E-03	7.74E-05	-	-	-	1.30E-06 to 6.82E-06	-
40120-74-9	-	1.41E-02	6.48E-05	-	-	-	~1.30E-06	-

- = no quantitative or semi-quantitative doses estimated.
[a]Estimated mouthing exposure for polyurethane-based materials.
[b]Estimated handwipe doses from kp method.
[c]Background exposure estimated to be <1.0E-05 mg/kg/day for chemicals for which product use was determined solely from patent data.
[d]Dose in brackets corresponds total dose for the spray polyurethane foam scenario, estimated from a hybrid approach combining elements of Approaches 1, 2, and 3.
[e]Dose corresponding to upholstered furniture.
[f]76649-15-5 did not have any product uses reported; however, given it is an isomer of 13674-84-5 and included in commercial mixtures with 13674-84-5 at approximately 10%, the same exposure scenarios were assigned.
[g]Dose corresponding to PIR foam.

5. Summary

We assessed exposure to PHOPs using four approaches: (i) mechanistic models (Approach 1), (ii) empirical measurements including migration rates from products to saliva, personal dermal loading, personal air monitoring data, and product emissions/parameters (Approach 2), (iii) indoor dust monitoring data (Approach 3), and (iv) reverse dosimetry with human biomonitoring and chemical-specific toxicokinetic data (Approach 4). A comparison of exposures estimated using the four approaches showed that with the exception of the aggregate consumer exposures calculated from Approach 1, the doses estimated from Approach 2 and Approach 3 were generally below the doses calculated from Approach 4. Because Approach 4 uses biomonitoring data, the estimated dose represents a total dose for all sources and pathways that a person is exposed to, and as such, it should be the highest dose among all four approaches.

The aggregate consumer exposures estimated were orders of magnitude higher than the doses calculated from biomonitoring data, suggesting an overinclusion of sources and the need for further refinement of the modeling input parameters. We noted several sources of uncertainty related to Approach 1 and implemented adjustment factors and a method of aggregating exposures across different consumer scenarios that uses the probability of the consumer product being in a household and containing an OFR in the same subclass. In the absence of data, we applied professional judgment to determine the adjustment factors and the probability of the consumer product being in a household and containing an OFR in the same subclass. For Approach 2, the doses estimated from empirical measurements were, in general, similar or below the dose calculated from the upper estimate (i.e., the maximum 95th percentile value) from NHANES data. Overall, there were limited data sets across all empirical measurement data types and therefore uncertainty in the estimated doses. For Approach 3, the indoor dust monitoring data were classified into bins based on the indoor environment sampled, with the residential general population bin having the largest number of data sets, especially for TCEP, TCIPP, and TDCIPP. Depending on the chemical, the estimated total doses from indoor dust data accounted for <1% to 30% of the dose calculated from biomonitoring data.

To perform class-based exposure assessments, we also identified trends or key parameters that would allow us to estimate doses for data-poor chemicals using data available for data-rich members. We used the modeled doses from Approach 1, in which we varied only the physicochemical parameters for one scenario, to identify one key property for each exposure pathway. All six of the physicochemical properties considered were moderately to highly correlated with each other. For dermal and total exposures, molecular weight was the key predictor, whereas for ingestion and inhalation

exposures, the key parameter was octanol-water partition coefficient and vapor pressure, respectively.

Using these identified trends, we extrapolated semi-quantitative doses for PHOPs identified to have product use data but no indoor dust data. The extrapolated doses were predicted using molecular weight and provided as doses relative to a data-rich chemical. For example, the one PHOP with a molecular weight between that of TCEP and TCIPP (i.e., CASRN 5324-12-9) is expected to have a total dose between 1.55×10^{-5} and 6.82×10^{-6} mg/kg/day for residential general population 3–5 year olds. Doses could not be extrapolated for the data types considered under Approach 2 because only three chemicals had data, the doses were generally calculated using a limited number of data sets, and/or the extrapolation results were inconclusive.

Overall, the analyses described in this report show that the approaches used to estimate exposure from empirical measurements and indoor dust monitoring data are able to provide doses that are within the expected range when compared to doses from biomonitoring data. Additional work is needed to refine the mechanistic modeling approach, primarily in data inputs. We also demonstrated a proposed methodology for extrapolating doses from data-rich to data-poor chemicals using indoor dust data, although additional data for other chemicals are needed to validate this method. Once additional exposure information becomes available through the DTT and CPSC search, this analysis can be updated to use the more comprehensive data.

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7. Supporting Files

Table 23. List of 37 Supporting Files.

Filename	Description	Section of Report
CO-3 Class Based Exposure Guide_2024-05-22.docx	Guidance Document for Conducting Class-based Exposure Assessments for OFRs	1
Supporting Files for Approach 1(28 files)		
PHOPs Appendix A-1_CEM Inputs_2024-04-24.xlsx	Input parameters used in CEM runs	4.1.1
PHOPs Appendix A-2_[CASRN]_CEM Results_2024-04-24.xlsx	Twenty-six files, one for each chemical, containing the CEM results for each individual scenario and the adjusted aggregate consumer exposure	4.1.2
PHOPs Appendix A-3_Aggregate Consumer Exposure Code_2024-04-25.R (.txt also available)	R code to calculate adjusted aggregate consumer exposure	4.1.3
Supporting Files for Approach 2 (5 files)		
PHOPs Appendix B-1_Migration Rates into saliva Data_2024-04-24.xlsx	Estimated migration rates into saliva and corresponding calculated doses	4.2.1
PHOPs Appendix B-2_Handwipe Data_2024-04-24.xlsx	Handwipe data identified from focused literature search and the doses calculated using the fabs and kp methods	4.2.2
PHOPs Appendix B-3_Personal Air Data_2024-04-24.xlsx	Personal air monitoring data identified from focused literature search and corresponding calculated doses	4.2.3
PHOPs Appendix B-4_Product Emissions Data_2024-04-29.xlsx	Product emissions data identified from focused literature search and corresponding calculated doses	4.2.4
PHOPs Appendix B-5_SPF Dose Hybrid_2024-05-30	Inhalation, Ingestion, and Dermal doses associated with Spray Polyurethane Foam across multiple approaches	4.2.5
Supporting Files for Approach 3 (2 files)		
PHOPs Appendix C-1_Indoor Dust Data_2024-04-24.xlsx	Dust data identified from focused literature search and doses calculated from R code	4.3.4
PHOPs Appendix C-2_Approach 3 Dust Code_2024-04-15.R (.txt also available)	R code to process dust data and calculated pooled geometric mean and corresponding doses	4.3.4
Supporting Files for Approach 4 (1 file)		
Exposure Assessment of Polyhalogenated Organophosphate (PHOP) Flame Retardants Using Human Biomonitoring Data.pdf	Calculated doses using Human Biomonitoring data and reverse dosimetry (There are 22 supporting files for this main report that were linked and posted under a separate contract)	4.4