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► To cite this version:

Hervé Plaisance, Mylène Ghislain, Valérie Desauziers. Assessment of gas-phase concentrations of organophosphate flame retardants at the material surface using a midjet emission cell coupled to solid-phase microextraction. *Analytica Chimica Acta*, 2021, 1186, pp.339100. 10.1016/j.aca.2021.339100 . hal-03354100

HAL Id: hal-03354100

<https://imt-mines-ales.hal.science/hal-03354100>

Submitted on 16 Oct 2023

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1 **Assessment of gas-phase concentrations of organophosphate flame**
2 **retardants at the material surface using a midget emission cell**
3 **coupled to solid-phase microextraction**

4
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13 **ABSTRACT**

14 Actual methods for on-site measurement of gaseous concentrations of Semi-Volatile Organic
15 Compounds (SVOCs) at the material surface (y^0) are not yet sufficiently developed mainly
16 due to sampling difficulties. These concentrations are the key data to improve knowledge
17 about indoor sources and human exposure to SVOCs. To the end, a specific emission cell
18 coupled to solid-phase microextraction (SPME) was developed. The main challenge with this
19 method is calibration because of very low volatility of SVOCs and static sampling mode. In
20 this study, a generating system of organophosphate flame retardants (OFRs) using
21 polyurethane foam as source combined with an active sampling method with Tenax tubes was
22 proposed as a novel calibration device for SPME-based method. The generating system
23 delivered stable OFR concentrations after 190 hours of operation with a variation not
24 exceeding $\pm 5\%$. It allowed to obtain robust calibrations for tris-(2-chloropropyl)-phosphate
25 (TCPP) and tri-butyl-phosphate (TBP) measured with the emission cell coupled to SPME-
26 based method, define the optimal sampling requirements and achieve reproducible and
27 accurate measurements of y^0 at $\mu\text{g}\cdot\text{m}^{-3}$ level.

28 TCPP and TBP gas-phase concentrations at the polyurethane foam surface (y^0) were followed
29 up over more 228 days under controlled temperature conditions. A high stability of these
30 concentrations was observed showing that polyurethane foam acts as a stable and continuous
31 source of organophosphate flame retardants indoors. This novel method should be useful for
32 assessing the dynamic of emissions from indoor sources and potential exposure to SVOCs in
33 indoor environments.
34

35 **KEYWORDS**

36 Indoor air quality, Organophosphate flame retardants, Material emission, Polyurethane foams,
37 Gas-phase SVOCs generation system.

38

39 **1. Introduction**

40 A large number of building materials and household products contain Semi-Volatile Organic
41 Compounds (SVOCs) which are used as plasticizers, flame retardants, preservatives,
42 repellents, combustion products, pesticides, surfactants and personal care products [1-3]. In
43 many materials, SVOCs account for a mass fraction from 1 to 30% [1,4]. Despite their low
44 saturated vapor pressures ranging from 10^{-2} to 10^{-8} kPa at 298 K, SVOCs can vaporize from
45 the surfaces of products containing them [5]. They are partitioned partly as gaseous chemicals
46 and partly as chemicals sorbed on indoor surfaces and onto airborne and settled particles [6].
47 People are exposed to SVOCs via multiple pathways (inhalation, ingestion and dermal
48 contact) [7-8]. Human exposure to many SVOCs has been associated with severe health
49 impacts as including asthma, allergies, endocrine disruption, reproductive disorders and
50 cancer [9-12]. As shown by Little *et al.* [13], the SVOCs gas-phase concentration adjacent to
51 the source material (y^0 , $\mu\text{g}\cdot\text{m}^{-3}$) is a key parameter to describe the behavior of these
52 compounds indoors.

53 Many methods have been developed to measure y^0 [14]. There are two main experimental
54 approaches: (1) the ventilated emission chambers (or cell) with active air sampling like
55 CLIMPAQ [15], FLEC [16], microchamber [17], sandwich-like chamber [18], Early stage C-
56 history method [19] and varied ventilation rate (VVR) method [20] and (2) the
57 closed emission chambers (or cell) with passive sampling like the passive flux sampler (PFS)
58 [21], thermal desorption tube [22] and SPME-based method [23]. Gong and Poppendieck [24]
59 discussed the main features, advantages and disadvantages of these methods.

60 Normally, the closed systems with passive sampling methods require shorter experimental
61 time (from one to several days) than ventilated devices (from a few days to many months) and
62 are the only devices that can be used for on-site measurement of SVOCs indoors [24].

63 In the case of the SPME-based method, y^0 can be measured directly inside the closed device
64 containing the source material after that the steady state is reached [23,25]. Indeed, when the
65 gaseous concentration becomes stable inside the closed device, there is no more mass transfer
66 of compound between the gas phase and the inner surfaces (source material and inner walls of

67 device). In consequence, the steady state SVOC concentration can be assimilated to y^0
68 [23,25]. The main difficulties of the SPME-based method for measuring y^0 concern the
69 calibration and setting of sampling parameters including air/material equilibrium time and
70 sampling time [24]. The SPME sampling is based on the molecular diffusion process of the
71 compound in air to a sorbent according to the Fick's first law [26]. In non-equilibrium
72 conditions (linear sorption), the mass of SVOC sorbed onto the fiber (m) and the product of
73 its concentration in air and the exposure time ($y^0 \times t$) are linearly related [26-27]. To establish
74 this linear relationship $m=k \times (y^0 \times t)$ with k constant, a calibration related to a traditional active
75 sampling method and the use of a generation of gas atmospheres are required.

76 . However, the conventional means used for the continuous production of gas atmospheres,
77 such as permeation tube, syringe pump or compressed gas cylinder, cannot be used for
78 SVOCs because of their very low volatility. Furthermore, SVOCs can be partially sorbed or
79 deposited onto all inner surfaces of the generation device and tubing [2].
80

81 In the literature, a few methods are available to generate gas-phase SVOCs with stable and
82 controlled concentrations. They most often require very long times (several days or even
83 several months) to reach stable concentrations [28]. The favored approach is gaseous release
84 from solid or liquid phase materials containing SVOCs [29,30]. As shown by Clausen *et al.*
85 [15], the DEHP generation from PVC placed in a FLEC cell was stable after 240 days, while
86 in a CLIMPAQ chamber, the stable concentration was not reached for the entire duration of
87 the experiment (450 days). Extended to phthalates from building materials, a special stainless-
88 steel chamber designed by Xu *et al.* [31] and its improved version [18] allowed to short the
89 times to reach stable generating states to 20 days and 1-2 days, respectively. More recently,
90 Chen *et al.* [28] used impregnated porous media (Carbon sponges and honeycomb ceramics)
91 to generate constant gas-phase concentrations of phthalates after 4.5, 18.5 and 89.5 hours
92 according to the compounds.

93 This work was part of development on an emission cell (MOSEC) coupled to SPME-based
94 method intended to on-site measurement of SVOCs gas-phase concentration at the material
95 surface already described in a previous paper [25]. It focused on the measurement of tris-(2-
96 chloropropyl)-phosphate (TCPP) and tri-butyl-phosphate (TBP), flame retardants emitted
97 from polyurethane (PU) foam. The objectives were: (1) to test and validate a calibration
98 procedure based on a new experimental device to generate gas-phase TCPP and TBP from PU
99 foam, (2) to define the optimal sampling conditions (steady state condition and extraction
100 time) and provide method performance characteristics, (3) to provide information on time
variation of TCPP and TBP gas-phase concentrations at the polyurethane foam surface.

101

102 **2. Materials and Methods**

103
104

104 **2.1. Passive sampling method**

105

106 The passive sampling device used for the determination of gaseous SVOC
107 concentrations at the material surface was already described in a previous article [25].
108 It consists of a home-made emission glass cell (named MOSEC) of 60 mL covering a
109 sampling area of 17 cm². The top of the cell has a cap with a septum for SPME fiber
110 introduction. The bottom was fitted with a thread for hermetically sealing the cell with
111 a silonite coated stainless steel screw cap equipped with a vacuum valve. This airtight
112 cell configuration is used in the cleaning procedure and in the experimental device for
113 calibration, as described below. First of all, the emission cell is placed directly on the
114 material surface (Fig.1a). SVOCs released from the material, diffuse inside the air
115 volume of the cell, and are partially sorbed onto the cell walls. When the gaseous
116 concentration is stable in the cell, the mass transfers from the source material to air and
117 from air to the cell walls become zero. At this steady state, the gaseous concentration is
118 measured using a 100 μm PDMS SPME fiber in the linear sorption conditions (Fig.1b).
119 A previous study [25] showed that there is no significant difference in the steady state
120 SVOC concentration measured in the 60 mL and 120 mL cells. This confirmed that
121 this gaseous concentration can be assimilated to y^0 , since its value does not depend on
122 the amount sorbed onto the cell walls before reaching the steady state.

122

123 Prior to sampling, the fiber was conditioned in the injection port at 300 °C. Before use, the
124 cell was soaked in water, rinsed with methanol and then dried in an oven at 100 °C. Some
125 vacuum/clean air filling cycles complemented the procedure of cleaning, in order to achieve
126 acceptable blank levels [25].

127

128

128 **2.2. Material samples and target SVOC**

129

130

131 The test material used as the SVOC emission source was a soft polyurethane (PU) foam. It
132 was part of a series of polyurethane foam models manufactured in an earlier study to assess
133 the migration and potential risks of phosphorus flame retardants from fireproofing of
134 domestic upholstered furniture [32]. Upholstered furniture is one of the main known sources
of phosphorus flame retardants indoors [33]. The manufacturing method of material test was

135 given in detail by Ghislain *et al.* [34]. It was obtained by polymerization of polyol mixture
136 with isocyanate following a commonly used procedure. Phosphorus flame retardants were
137 directly incorporated in the reactant mixture during foam polymerization. The test material
138 initially contained TCPP and TBP in mass fractions of 7.6 %. Polyurethane foam samples
139 were 41 × 24 cm panels with a thickness of 1 cm and a density of 200 kg.m⁻³. Each material
140 sample was wrapped in aluminum foil and stored at room temperature prior to the tests.
141 TCPP and TBP were the target compounds chosen for these tests. TBP is an alkylphosphate
142 and its vapor pressure is to 4.65 × 10⁻¹ Pa at 298 K. TCPP is a chlorinated organophosphate
143 less volatile than TBP with a vapor pressure of 7.52 × 10⁻³ Pa at 298 K. They are in a class of
144 organophosphate esters commonly used as flame retardants, plasticizers and anti-foaming
145 agents in a wide variety of consumer products like foams, textiles, resins and vinyl polymers
146 [35,36].
147

148 **2.3. Implemented experimental device for calibration**

149
150 A new experimental device was especially developed to generate gas-phase TCPP and TBP
151 from PU foam. It consisted of three 89 mm long and 6.35 mm diameter stainless steel tubes
152 filled each one with 0.35 g of PU foam and connected in series to the MOSEC cell (Fig.2a).
153 These tubes were flowed by humidified clean air at the stable conditions of relative humidity
154 and temperature (HR=50 ± 3% at T=23 ± 2°C) produced by a dry zero air generator (Claind,
155 Marcq-en-Baroeul, France) and a humidifier made of a water bubbler and regulated by mass
156 flow controllers (Bronkhorst, Montigny-les-Cormeilles, France). The airflow rate was
157 maintained at 60 mL.min⁻¹ for all the duration of test. The air flow was transferred from the
158 tubes to MOSEC cell via a needle introduced in two septa (the one placed in the nut of the last
159 tube and the other one at the cap of MOSEC cell). This connection and the source material set
160 in thin tubes had the advantage of reducing the air volume upstream from the MOSEC cell
161 favouring a fast transfer of SVOC from the source to the cell. The sealed closing of the cell
162 was provided by an o-ring placed in the screw cap. The air leakage rate in this generation
163 device of SVOC was assessed at less than 5% and checked systematically after each sampling
164 throughout the test using a soap film flowmeter (Model M-30, AP BUCK, USA).
165 First, the emission cell was continuously crossed by air coming from the tubes containing the
166 source material until the gas-phase SVOC concentrations became stable (Fig.2a). The SPME-
167 based method described in section 2.1 was used to describe the increase in gaseous SVOC
168 concentrations in the cell. To this end, the MOSEC cell was temporally isolated for sampling

169 by SPME as shown in Fig.2b. Once the gaseous concentrations achieved stability, an active
170 sampling with Tenax tubes was performed at 40 mL.min⁻¹ for 6 hours (Fig.2c). This allowed
171 to assess the gaseous SVOC concentrations under the stable conditions of the generation
172 system. Then, a series of SPME measurements with variable extraction time from 1 to 10
173 minutes was carried out (in isolated cell) in order to plot the calibration curve between the
174 amount of compound adsorbed on the fiber and the product of its gaseous concentration
175 (assessed by active sampling method with Tenax tube) and the extraction time [27,37]. This
176 method of calibration was used to convert the compound amount sampled by SPME fiber into
177 the gaseous concentration.

178
179

2.4. Tenax cartridge analysis

180
181 Analysis of Tenax tubes was carried out with a TurboMatrix 650 ATD thermal desorption
182 system (PerkinElmer, Waltham, MA, USA). The Tenax tubes were heated at 330 °C for 15
183 min, using a helium flow rate of 100 mL.min⁻¹ without inlet split to desorb the analytes and
184 focus them into a cold trap kept at 1 °C. Desorption trap was ramped at 99 °C.s⁻¹ to 350 °C,
185 held for 10 min, with an outlet split of 5 mL.min⁻¹. The transfer line to the GC and the valve
186 were maintained at 250 °C. Separation and detection were performed with a PerkinElmer
187 Clarus 680 gas chromatograph. The carrier gas was helium with a flow rate of 1.3 mL.min⁻¹.
188 A 5% phenyl Elite-5 capillary column (PerkinElmer, Waltham, MA, USA) of 60 m, 0.25 mm
189 i.d. and 0.25 µm film thickness was used. The oven temperature was maintained 2 min at 50
190 °C, then ramped at 15 °C.min⁻¹ to 200 °C, held for 2 min, then ramped at 15 °C.min⁻¹ to 300
191 °C, held for 14 min. The gas chromatograph was equipped with dual MS/FID detection. MS is
192 a PerkinElmer Clarus SQ 8T. Acquisition was operated in full scan (50 to 470 amu) using
193 electron impact mode (70 eV). MS data were used to identify target SVOCs and check there
194 was no co-elution with other compounds. Quantitative analysis was performed by FID and
195 based on an external calibration. To this end, Tenax tubes were loaded with 2 µL of standard
196 mixtures of the analytes in methanol using a GC syringe and then purged for 5 min with a
197 helium flow of 50 mL.min⁻¹ to remove the solvent. The calibration ranges were from 0.1 to
198 1.6 µg for TCPP and from 0.8 to 4.6 µg for TBP according to the sampling conditions and
199 concentrations produced by the SVOC generation system. The calibration curves with six
200 standard levels obtained showed higher correlation $R^2 > 0.99$ for the two compounds (as
201 shown in Fig. S1 in the Supplementary materials).

202

203

2.5. SPME analysis

204

205 After sampling, the SPME fiber was directly desorbed in the injector port of a gas
206 chromatograph for analysis. An Agilent 7890B gas chromatograph (Agilent Technologies,
207 Les Ulis, France) equipped with dual MS/FID detection was used. The injection port was
208 equipped with a 0.75 mm i.d. liner and operated at 300 °C in splitless mode. The carrier gas
209 was helium with a flow rate of 2 mL.min⁻¹. A 5% phenyl Elite-5 capillary column
210 (PerkinElmer, Waltham, MA, USA) of 60 m, 0.25 mm i.d. and 0.25 µm film thickness was
211 used. The oven temperature was maintained at 60 °C for 2 min, then ramped at 30 °C.min⁻¹ to
212 200 °C, held for 2 min, then ramped at 15 °C. min⁻¹ to 310 °C, held for 22 min. MS is an
213 Agilent 5977B MSD. Acquisition was operated in full scan (50 to 400 amu) using the electron
214 impact mode (70 eV). Quantitative analysis was performed by FID basing on an external
215 calibration. The latter was used to express the result as the SVOC amount extracted by the
216 SPME fiber. It consisted in injecting and analyzing standard mixtures of TCPP and TBP in
217 methanol under the same chromatographic conditions than those for SPME desorption and
218 analysis. Due to volume expansion of standard solutions during the vaporization in the
219 injection port, a small volume (0.1 µL) compatible with the 0.75 mm I.D. liner was injected
220 [38]. Calibration curves used for the quantification of TCPP and TBP amounts sampled with
221 the SPME fiber are shown in Fig. S2 (Supplementary materials).
222

223

3. Results and discussions

224

225

3.1. Stability of SVOC generation system and calibration

226

227

228 Fig. 3 shows the generated TBP and TCPP concentrations over a 500-h period obtained with
229 the experimental device described in section 2.3. The results are expressed in gaseous
230 concentrations using the calibration curves given below.

231

232 The concentrations increase in the first tens of hours to reach the maxima of 382 µg.m⁻³ for
233 TBP and 35 µg.m⁻³ for TCPP around 70 hours. Large fluctuations are observed in
234 concentrations around the maximum values. Then, the concentrations slightly decrease by 20
235 % reaching a stable level of 298 µg.m⁻³ for TBP and 27 µg.m⁻³ for TCPP after 190 h (mean
236 concentrations after 190 h). High stability of concentrations was obtained between 190 and
500 h. In this time interval, the concentrations do not exceed the mean value by more than ±5
%. The coefficients of variation calculated from the last twelve measures performed after 190

237 h are 1.3 % for TBP and 3.0 % for TCPP. This experimental device provides a technical
238 solution for calibration of organophosphate flame retardants measurement methods. Its
239 characteristics in terms of time to reach a stable generating state and concentration stability
240 are comparable to those of the most advanced techniques using the solid materials to generate
241 gas-phase SVOCs [18,28].

242 Fig. 4 shows the calibrations obtained on a wide range of exposure dose extending up to 400
243 $\mu\text{g}\cdot\text{m}^{-3}\cdot\text{min}$ for TCPP and 4400 $\mu\text{g}\cdot\text{m}^{-3}\cdot\text{min}$ for TBP. The concentration determined by an
244 active sampling method with Tenax tubes was considered here as reference value. To check
245 linearity and robustness in calibration, several SPME measurements were performed by
246 changing exposure time (from 2 to 12 min) and three series with different samples of
247 polyurethane foam. These results confirm good linearity between the amount sampled by
248 SPME fiber and the product of gaseous concentration and the exposure time with a squared
249 correlation coefficient greater than 0.98. No significant deviation was observed between
250 points belonging to different calibration series. These results demonstrate that the linear
251 sorption domains extend up to 400 $\mu\text{g}\cdot\text{m}^{-3}\cdot\text{min}$ for TCPP and 4400 $\mu\text{g}\cdot\text{m}^{-3}\cdot\text{min}$ for TBP. When
252 the sampling time is increased, this SPME method is sensitive enough to measure
253 concentrations in the $\mu\text{g}\cdot\text{m}^{-3}$ range. However, the SPME fiber extracts a SVOC amount at
254 each sampling. It may not exceed the SVOC amount in the gas phase of the cell. According to
255 the slopes of calibration curves given in Fig.4, the uptake rates of TCPP and TBP on the
256 SPME fiber are 0.0048 and 0.0051 $\text{ng}\cdot(\mu\text{g}\cdot\text{m}^{-3}\cdot\text{min})^{-1}$, respectively. Considering these uptake
257 rates and the cell volume (60 mL), the sampling time required to extract the total amount in
258 gas phase was determined to 12.5 min for TCPP and 11.8 min for TBP. Then, to respect this
259 sampling limit, the extraction time should be less than 11 min.

260
261

3.2. Time to reach the steady state concentration in the MOSEC cell

262
263 To assess the time required to reach the steady state in the emission cell (stable gaseous
264 concentration), a series of tests was performed using selected polyurethane foam placed in a
265 room where temperature was kept at 23 ± 3 °C. To this end, the emission cell was placed on
266 the material surface for increasing periods before sampling. After each period, a SPME
267 sampling was performed to measure the gaseous concentration in the cell. The results are
268 shown in Fig. 5 for both compounds. Steady state was reached after 3 hours for TBP and 3.5
269 hours for TCPP. These results confirm that the time to reach the steady state is shorter for a
270 closed cell (Fig.5) than for a ventilated device (Fig.3). This trend was already observed in

271 previous studies [23]. In the case of closed cell, this time is probably shortened due to the
 272 small volume of the cell (60 mL). It depends on numerous characteristics of SVOC/material
 273 couple like the diffusion of compound in the material, the material/air partition, the initial
 274 emittable SVOC concentration in the material and the fraction sorbed on the inner walls of the
 275 cell [25,39,40]. Consequently, the pattern of gaseous concentration should vary according to
 276 material and SVOC and it is necessary to check this time required to reach the steady state for
 277 each compound and type of sampled material.

278 Considering the beginning of increase in concentration in Fig.5, the initial emission rates in
 279 the cell can be evaluated to 0.66 ng.min⁻¹ for TBP and 0.0014 ng.min⁻¹ for TCPP.

280 Basing on the calibration data (section 3.1) and the steady state concentrations, the uptake
 281 rates on the SPME fiber were 5.9 ng.min⁻¹ for TBP and 0.17 ng.min⁻¹ for TCPP, i.e. values 9
 282 and 13 times higher than the initial emission rates given above. So, the extracted amount by
 283 SPME during sampling mainly comes from the gas-phase. The emission rate is too slow for
 284 that a significant part emitted by the material during the extraction phase contributes to the
 285 amount sampled by the fiber.

286
 287

3.3. Method performance

288

289 The limits of detection (LoD) and quantification (LoQ) were calculated as three times and ten
 290 times the standard deviation of the blank for both compounds. Blank test consisted in placing
 291 the cell on a glass plate and performing a SPME measurement. Low detectable quantities of
 292 0.05 and 0.04 ng were obtained for TCPP and TBP in the blank analysis. Consequently, all
 293 the measurements by SPME sampling method were systematically subtracted from the
 294 average of blanks. As shown in Table 1, the sampling time should be close to 11 min in order
 295 to accurately measure concentrations of a few μg.m⁻³.

296

297 Table 1. Limits of detection (LoD) and quantification (LoQ) obtained from the analysis of 6
 298 blanks.

299

	Sampling time		
	1 min	7 min	11 min
TCPP:			
LoD (μg.m ⁻³)	8.5	1.2	0.8
LoQ (μg.m ⁻³)	28	4.1	2.6
TBP:			
LoD (μg.m ⁻³)	11	1.6	1.0
	38	5.4	3.4

LoQ ($\mu\text{g}\cdot\text{m}^{-3}$)			
---	--	--	--

300
 301 Reproducibility was evaluated from a series of ten replicate measurements performed on the
 302 selected PU foam using three different SPME fibers for different days (Table 2). The
 303 sampling times were from 7 to 11 min and these tests were carried out in a room where
 304 temperature was kept at 23 ± 3 °C. A satisfying level of reproducibility was achieved with a
 305 relative standard deviation (RSD) of 3.6% for TBP and 9.3% for TCPP. The RSD values are
 306 higher than those obtained in the cell of the generation system after stabilization of
 307 concentrations (RSD of 1.3% for TBP and 3.0% for TCPP). The difference in RSD suggests
 308 that the variability in emission of a same material surface is the main source of uncertainty in
 309 measurement for this method.

310 Note also that the high TBP gaseous concentration at the polyurethane foam surface ($y^0= 472$
 311 $\mu\text{g}\cdot\text{m}^{-3}$) tends to reduce RSD%. These results confirm those previously obtained by Ghislain
 312 *et al.* [25] giving RSD values from 2 to 10% for the measurements of three organophosphate
 313 esters with this same method. Reproducibility was also assessed by performing an additional
 314 series of measurements at the surface of a cushion consisted of a PU foam containing TCPP at
 315 2% by mass covered with a fabric. A RSD of 10.8 % for a TCPP concentration (y^0) of 3.4
 316 $\mu\text{g}\cdot\text{m}^{-3}$ was obtained from six replicate samplings at the cushion surface under laboratory
 317 conditions. Despite a low concentration close to LoQ, RSD value remains acceptable.

318
 319 Table 2. Reproducibility (RSD) obtained from replicate measurements performed on the
 320 selected PU foam surface with the emission cell coupled to SPME-based method.
 321

	Number of replicate measurements	y^0 ($\mu\text{g}\cdot\text{m}^{-3}$) mean \pm standard deviation	RSD (%)
TCPP	10	29.6 \pm 2.7	9.3
TBP	10	472 \pm 17	3.6

322
 323
 324
 325 **3.4. Time variation of TCPP and TBP gas-phase concentrations at the polyurethane
 foam surface**

326
 327 The y^0 changes over time of selected polyurethane foam for TCPP and TBP was followed
 328 from November 8, 2019 to June 23, 2020 (228 days in total). For this experiment, the material
 329 was placed in a laboratory room where temperature was kept at 23 ± 3 °C. y^0 was measured
 330 eight times during the experiment period using the method developed in this study. The
 331 sampling time was 7 min. As shown in Fig.6, no trend was observed in the y^0 variation

332 compared to the value measured on the 1st day (designated as initial value). These y^0 values
333 do not differ by more than 20% for TCPP and 10% for TBP from its initial value. The release
334 of TCPP and TBP from soft polyurethane foam appears as very stable for more than 200 days
335 compared to emission kinetics that usually have a decay phase observable over several
336 months [41,42]. Pei *et al.* [43] also found no decrease in y^0 after 60 days for TCPP emitted
337 from a PU foam.

338 The tests for assessing the time to reach the steady state shown in section 3.2 were performed
339 with the selected PU foam in October 2015, i.e. 4 years before the start of temporal follow-up
340 of y^0 for this same material and shown in Fig.6. y^0 for 228 days in Nov. 2019/June 2020 (460
341 and 29.5 $\mu\text{g.m}^{-3}$ for TBP and TCPP, respectively) were lower than y^0 measured in October
342 2015 (1150 $\mu\text{g.m}^{-3}$ for TBP and 37 $\mu\text{g.m}^{-3}$ for TCPP) for the same piece of PU foam. This
343 indicates that y^0 decreased 60% for TBP and 20% for TCPP after about 4 years. Although the
344 medium-term trend (over many months) showed no decrease in y^0 , there seems that a slow
345 decay occurred over the longer term (over many years).

346 In a context of using the PU foam in upholstered furniture, this stable character of y^0 is a
347 factor favoring the persistence of SVOC indoors and contributing to long-term exposure of
348 people to these contaminants.

349 350 **4. Conclusions and perspectives**

351
352 One of the main challenges in the use of the SPME-based method for accurately measuring y^0
353 concern the calibration. In this study, an atmosphere generation system coupled with an active
354 sampling with Tenax tubes was developed as a means to set up an external calibration of the
355 SPME-based method suitable for y^0 measurements of TCPP and TBP. Using a PU foam as
356 source of organophosphate flame retardants, the generating system delivered stable
357 concentrations after 190h of operation with variation not exceeding $\pm 5\%$. This experimental
358 set-up allowed to make calibration curves for the SPME-based method on a wide range of
359 exposure dose extending up to 400 $\mu\text{g.m}^{-3}.\text{min}$ for TCPP and 4400 $\mu\text{g.m}^{-3}.\text{min}$ for TBP. This
360 new calibration mode improves the accuracy of y^0 measurements using a conversion
361 relationship with an active sampling method. Emission cell (MOSEC) coupled to the SPME-
362 based method achieves low detection limits of 0.8 $\mu\text{g.m}^{-3}$ for TCPP and 1 $\mu\text{g.m}^{-3}$ for TBP and
363 satisfying reproducibility expressed in RSD of 3.6% for TBP and 9.3% for TCPP. Limitations
364 in the sampling conditions were identified as the time of at least 3.5 hours required to reach
365 the steady state in the emission cell before the extraction step and a maximum extraction time

366 of 11 min for a 100 μm PDMS fiber. To complete the evaluation of the method, additional
367 tests will be carried out to investigate temperature and humidity influences on SPME
368 sampling. The influences of these factors can not be directly assessed from tests performed in
369 static sampling mode with the emission cell placed on the material surface because the
370 material emission also varies with temperature and humidity. In the device of generation and
371 control of gas atmospheres containing SVOC, the emission cell is isolated from material
372 during SPME sampling and the gas concentration in the emission cell is measured with an
373 active sampling method independent from that of SPME-based method. It would therefore be
374 possible to investigate temperature and humidity influences on SPME sampling only,
375 regardless of material emission changes. These additional tests provide to extend the field of
376 application of this method to other environmental conditions than the standard indoor
377 conditions examined in this study ($\text{HR}=50 \pm 3\%$ and $T=23 \pm 2^\circ\text{C}$).

378 This method was applied to determine gas-phase concentrations of TCPP and TBP at the
379 polyurethane foam surface (y^0) over more 228 days under controlled temperature conditions.

380 A stability of concentrations was observed over this period confirming that the impact of
381 emissions of organophosphate flame retardants from PU foam on indoor air quality can
382 persist in the long term after introduction of material indoors. PU foam acts as a stable and
383 continuous source of organophosphate flame retardants for at least several months.

384 Further studies will be conducted to extend this method to other SVOCs and source materials
385 and carry out field measurement campaigns to locate the sources in indoor environments,
386 examine the variation of source term in real conditions and provide the input data for
387 modelling SVOCs behaviour indoors.

388

389 **Acknowledgement**

390

391 The authors acknowledge ADEME (French Agency of Environment and Energy Mastery) for
392 financial support (PhD agreement ADEME TEZ13-03).

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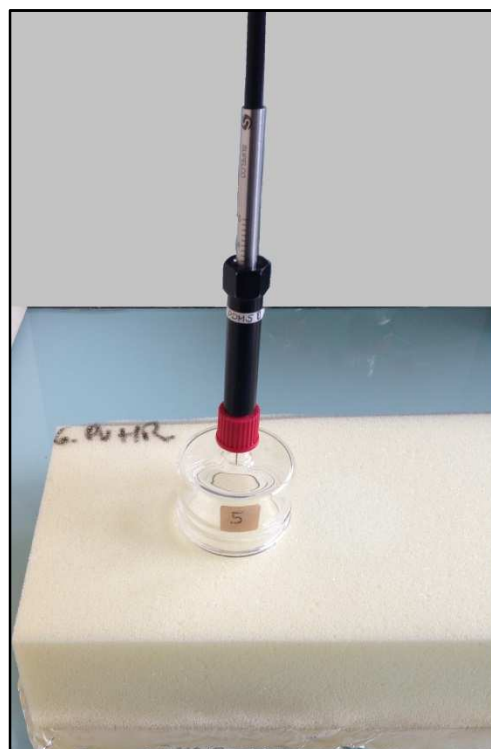
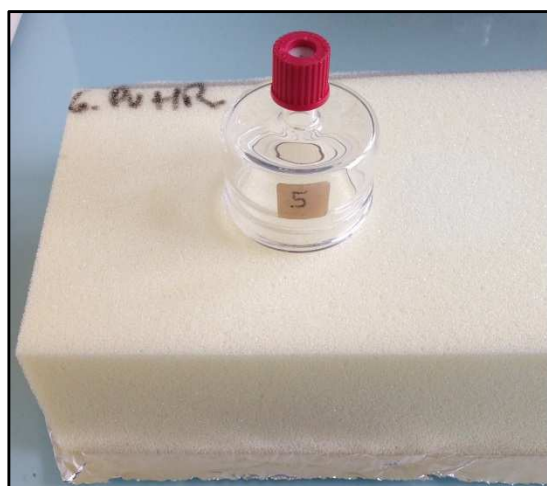
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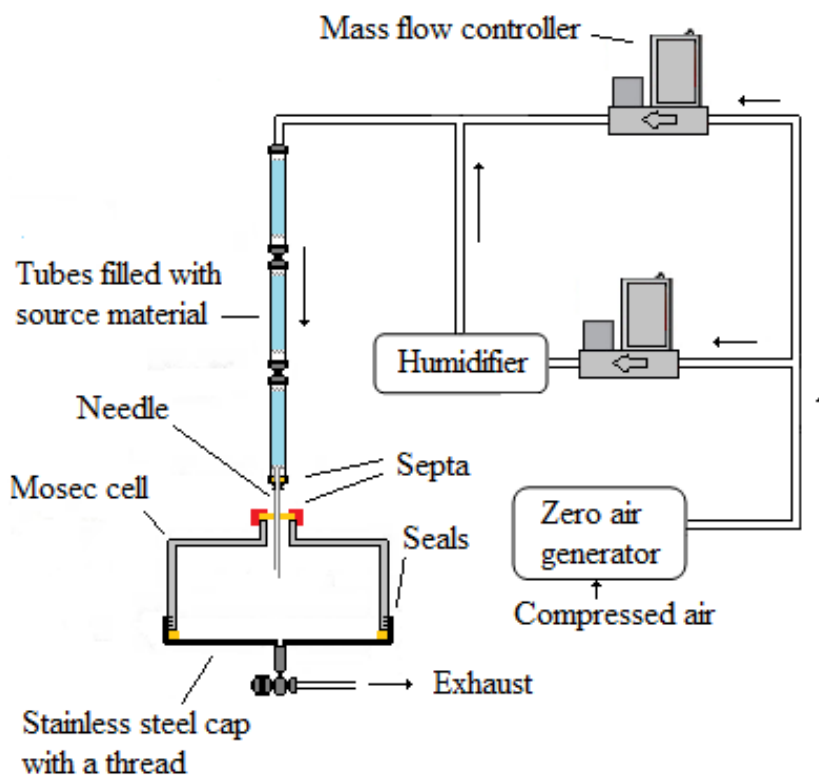
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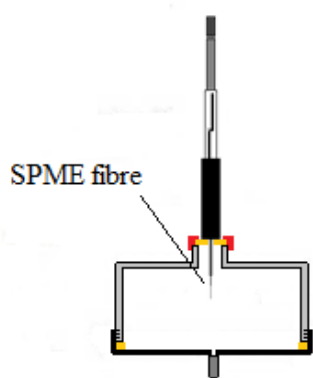
Figure 1. Pictures showing the emission cell placed on the material surface before sampling (a) and SVOCs sampling by SPME in the cell (b).

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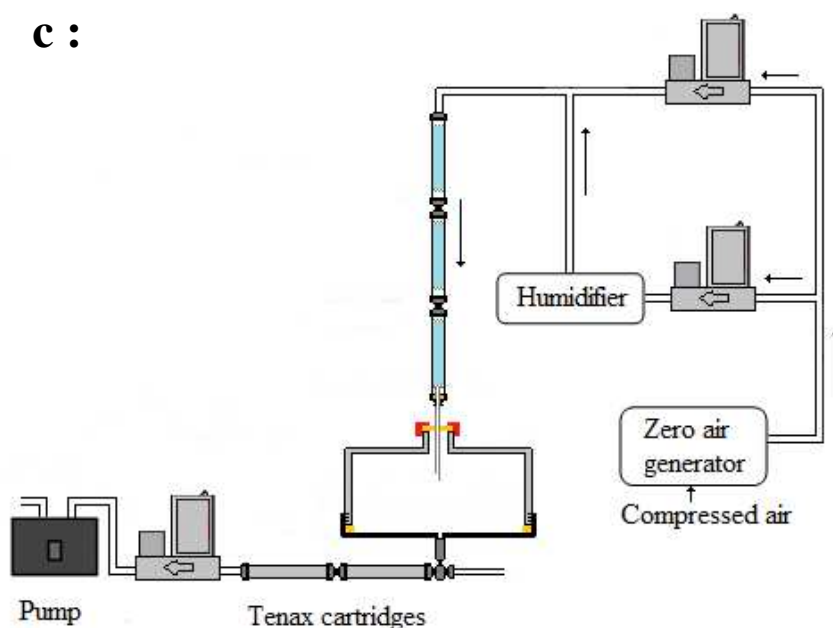
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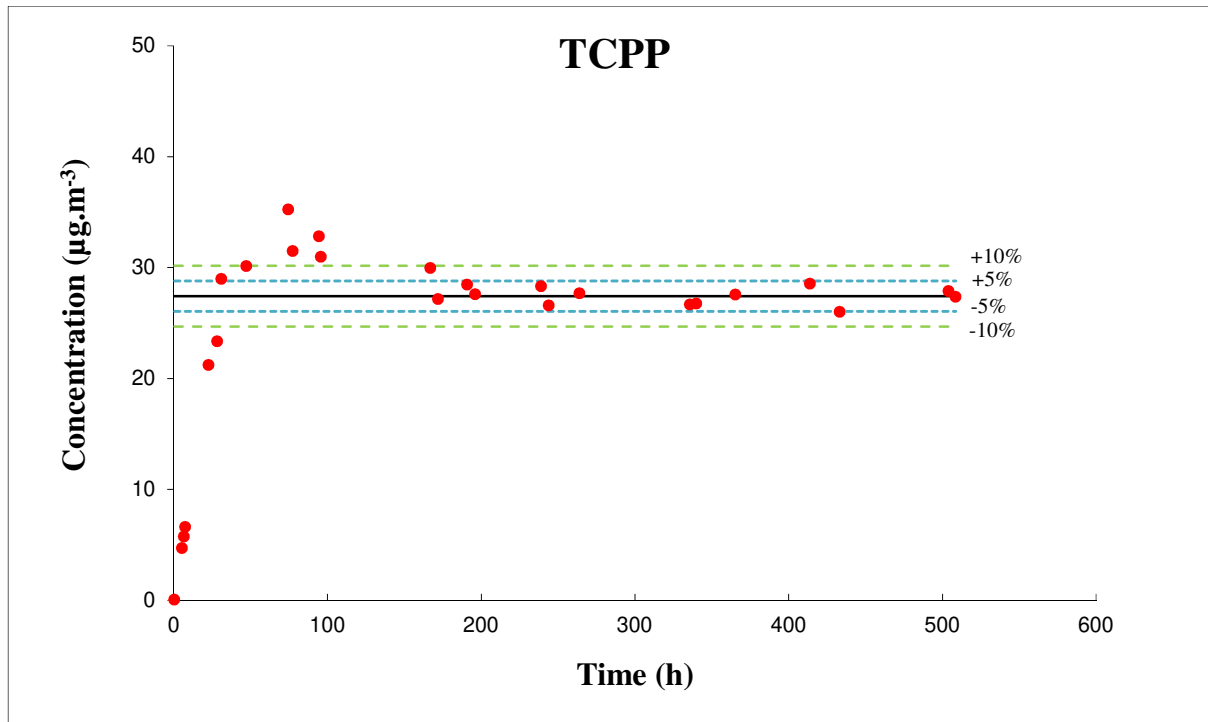


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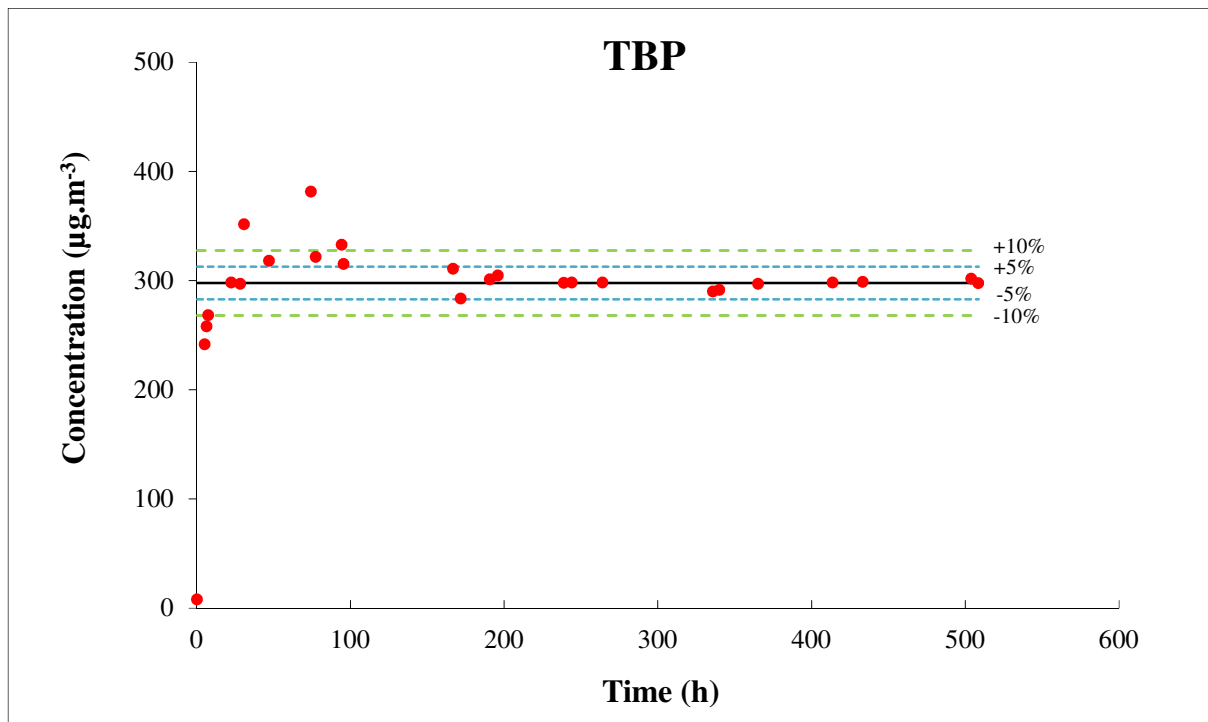
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626 Figure 2. Experimental device to generate gas-phase TCPP and TBP and steps for calibration
627 of the SPME-based method: the emission cell is connected in series with the generation
628 system to transfer SVOCs in the air of cell (a), the emission cell is isolated and SPME fibre is
629 introduced in the cell for sampling (b) and (c), an active sampling with Tenax tubes was
630 performed when the concentrations are stabilized.

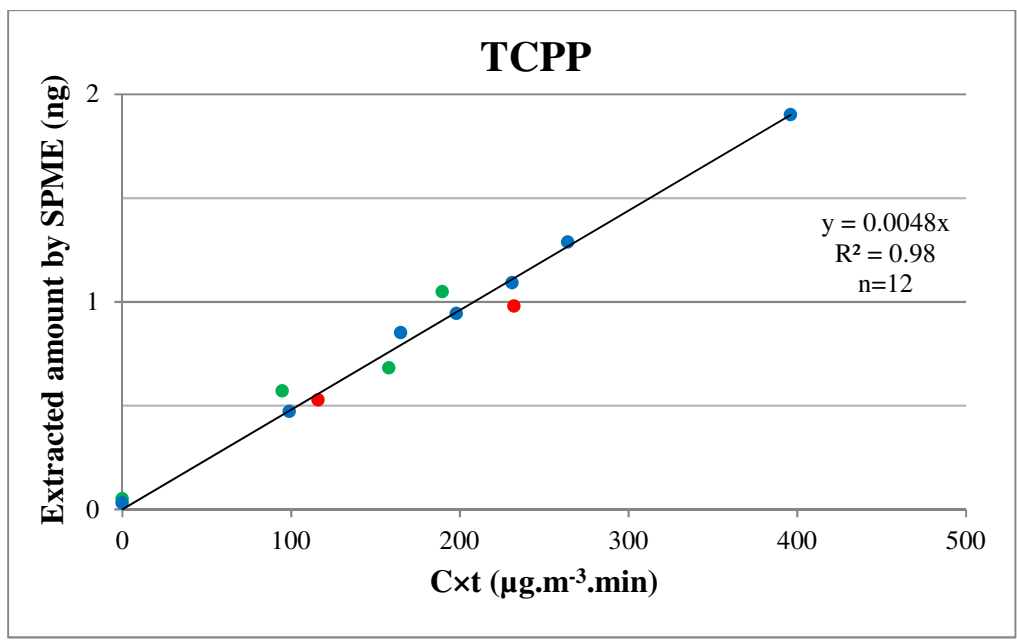


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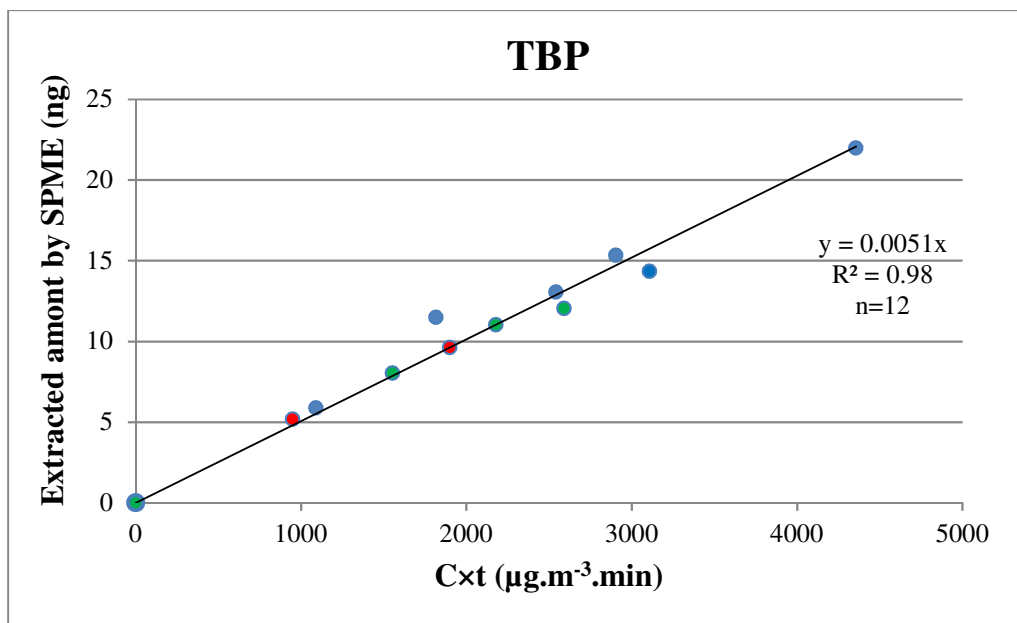


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Figure 3. Time variation of TBP and TCPP concentrations produced by the generation system over a 500-h period. The solid line corresponds to the mean concentration during stable generating state ($t > 190$ h). The solid line corresponds to this mean concentration. The dotted lines represent the intervals of $\pm 5\%$ and $\pm 10\%$ around this mean concentration.



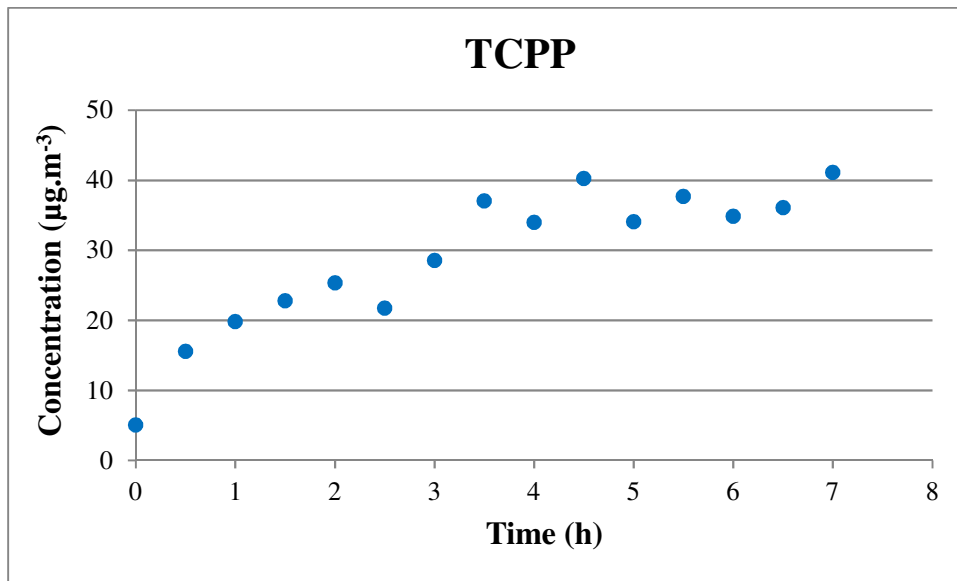
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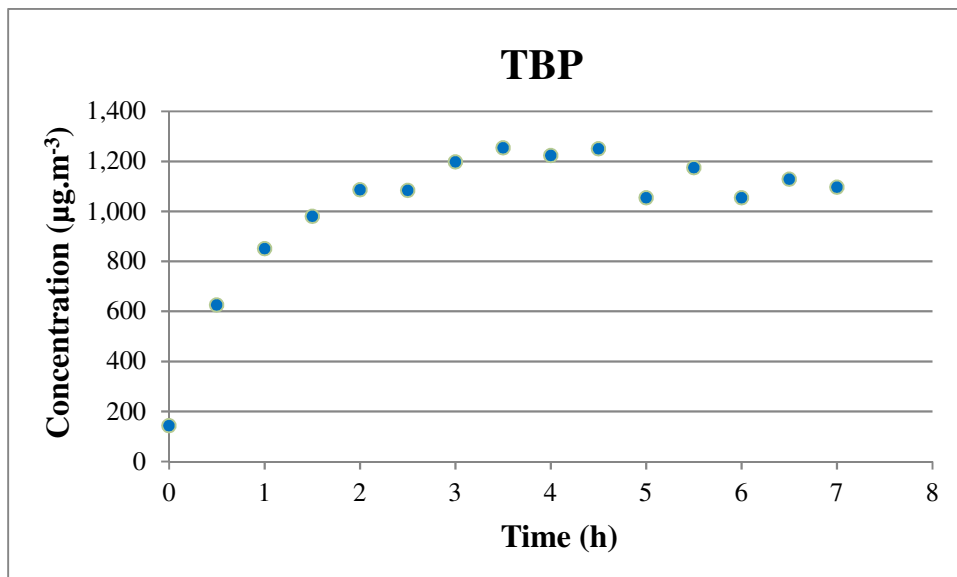
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Figure 4. Calibration curves obtained for TCPP and TBP. Extracted mass by SPME versus the product of sampling time (t) and gas-phase SVOC concentration in the air (C) by combining the data of three calibration series (blue, green and red circles).

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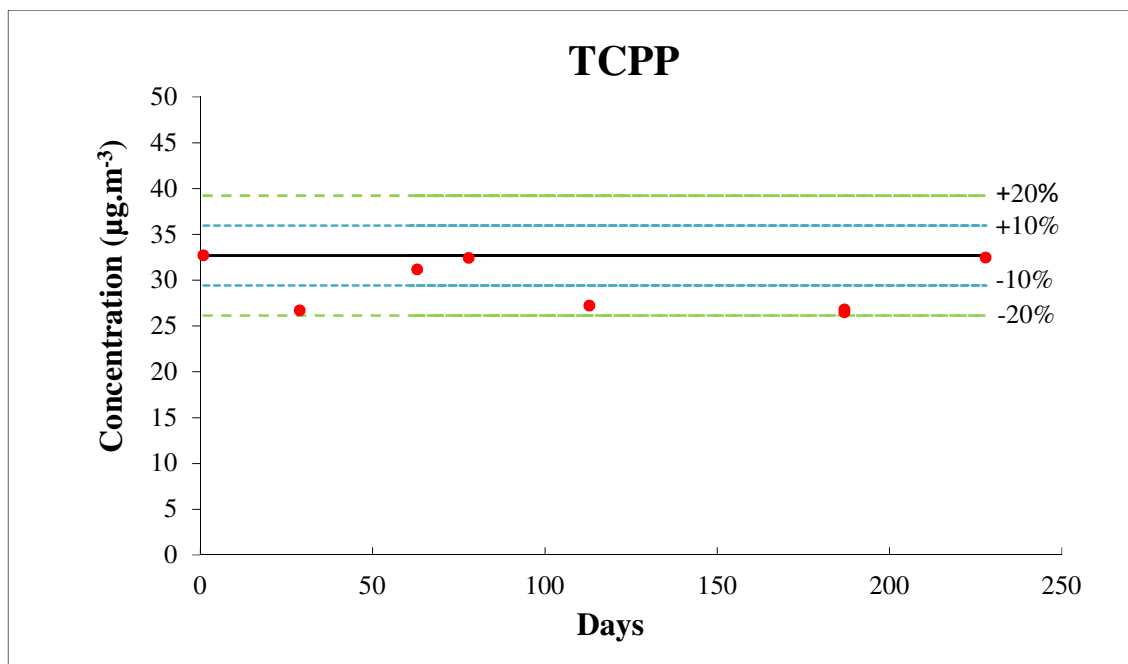


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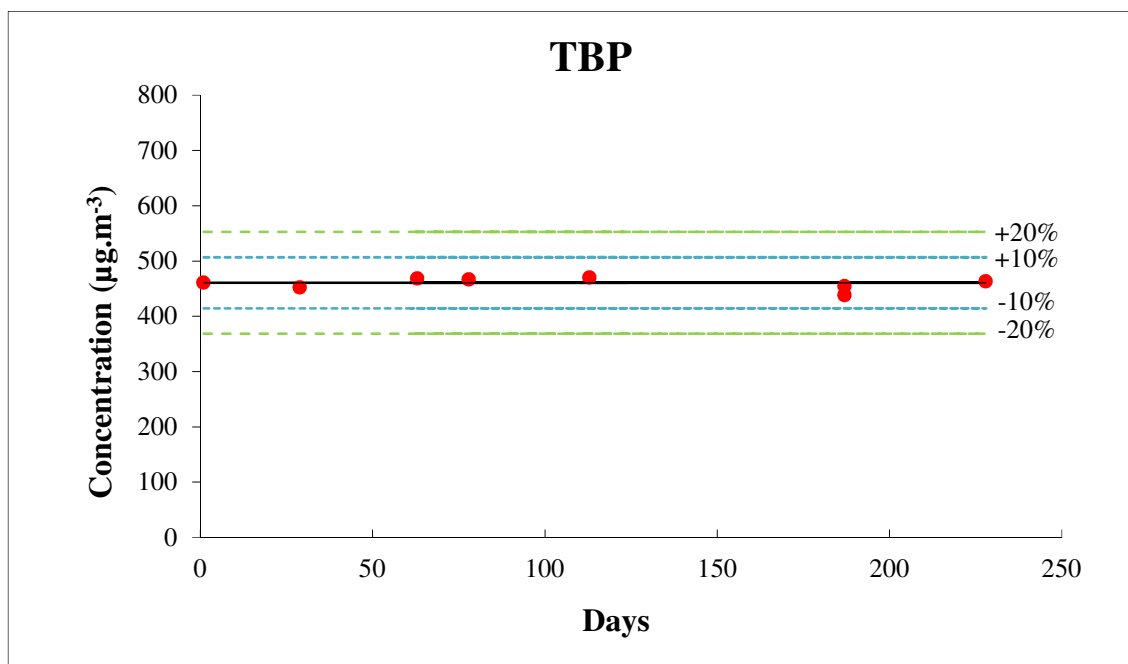


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Figure 5. Gas-phase concentration of TCPP and TBP versus time during which the emission cell is placed on the polyurethane foam before sampling by SPME.



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685 Figure 6. Time variation of TCPP and TBP gas-phase concentration at the polyurethane foam
686 surface (y^0) for the period of 228 days. The solid line corresponds to the concentration
687 measured on the 1st day (designated as initial value). The dotted lines represent the intervals
688 of $\pm 10\%$ and $\pm 20\%$ around the initial value.

