Supplementary Information (SI) for Environmental Science: Advances.
This journal is © The Royal Society of Chemistry 2025

Supplementary Information

for

Flame retardants in dust from the indoor environments of expedition cruise ships

Veronica van der Schyff[1*], Verena Meraldi[2], Andrew Luke King[3], Simona Rozárka Jílková[1], Ondřej Audy[1], Petr Kukučka[1], Jiří Kohoutek[1], Lisa Melymuk[1]

* Corresponding author: Veronica van der Schyff

[1]RECETOX, Faculty of Science, Masaryk University, Kotlarska 2, 61137 Brno, Czech Republic

[2] HX (formerly Hurtigruten Expeditions), N1 9JY, London, U.K.

[3]Norwegian Institute for Water Research (NIVA), Økernveien 94, 0579, Oslo, Norway

Contains 4 texts, 11 tables, 10 figure. 2 tables in seperate excel files.

Contents

List of Tables and Figures

excell file

*Table S1. Full list of target analytes with identifiers and *MDL/LOQ concentrations (ng/g)*

	CHEMICAL ABBREVIATION	CHEMICAL_NAME	CAS	INCHIKEY	MDL/LOQ*
PBDEs	PBDE28	2,4,4'-Tribromodiphenyl ether	41318-75-6	UPNBETHEXPIWQX-UHFFFAOYSA-N	0.0146
	PBDE47	2,2',4,4'-Tetrabromodiphenyl ether	5436-43-1	XYBSIYMGXVUVGY-UHFFFAOYSA-N	0.0110
	PBDE66	2,3',4,4'-Tetrabromodiphenyl ether	189084-61-5	DHUMTYRHKMCVAG-UHFFFAOYSA-N	0.0168
	PBDE100	2,2',4,4',6-Pentabromodiphenyl ether	189084-64-8	NSKIRYMHNFTRLR-UHFFFAOYSA-N	0.0193
	PBDE99	2,2',4,4',5-Pentabromodiphenyl ether	60348-60-9	WHPVYXDFIXRKLN-UHFFFAOYSA-N	0.0280
	PBDE85	2,2',3,4,4'-Pentabromodiphenyl ether	182346-21-0	DMLQSUZPTTUUDP-UHFFFAOYSA-N	0.0311
	PBDE154	2,2',4,4',5,6'-Hexabromodiphenyl ether	207122-15-4	VHNPZYZQKWIWOD-UHFFFAOYSA-N	0.0363
	PBDE153	2,2',4,4',5,5'-Hexabromodiphenyl ether	68631-49-2	RZXIRSKYBISPGF-UHFFFAOYSA-N	0.0482
	PBDE183	2,2',3,4,4',5',6-Heptabromodiphenyl ether	207122-16-5	ILPSCQCLBHQUEM-UHFFFAOYSA-N	0.0822
	PBDE209	2,2',3,3',4,4',5,5',6,6'-Decabromodiphenyl ether	1163-19-5	WHHGLZMJPXIBIX-UHFFFAOYSA-N	1.047
AHFRs	PBBZ	1,2,3,4,5-Pentabromobenzene	608-90-2	LLVVSBBXENOOQY-UHFFFAOYSA-N	0.021948
	PBT	2,3,4,5,6-Pentabromotoluene	87-83-2	OZHJEQVYCBTHJT-UHFFFAOYSA-N	0.0474795
	PBEB	2,3,4,5,6-Pentabromoethylbenzene	85-22-3	FIAXCDIQXHJNIX-UHFFFAOYSA-N	0.0586975
	TBP-DBPE	1,3,5-Tribromo-2-(2,3-dibromopropoxy)benzene	35109-60-5	QXWYPAKUEHGJSG-UHFFFAOYSA-N	0.0027991
	HBB	Hexabromobenzene	87-82-1	CAYGQBVSOZLICD-UHFFFAOYSA-N	0.0396235
	PBBA	(Pentabromophenyl)methyl acrylate	59447-55-1	GRKDVZMVHOLESV-UHFFFAOYSA-N	0.0003891
	EH-TBB	2-Ethylhexyl 2,3,4,5-tetrabromobenzoate	183658-27-7	HVDXCGSGEQKWGB-UHFFFAOYSA-N	0.188582
	TDBP-TAZTO	1,3,5-Tris(2,3-dibromopropyl) isocyanurate	52434-90-9	NZUPFZNVGSWLQC-UHFFFAOYSA-N	0.0008953
	BEH-TEBP	Bis(2-ethylhexyl) tetrabromophthalate	26040-51-7	UUEDINPOVKWVAZ-UHFFFAOYSA-N	0.2438225
	TBCT	2,3,4,5-tetrabromo-6-chloromethylbenzene	39569-21-6	WMXWTOJJASZOCL-UHFFFAOYSA-N	0.0002754
	DBDPE	Decabromodiphenyl ethane	84852-53-9	BZQKBFHEWDPQHD-UHFFFAOYSA-N	0.00296
	aDBE-DBCH	1,2-Dibromo-4-(1,2-dibromoethyl)cyclohexane	3322-93-8	PQRRSJBLKOPVJV-OSMVPFSASA-N	0.0000739
	bDBE-DBCH			PQRRSJBLKOPVJV-LXGUWJNJSA-N	0.0000746
	gdDBE-DBCH				0.0002719
	TBX	2,3,5,6-Tetrabromo-p-xylene	23488-38-2	RXKOKVQKECXYOT-UHFFFAOYSA-N	0.0002786
	TBP-AE	1,3,5-Tribromo-2-(prop-2-en-1-yloxy)benzene	3278-89-5	RZLLIOPGUFOWOD-UHFFFAOYSA-N	0.0002165
	BATE	2-Bromoallyl 2,4,6-tribromophenyl ether	99717-56-3	RLPZXGWCSHFKJI-UHFFFAOYSA-N	0.0002078
	bTBCO	*1,2,5,6-Tetrabromocyclooctane*	3194-57-8	RZLXIANUDLLFHN-UHFFFAOYSA-N	0.0001963
	aTBCO				0.0005239
	DBHCTD	Hexachlorocyclopentadienyl-dibromocyclooctane	51936-55-1	XRFONNJUMOCNHA-UHFFFAOYSA-N	0.0002246
	BTBPE	1,2-Bis(2,4,6-tribromophenoxy)ethane	37853-59-1	YATIGPZCMOYEGE-UHFFFAOYSA-N	0.461
	sDP	syn-Dechlorane Plus	135821-03-3	UGQQAJOWXNCOPY-MXYLTYEXNA-N	0.307
	aDP	anti-Dechlorane Plus	135821-74-8	UGQQAJOWXNCOPY-VBCJEVMVNA-N	0.719
OPEs	TCEP	Tris(2-chloroethyl) phosphate	115-96-8	HQUQLFOMPYWACS-UHFFFAOYSA-N	7.23
	TCIPP	Tris(2-chloroisopropyl)phosphate	13674-84-5	KVMPUXDNESXNOH-UHFFFAOYSA-N	49.3
	TDCIPP	Tris(1,3-dichloro-2-propyl) phosphate	13674-87-8	ASLWPAWFJZFCKF-UHFFFAOYSA-N	1.98
	TBOEP	Tris(2-butoxyethyl) phosphate	78-51-3	WTLBZVNBAKMVDP-UHFFFAOYSA-N	0.638
	TPhP	Triphenyl phosphate	115-86-6	XZZNDPSIHUTMOC-UHFFFAOYSA-N	5.34
	TEHP	Tris(2-ethylhexyl) phosphate	78-42-2	GTVWRXDRKAHEAD-UHFFFAOYSA-N	2.11
	CDP	Cresyl diphenyl phosphate	26444-49-5	XMNDMAQKWSQVOV-UHFFFAOYSA-N	0.356
	EHDPP	2-Ethylhexyl diphenyl phosphate	1241-94-7	CGSLYBDCEGBZCG-UHFFFAOYSA-N	10.3
	TDBPP	Tris(2,3-dibromopropyl) phosphate	126-72-7	PQYJRMFWJJONBO-UHFFFAOYSA-N	0.43
	TnPP	Tripropyl phosphate	513-08-6	RXPQRKFMDQNODS-UHFFFAOYSA-N	0.01
	ip-TPP	Triphenyl phosphates isopropylated	68937-41-7	No INCHIKEY	0.0119
	TEP	Triethyl phosphate	78-40-0	DQWPFSLDHJDLRL-UHFFFAOYSA-N	22.73
	oTMPP	Tri-o-cresyl phosphate	78-30-8	YSMRWXYRXBRSND-UHFFFAOYSA-N	0.035
	m/p TMPP	Tris(methylphenyl) phosphate	1330-78-5	No INCHIKEY	0.0146
	TiBP	Triisobutyl phosphate	126-71-6	HRKAMJBPFPHCSD-UHFFFAOYSA-N	2.54
	TnBP	Tributyl phosphate	126-73-8	STCOOQWBFONSKY-UHFFFAOYSA-N	0.01

*Colour code: Green: No concentrations in blank values. LOQ's were determined. Median of LOQ values reported
Blue: No concentrations in blank values. Instrumental LOQs used
Yellow: MDL calculated as average + 3*SD of blank values

Text S1: Detailed location selection and sampling limitations

We attempted to collect dust from representative and comparable areas on board all ships, with a balance of crew and passenger areas.

While the layouts of the ships were similar, they were not identical, and some adjustments had to be made (for instance, the shop and reception on Ship 3 occupied the same space and were sampled together, while they were distinctly different in other ships). Figures S1A-H indicate examples of different public areas (and crew cabin) present on all ships. No photographs of technical spaces were allowed.

Because of strict cleaning routines, it was difficult to obtain sufficient amounts of dust from every area. Especially during the first sampling campaign (Ship 2), not enough dust was collected in every location. This was rectified in the other campaigns (except the crew mess in Ship 3). In the instances of low dust mass collected, dust was prioritized for methanol extractions.

*Table S2: Sampling locations on different ships and analyses conducted (#Methanol extraction: OPEs; *SUPRA: PBDE & AHFRs)*

Ship 1	# M	* S	Ship 2	# M	* S	Ship 3	#M	*S
Restaurant 1	X	X	Restaurant 1	X	X	Restaurant 1	x	X
Restaurant 2	X	X	Restaurant 2	X	X	Restaurant 2	X	X
Restaurant 3	X	X	Restaurant 3	X	X	Restaurant 3	X	X
Science center	X	X	Science center	X	X	Science center	X	X
Lounge	X	X	Lounge	X		Lounge	X	X
Passenger cabin	X	X	Passenger cabin	X	X	Passenger cabin	X	X
Crew cabin	X	X	Crew cabin	X	X	Crew cabin	X	X
Crew mess/day room	X	X	Crew mess	X	X	Crew mess	X	
Shop	X	X	Shop	X		Crew day room	X	X
Reception	X	X	Reception	X		Shop and reception	X	X
Hallway	X	X	Hallway	X	X	Hallway	X	X
Lecture hall	X	X	Crew corridor	X		Lecture hall	X	X
Bridge	X	X				Bridge	X	X
Laundry	X	X						
Engine control room	X	X						
Engine room	X	X						

Figure S1A: Science center

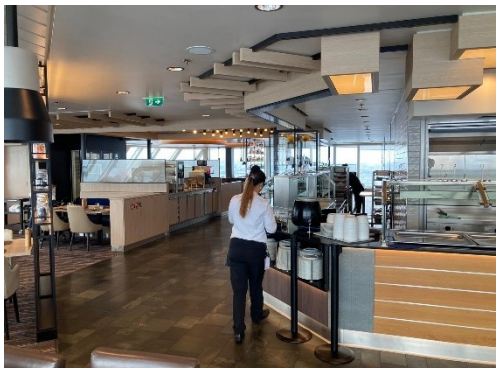

Figure S1B: Restaurant 1

Figure S1C: Restaurant 2

Figure S1D: Restaurant 3

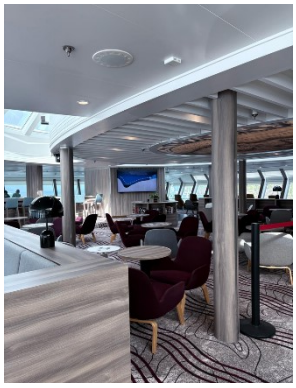

Figure S1E: Lounge

Figure S1F: Shop

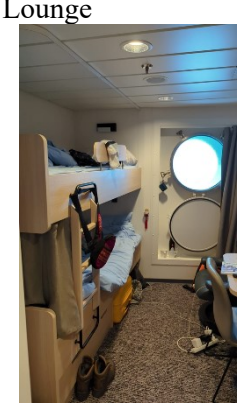

Figure S1G: Crew cabin

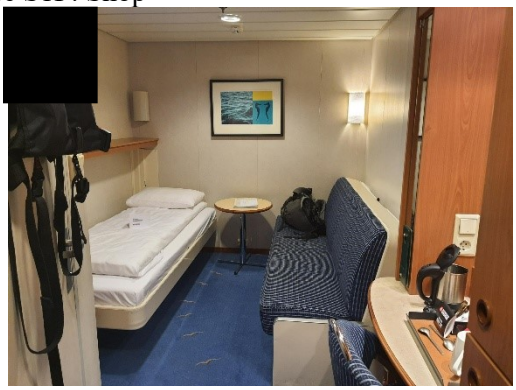

Figure S1H: Passenger cabin

Figure S1A-H: Examples of different locations present on all sampled ships

Figure S2: Photographs of specialized dust sampling vacuum head (photo credit: Paula Marcineková)

Text S2: Homogenization and extraction

Dust samples were homogenized using a Retsch MM 301 mixer mill (Retsch GmbH, Germany) equipped with tungsten carbide grinding jars and a wolframite weight. Prior to homogenization, the grinding jars containing dust samples and quartz filters, were cooled in liquid nitrogen for two minutes to embrittle the dust matrix. This step enhanced mechanical pulverization and prevented the material from agglomerating into compacted masses during milling. The samples were ground for 30 seconds at 25 s^{-1}. The resulting homogenized samples were transferred to pre-weighed, baked glass vials and stored at −20 °C until analysis.

Polybrominated diphenyl ethers (PBDEs) and alternative halogenated flame retardants (AHFRs) were extracted using supramolecular solvent extraction (SUPRAS), following the method

described by Marcinekova et al.[1] Organophosphate esters (OPEs) were extracted using a methanol-based extraction protocol adjusted from Svobodová et al.[2]

Dust from Ship 2 was analyzed in summer of 2023 and from Ships 1 and 3 late 2023/ early 2024. Slight differences were made to the extraction protocols – For Ship 2, 10 mg of dust was used to extract OPEs (methanol extraction), but only 1 mg was used to extract from Ships 1 and 3.

2.1 SUPRA Extraction

A SUPRA mixture was made using 3 ml of 1-Hexanol, 6 ml tetrahydofuran (THF), and 21 ml Milli-Q ultrapure water. The mixture was shaken well by hand before being centrifuged for 30 minutes at 2400 rpm (1250 G). The upper layer (SUPRA layer) was transferred to a 15 ml centrifuge tube, and the equilibrium solution was kept in the main glass container. For extraction, 100 mg of homogenized dust was spiked with 50 µL of recovery standard consisting of isotopic labelled PBDEs and AHFRs (Table S2). The solvent was evaporated to dryness under a gentle stream of nitrogen. The dried dust was then reconstituted with 600 µL of SUPRA equilibrium solution to ensure full wetting, followed by an additional 400 µL of the SUPRA solution. Samples were sonicated at room temperature for 20 minutes, then centrifuged at 11,000 rpm (5411G) for 15 minutes. The resulting supernatants were transferred into clean GC/LC vials and evaporated to dryness under nitrogen. 50 µL of nonane was added. Prior to instrumental analysis, each extract was spiked with 50 µL of recovery standards (0.2 mg/mL 13C-labelled PCB-95 and 4 µg/mL p-terphenyl) and with 10 µL of 100 ng/mL BDE-77 and BDE-138 as syringe standards. The recovery standards were used to monitor and account for extraction efficiency, while the syringe standards were used to verify injection consistency and the accuracy of the instrumental analysis

2.2 Methanol extraction

To analyze OPEs, 10 mg (for Ship 2) and 1 mg (Ships 1 and 3) of dust was spiked with 50 µl recovery standard (deuterated OPEs; Table S3). 3 ml of methanol was added to each sample, after which it was placed in an ultrasonic bath for 20 minutes and left to settle for a further 20 minutes. The extract was transferred to a new clean vial. The process was repeated twice more (3 times total) until 9 ml of extract was in vials. The volume was reduced to 1 ml under nitrogen flow. The extract was filtered through a syringe filter (Chromafil Xtra PA-45/13; Macherey-Nagel) into a mini vial, after which it was reduced to <0.5 ml under nitrogen flow. Methanol was added to an exact volume of 0.5 ml (determined by weight), followed by 0.5 ml of ultrapure Milli-Q water. All internal standards were procured from Wellington Laboratories, Canada.

Table S3: Internal Standards for compounds used in GC/MS analysis. Spiked volumes for all standards were 50 µl.

Group	**Internal Standard**	**Concentration** (µg/ml)
PBDEs	13C12 PBDE 28	0.02
PBDEs	13C12 PBDE 47	0.02
PBDEs	13C12 PBDE 99	0.02
PBDEs	13C12 PBDE 100	0.02
PBDEs	13C12 PBDE 153	0.02
PBDEs	13C12 PBDE 154	0.02
PBDEs	13C12 PBDE 183	0.02
PBDEs	13C12 PBDE 209	0.1
AHFRs	13C6 PBBZ	0.02
AHFRs	13C6 HBB	0.02
AHFRs	13C aDP	0.02
AHFRs	13C sDP	0.02
AHFRs	13C6 BTBPE	0.02
AHFRs	13C6 d17-BEH-TEBP	0.02
AHFRs	13C6 d17-EH-TBB	0.02
AHFRs	13C14 DBDPE	0.03

Table S4: Internal Standards for compounds used in LC/MS analysis. Spiked volumes for all standards were 50 µl.

Group	**Internal Standard**	**Concentration**

		(µg/ml)
OPEs	D15 TDCIPP	0.2
OPEs	D27 TNBP	0.2
OPEs	D21 TnPP	0.2
OPEs	13C12 TPHP	0.2

Text S3: Instrumental analyses

S3.1 OPEs

OPEs were quantified using an Agilent 1290 Infinity high performance liquid chromatography (HPLC) (Agilent Technologies, Santa Clara, CA, USA) coupled to an Agilent 6495 triple quadrupole mass spectrometer operating in positive electrospray ionization mode (ESI+). Chromatographic separation was performed on an ACQUITY BEH C18 column (2.1 mm × 100 mm, 1.7 µm; Waters Corporation, Milford, MA, USA), maintained at 30 °C. A 3 µL injection volume was used for all samples. The mobile phases consisted of 0.1% formic acid in water (A) and 0.1% formic acid in methanol (B), with a flow rate of 0.2 mL/min. Mass spectrometric detection was conducted under the following source conditions: capillary voltage of 2700 V, source temperature of 400 °C, and nitrogen as the sheath gas. Quantification was performed using isotope dilution with 13C- or deuterium-labeled standards for TPHP, TnBP, TDCIPP, and TnPP. The method operated in multiple reaction monitoring (MRM) mode, with a linear calibration range of 0.09–90 µg/L and limits of quantification (LOQs) between 0.01 and 0.79 µg/L for individual analytes.

Table S5. Ion source parameters of LC/MS analyses

Parameter	
Drying gas temperature (°C)	290
Drying gas flow (L/min)	11
Nebulizer (psi)	25
SheathGasHeater (°C)	400
SheathGasFlow (L/min)	12
Capillary voltage (V)	2700

Table S6. Mass spectrometric parameters for OPE analyses (LC/MS)

Analyte	Precursor ion (m/z)	Product ion (m/z)	Fragmentor (V)	Collision energy (V)	Retention time (min)
CDP (Quan)	341.1	152	166	40	7.1
CDP (Qual)	341.1	91	166	40	7.1
EHDPP (Quan)	363.17	251	166	13	10.0
EHDPP (Qual)	363.17	77.2	166	50	10.0
ip-TPP (Quan)	453.22	411.1	166	13	12.0
ip-TPP (Qual)	453.22	327	166	29	12.0
TBOEP (Quan)	399.25	299.1	166	9	7.8
TBOEP (Qual)	399.25	199.1	166	9	7.8
TCEP (Quan)	284.96	222.9	166	9	2.3
TCEP (Qual)	284.96	63.2	166	41	2.3
TCIPP (Quan)	329	99	166	20	4.0
TCIPP (Qual)	327	99	166	25	4.0
TDBPP (Quan)	698.6	99	166	30	7.5
TDBPP (Qual)	692.6	99	166	25	7.5
TDCIPP (Quan)	432.9	99	166	30	6.0
TDCIPP (Qual)	430.9	99	166	30	6.0
TDCIPP-d15 (Quan)	448	102	166	30	6.0
TDCIPP-d15 (Qual)	446	102	166	30	6.0
TEHP (Quan)	435.36	99.1	166	10	14.7
TEHP (Qual)	435.36	71	166	20	14.7
TEP (Quan)	183.08	99	166	29	3.0
TEP (Qual)	183.08	81	166	49	3.0
TiBP (Quan)	267.2	99	166	15	7.4
TiBP (Qual)	267.2	81	166	30	7.4
m/pTMPP (Quan)	369.1	166	166	30	9.2
m/pTMPP (Qual)	369.1	91.2	166	40	9.2
oTMPP (Quan)	369.1	166	166	30	9.1
oTMPP (Qual)	369.1	91.2	166	40	9.1
TNBP (Quan)	267.17	99	166	13	7.1
TNBP (Qual)	267.17	81	166	49	7.1
TNBP-d27 (Quan)	294.34	166.1	166	13	7.1
TNBP-d27 (Qual)	294.34	102	166	13	7.1
TnPP (Quan)	225.13	141	166	9	4.0
TnPP (Qual)	225.13	99	166	29	4.0
TnPP-d21 (Quan)	246.26	150.1	166	13	4.0
TnPP-d21 (Qual)	246.26	102	166	21	4.0
TPHP (Quan)	327.08	152.1	166	45	6.0
TPHP (Qual)	327.08	77.1	166	41	6.0
TPHP-C13 (Quan)	345.08	164.1	166	33	6.0
TPHP-C13 (Qual)	345.08	83.1	166	41	6.0

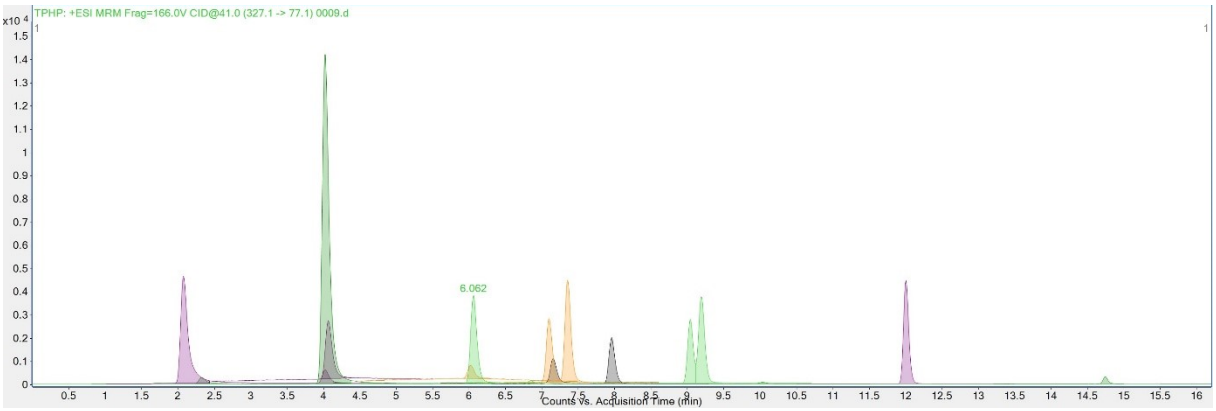

Figure S3.Chromatographic separation of OPE - analytical standards mixture at 10ppb, column Waters Acquity UPLC BEH C18 100x2,1mm

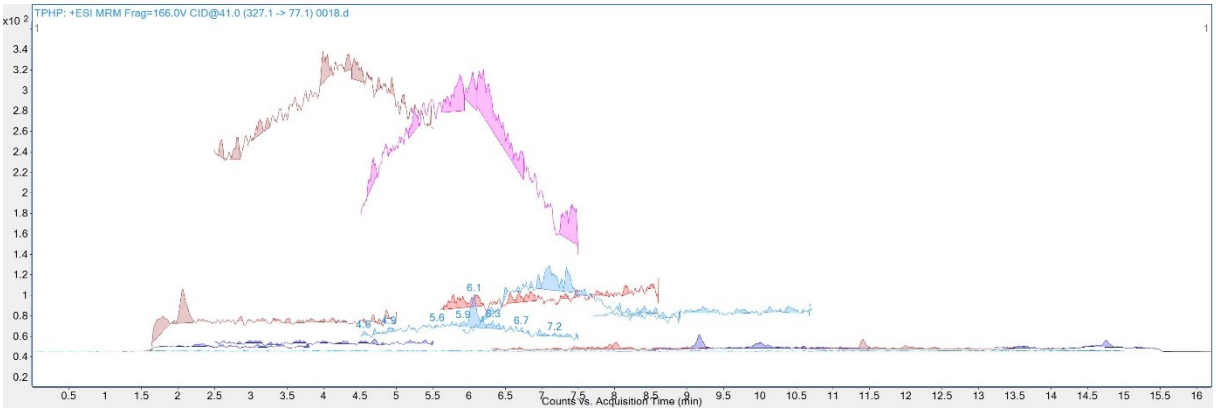

Figure S4. Chromatographic separation of OPE - blank sample, column Waters Acquity UPLC BEH C18 100x2,1mm

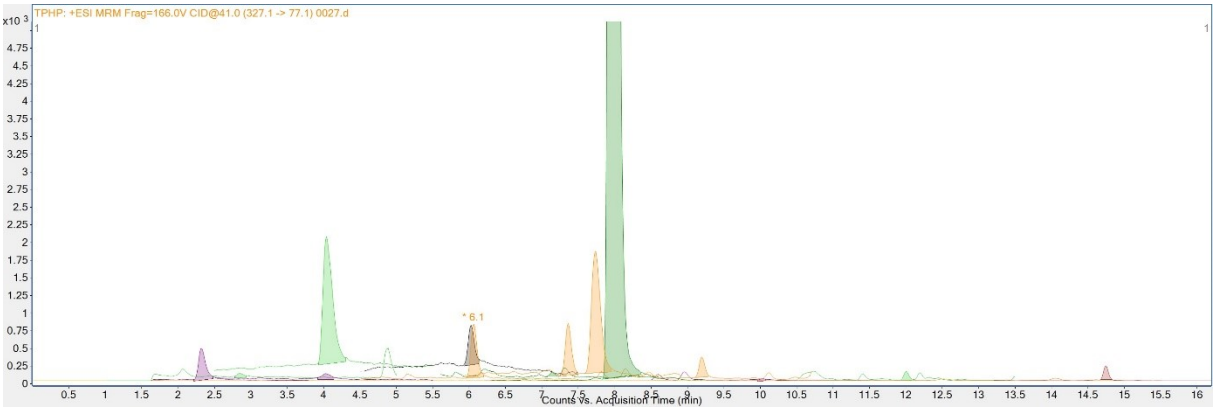

Figure S5. Chromatographic separation of OPE - dust sample (NIST® SRM® 2585), TBOEP (tR=7.9 min) intensity 8x104 counts, column Waters Acquity UPLC BEH C18 100x2,1mm

S3.2 PBDEs

PBDEs were analyzed using an Agilent 7890A gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) equipped with an RTX-1614 capillary column (15 m × 0.25 mm i.d., 0.10 µm film thickness; Restek, France), coupled to a Waters AutoSpec Premier high-resolution mass spectrometer (Waters Corporation, Milford, MA, USA). The GC oven temperature program was as follows: an initial hold at 80 °C for 1 minute; ramp at 20 °C/min to 250 °C (no hold); then 1.5 °C/min to 260 °C (2 minute hold); and finally 25 °C/min to 320 °C with a 4.5 minute hold. The GC–MS interface and ion source were maintained at 280 °C and 250 °C, respectively. A 2 µL injection was performed in pulsed splitless mode at 280 °C. Helium was used as the carrier gas at 1.0 mL/min, increased to 1.4 mL/min after 15 minutes. Mass spectrometric detection was conducted in electron impact (EI+) mode using selected ion monitoring (SIM) at a resolving power of >10,000. For BDE-209, a reduced resolution of >5,000 was applied to improve sensitivity.

Table S7. Mass spectrometric parameters for PBDE analyses (GC/MS).

Abbreviation	Quantifier Ion [m/z]	Qualifier Ion [m/z]	Retention time [min]
PBDE28	405.8027	407.8007	7.97
PBDE47	485.7112	483.7132	9.00
PBDE66	485.7112	483.7132	9.15
PBDE85	563.6216	565.6197	10.55
PBDE99	563.6216	565.6197	10.02
PBDE100	563.6216	565.6197	9.77
PBDE153	643.5302	641.5322	11.40
PBDE154	643.5302	641.5322	10.87
PBDE183	721.4407	723.4387	13.55
PBDE209	799.3335	797.3355	22.18
13C-PBDE28	417.8429	419.8409	7.97
13C-PBDE47	497.7513	495.7533	9.00
13C-PBDE99	575.6618	577.6598	10.02
13C-PBDE100	575.6618	577.6598	9.77
13C-PBDE153	655.5703	653.5723	11.40
13C-PBDE154	655.5703	653.5723	10.87
13C-PBDE183	733.4808	735.4788	13.55
13C-PBDE209	811.3737	809.3757	22.18
13C-PBDE77	497.7513	495.7533	9.37
13C-PBDE138	655.5703	653.5723	12.26

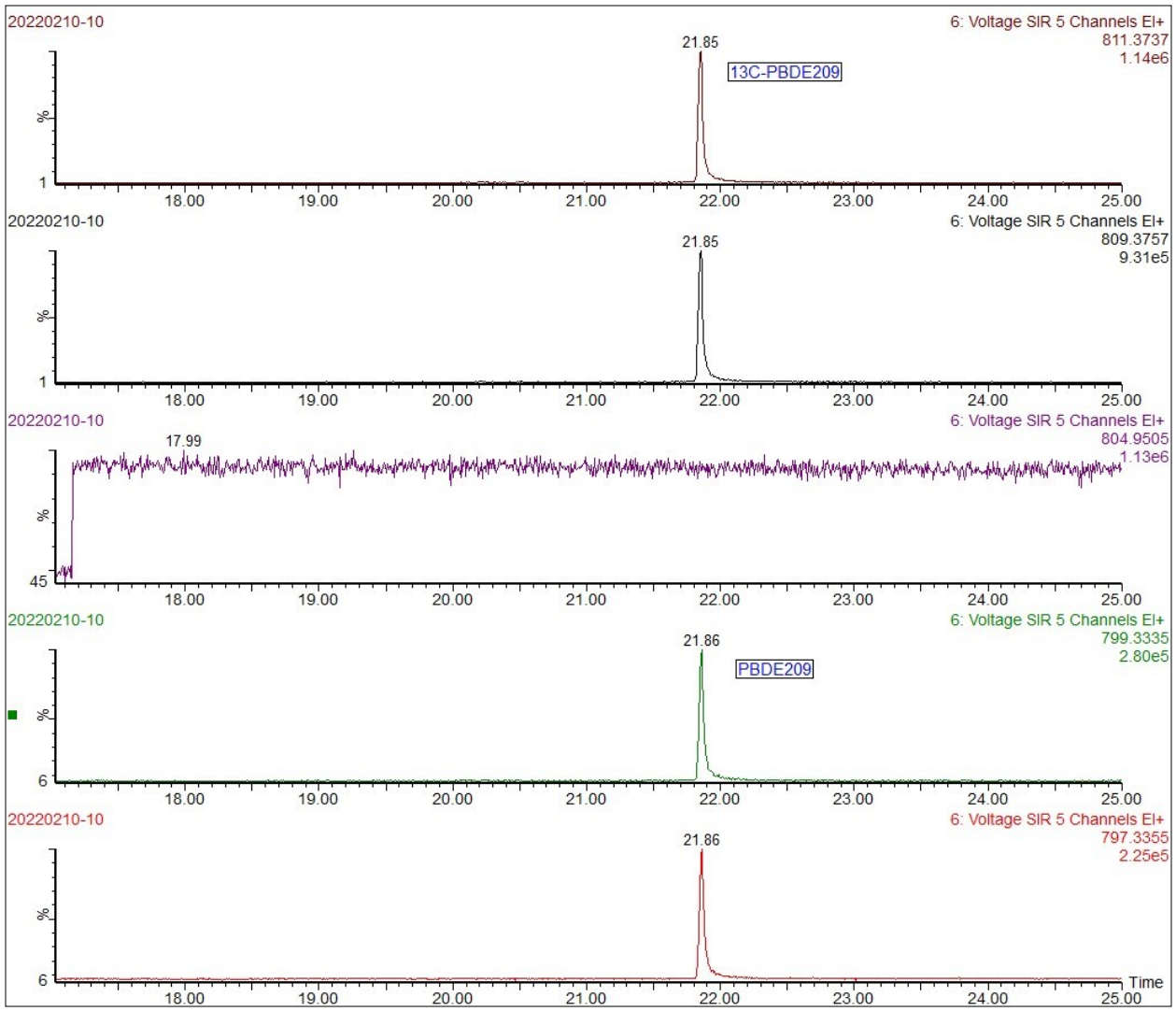

Figure S6. Example chromatograph of BDE-209 standard

S3.3 AHFRs

AHFRs were analyzed using an Agilent 7890A gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) equipped with an RTX-1614 capillary column (15 m × 0.25 mm i.d., 0.10 μm film thickness; Restek, France), coupled to a Waters AutoSpec Premier high-resolution mass spectrometer (Waters Corporation, Milford, MA, USA). The GC oven temperature program was as follows: initial hold at 80 °C for 1 minute; ramp at 30 °C/min to 140 °C; then 4 °C/min to 175 °C;

8 °C/min to 270 °C; and finally 15 °C/min to 325 °C with a 5-minute hold. A 2 µL injection was performed in pulsed splitless mode at 250 °C. Helium was used as the carrier gas at 1.0 mL/min, increased to 1.4 mL/min after 15 minutes. Mass spectrometric detection was conducted in electron impact (EI+) mode using selected ion monitoring (SIM) at a resolution of >10,000.

Table S8. Mass spectrometric parameters for AHFR analyses (GC/MS)

Abbreviation	Quantifier Ion [m/z]	Qualifier Ion [m/z]	Retention time [min]
ATE	369.8027	371.8027	5.66
pTBX	340.7999	342.7979	9.43
BATE	329.7714	331.7693	9.57
PBBZ	471.5954	473.5934	9.86
TBCT	441.6614	443.6593	10.75
PBT	485.6111	487.6090	12.72
PBEB	499.6266	501.6247	13.49
DPTE	531.6353	529.6372	15.10
HBB	551.5038	549.5059	15.21
PBBA	476.6983	474.7003	17.68
EH-TBB	420.6720	418.6740	18.75
BTBPE	358.7928	356.7984	23.34
BEH-TEBP	464.6618	462.6638	24.33
sDP	271.8102	273.8072	24.33
aDP	271.8102	273.8072	24.74
DPMA	344.9353	379.9041	11.91
aDBE-DBCH	266.9207	268.9187	8.61
bDBE-DBCH	266.9207	268.9187	8.81
gdDBE-DBCH	266.9207	268.9187	10.14
aTBCO	266.9207	268.9187	10.78
bTBCO	266.9207	268.9187	9.76
DBHCTD	267.9285	269.9265	18.59
T23BPIC	487.8643	447.8330	23.99
DBDPE	486.6012	484.6032	29.25
13C-PBBZ	477.6155	479.6135	9.86
13C-HBB	559.5219	561.5199	15.21
13C-EH-TBB	444.7011	446.6991	18.62
13C-BEH-TEBP	471.6882	469.6903	24.16
13C-BTBPE	362.8149	364.8129	23.34
13C-DBDPE	491.6267	493.6246	29.25
13C-sDP	276.8269	278.8240	24.33
13C-aDP	276.8269	278.8240	24.74

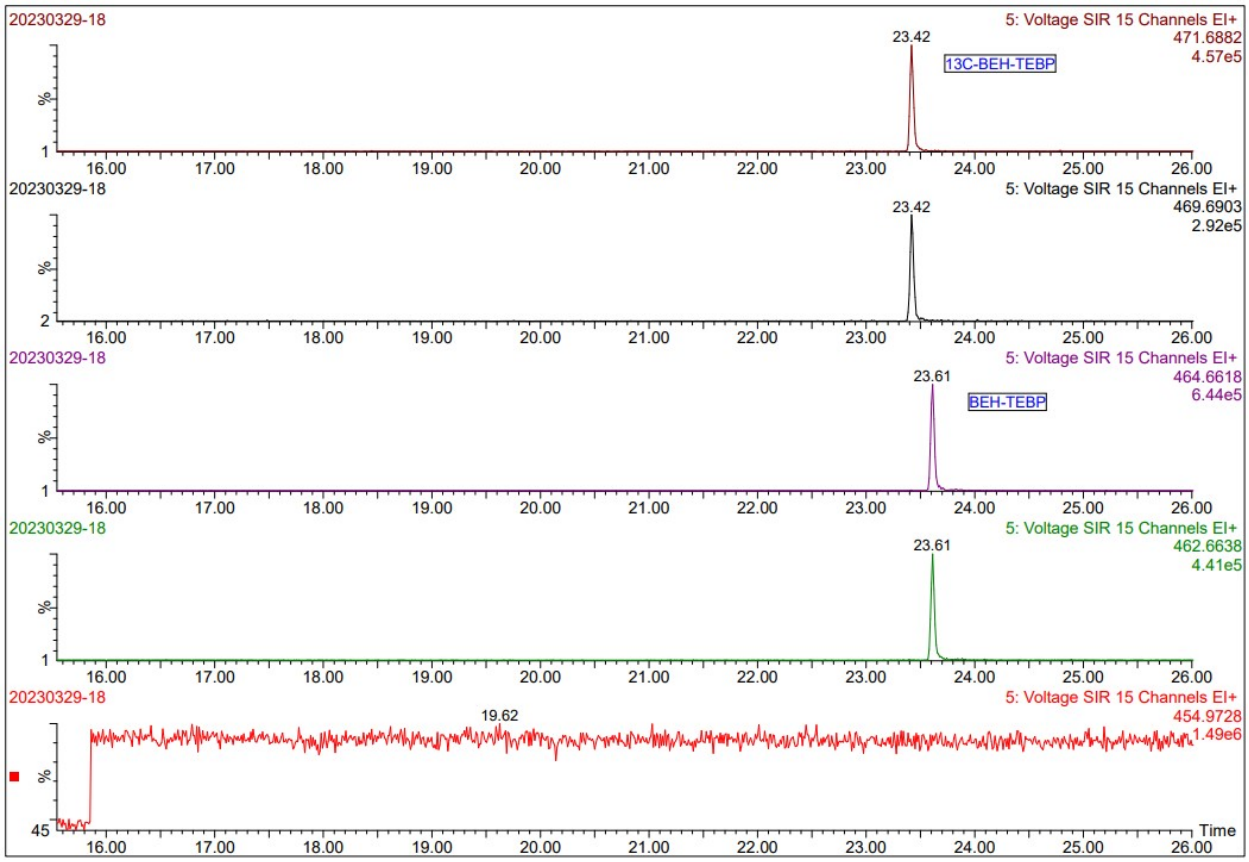

Figure S7. Example chromatograph of BEH-TEBP analyes

Text S4: Quality assurance/ Quality control

Recovery efficiencies for samples were tracked by spiking dust samples with labeled analytes prior to extraction. All compounds are adjusted for recoveries through the use of internal (recovery) standards.

Field blanks were collected aboard each research vessel to assess background contamination. These consisted of clean sampling filters briefly exposed to ambient air (30 seconds) and then sealed. A total of seven field blanks were collected: Four from Ship 1, and three from Ships 2 and 3 (although one from Ship 3 was excluded due to contamination from an improperly sealed shaker container during liquid nitrogen processing).

Method detection limits (MDLs) were calculated as the average field blank concentration plus three times the standard deviation of the blank values. For analytes not detected in any blank samples, the instrument detection limit (IDL) was used as the MDL. Sample concentrations above MDL were corrected by subtracting the average blank concentration of the corresponding matrix; values below MDL were reported as such.

All instrumental methods rely on mass-labelled or structurally similar non-environmental congeners to compensate for potential losses during extraction and handling. This is necessary as absolute recoveries can be highly variable due to the heterogeneous composition and heavy matrix effect of dust.

Table S9. Recovery rates (%) of deuterated OPE internal standards

	Min	Max	Median
TNBP-d27	10.3	63.5	45.8
TnPP-d21	14.4	41.2	29.7
TDCIPP-d15	17.7	86.3	61.1
TPHP-C13	4.4	98.7	61.9

Table S10. Recovery rates (%) of isotopically labeled PBDE internal standards

	Min	Max	Median
13C-BDE 28	20.2	90.0	50.2
13C-BDE 47	22.4	69.8	53.3
13C-BDE 100	17.8	73.5	41.7
13C-BDE 99	16.8	73.3	42.7
13C-BDE 154	16.3	63	43.1
13C-BDE 153	18.6	65.8	49.3
13C-BDE 183	26.4	81.9	58.6
13C-BDE 209	5.1	464	32.7

Table S11. Recovery rates (%) *of isotopically labeled AHFR standards*

	Min	Max	Median
13C BTBPE	26.9	184.3	57.5
13C sDP	11.5	87.6	31.9
13C aDP	7.5	75.	25.1
13C PBBZ	13.1	40.4	27.1
13C HBB	20.3	59	36.7
13C EHTBB	30.1	124	75.2
13C BEHTBP	84.9	293	153

Results

Table S12: Full list of measured concentrations .....See excel file

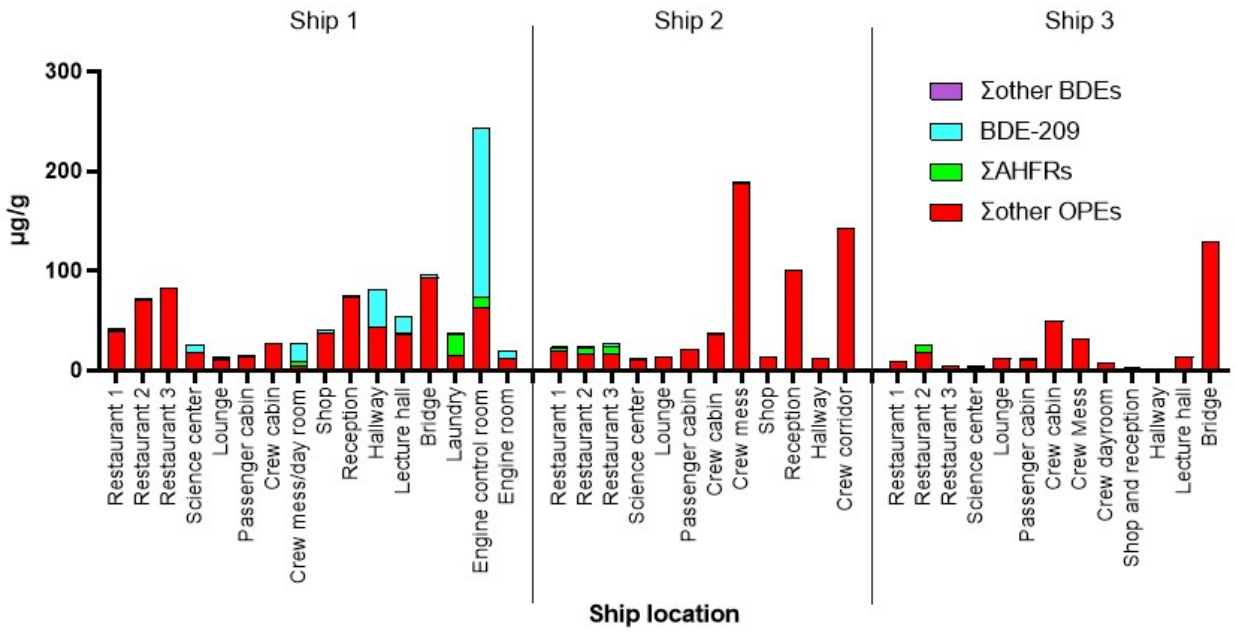

Figure S8. Flame retardant concentrations in different locations across the three sampled ships; excluding TCIPP.

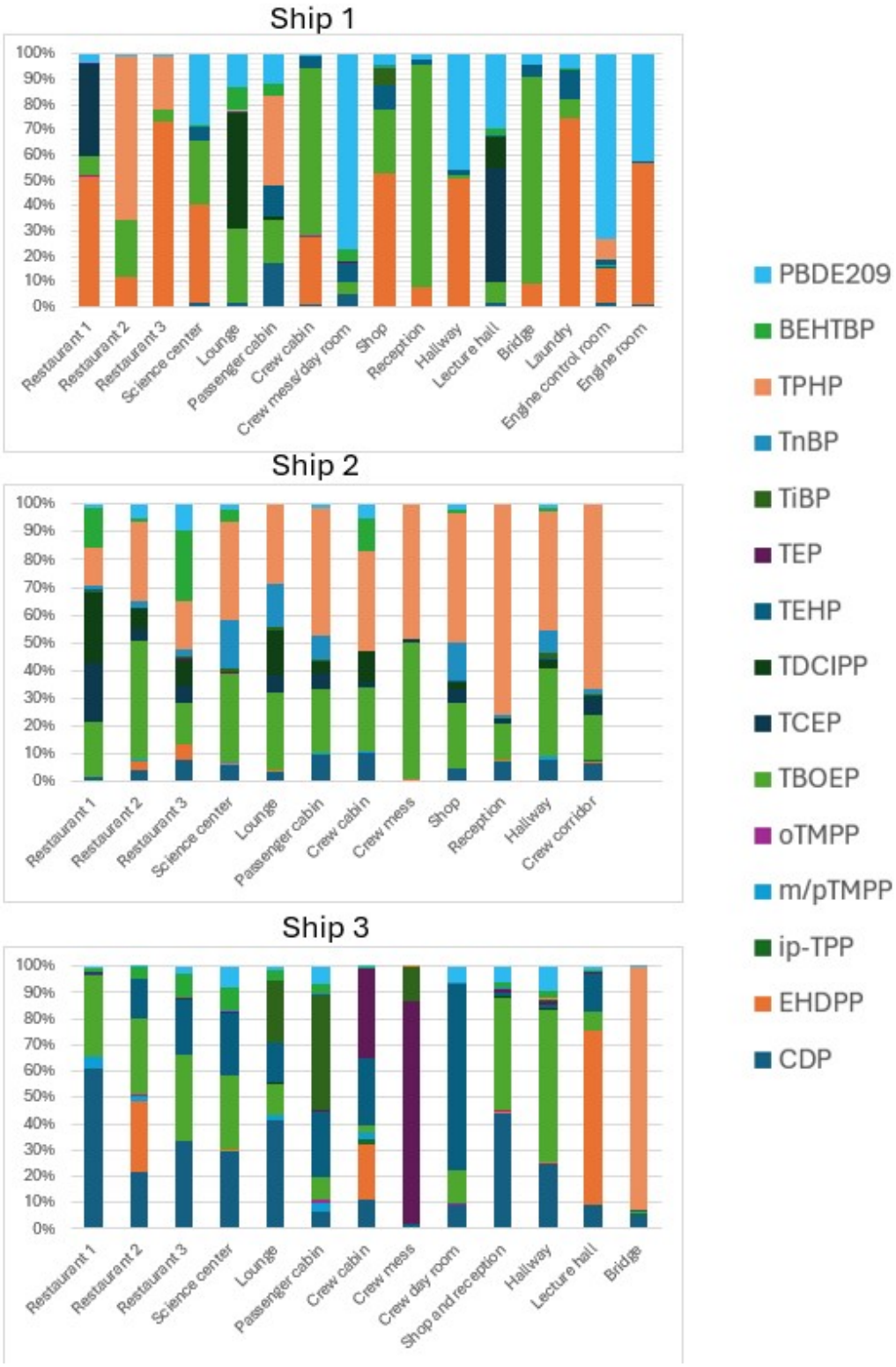

Figure S9. Relative compositions of major flame retardants in different areas of three expedition ships excluding TCIPP.

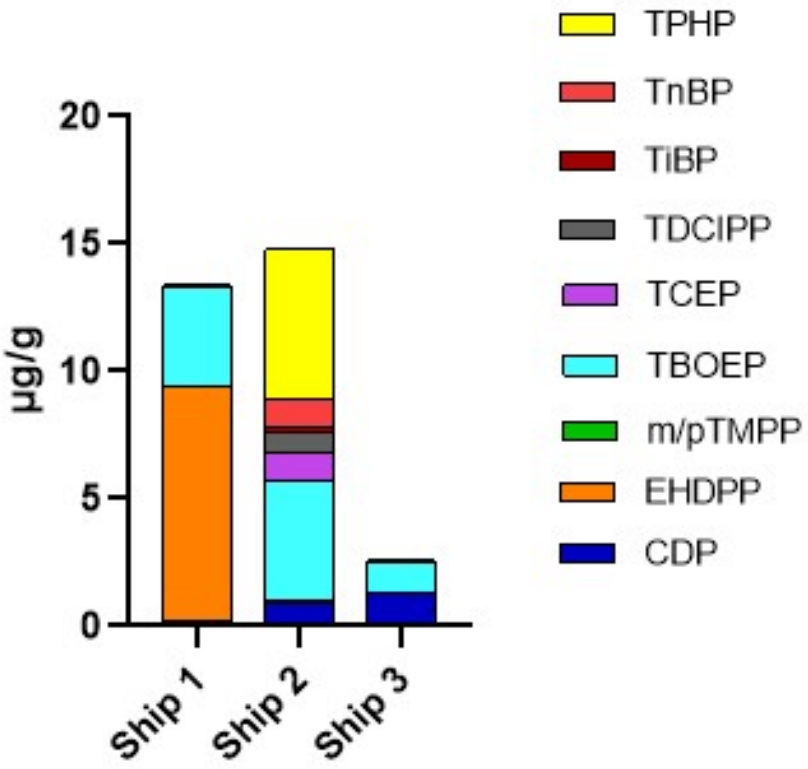

Figure S10. Median OPE concentrations across different ships, excluding TCIPP.

Table S13: Estimated FR exposures via dust **See excel file**

References

1 P. Marcinekova, L. Melymuk, P. Bohlin-Nizzetto, E. Martinelli, S. R. Jílková, J. Martiník, P. Šenk, P. Kukučka, O. Audy, J. Kohoutek, M. Ghebremeskel, A. Håland, A. R. Borgen, H. Eikenes, L. Hanssen, M. Harju, Z. Cebula and P. Rostkowski, Development of a supramolecular solvent–based extraction method for application to quantitative analyses of a wide range of organic contaminants in indoor dust, *Anal Bioanal Chem*, 2024, **416**, 4973–4985.

2 P. Svobodová, S. R. Jílková, J. Kohoutek, O. Audy, P. Šenk and L. Melymuk, High levels of flame retardants in vehicle dust indicate ongoing use of brominated and organophosphate flame retardants in vehicle interiors, *Environ Monit Assess*, 2025, **197**, 1–17.