Environmental Contamination Following the Grenfell Tower Fire

Anna A Stec, Kathryn Dickens, Jessica L.J Barnes, and Clare Bedford

Centre for Fire and Hazards Science, University of Central Lancashire, Preston, PR1 2HE, UK

*Corresponding author: aastec@uclan.ac.uk

Abstract

The Grenfell Tower fire in central London, started within a flat, engulfed the whole 24 storey building in flames, killed 72 people and spread toxic effluent via the plume and particulate deposits.

Soil samples from 6 locations up to 1,2 km from the Tower, together with semi-burnt fire debris and char samples, were collected 1 and 6 months after the fire. Additionally, dust samples and condensates were collected from a flat 160 m away from the Tower after 17 months. Samples were analysed for common potentially toxic components of fire effluents and synthetic vitreous fibres.

Samples collected within 140 m of the Tower showed, amongst other toxicants, polychlorinated dibenzo-p-dioxin concentrations 60 times greater than UK urban reference soil levels; benzene levels were 40 times greater; levels of 6 key polycyclic aromatic hydrocarbons (PAHs) were approximately 160 times greater. PAHs levels are approximately 20 times greater than those reported from nearby Hyde Park before the fire. To explain the presence

22   of these pyrogenic contaminants char and partially burnt debris were also collected and

23   analysed. Benzene, PAHs, isocyanates and phosphorus flame retardants were found.

24   Hydrogen cyanide and synthetic vitreous fibres were present in both soil and debris.

25   Particulate and pyrogenic contamination in the immediate vicinity is clearly evident, and may

26   have leached out of fire debris, char and dust. Further analysis of the area around the Tower

27   is necessary to understand potential health risks.

1. Introduction

1.1 Harmful Effects of Fire Effluents

30   UK National Fire Statistics (2018) show that the acute toxicity of fire effluents is the biggest

31   short-term cause of death and injury from unwanted fires. Large fires produce smoke

32   containing high concentrations of particulates and toxic gases such as, the asphyxiant gases,

33   carbon monoxide (CO), hydrogen cyanide (HCN) and respiratory tract deep lung irritants. As

34   the fire develops, the yields of all products of incomplete combustion including CO, HCN,

35   organic compounds and soot increase - typically by factors of 10 to 50. Molecular toxicants

36   bind to smoke particles (airborne soot and tarry droplets) allowing them to penetrate deep into

37   the lung causing respiratory distress and pulmonary oedema (flooding of the lungs). This is

38   closely followed by incapacitation and death, from few hours to several days or even years

39   after exposure (Stec and Hull 2010; Stec 2017).

40   There have been surprisingly few reports of the long term consequences of unwanted fires.

41   Persson and Simonson (1998) showed that in Sweden they contributed around 10% as much

42   as transport-derived particulate emissions. Fires also release a rich cocktail of pollutants,

43   many of them acutely or chronically toxic, including carcinogens such as semi and volatile

44   organic compounds (SVOC/VOCs), PAHs, respiratory sensitizers such as isocyanates from

45   some nitrogen-containing fuels, and persistent, bioaccumulative and toxic compounds such

46   as polychloro- and polybromo dibenzo-p-dioxins and dibenzofurans (PCDD/Fs and PBDD/Fs)

47 and polychlorinated biphenyls (PCBs), formed by burning halogen containing fuels (McGee

48 *et al.* 2003; Landrigan *et al.* 2004).

49 Benzene is a carcinogen in its own right (ATSDR 2018a). Other aromatic SVOC/VOCs are of

50 particular toxicological significance as precursors of PAHs and carcinogens Some PAHs,

51 PCDD/Fs and PBDD/Fs (the most toxic is 2,3,7,8-tetrachlorodibenzodioxin (TCDD)) are also

52 genotoxic and mutagenic (ATSDR 2018b). Benzo(a)pyrene (BaP) was initially identified as

53 the most toxic PAH species, however more recent studies have identified 7,12-

54 dimethylbenzo(a)anthracene as having a 20-fold higher toxic equivalence factor (TEF) than

55 its parent compound and twice that of BaP (Andersson and Achten 2015). A study by Wang

56 *et al.* (2009) showed that PAHs are transformed in the atmosphere or metabolically into

57 hydroxy-PAHs, which are more genotoxic than the parental PAHs. These compounds have

58 been linked to firefighter cancers through the analysis of their exposure (Stec 2018).

59 The study by Bengtström *et al.* (2016) showed that isocyanates have been positively identified

60 in fire smoke and are widely used in the manufacture of flexible polyurethane (PU) foams for

61 upholstered furniture and rigid PU or polyisocyanurate (PIR) foams for insulation in buildings.

62 Isocyanates are respiratory sensitizers that can cause asthma attacks. They also trigger

63 irritant and allergic forms of contact dermatitis (rashes, itching, swelling of extremities etc.)

64 and less frequently hypersensitivity pneumonitis - an inflammation of the alveoli caused by

65 inhaled isocyanate particles. A common decomposition product of isocyanates is methyl

66 isocyanate (MIC) which also causes swelling of the lungs and breathing difficulties.

67 Studies by Lippmann (2014 and 2015) on the aftermath of the World Trade Centre showed

68 that synthetic vitreous fibres (SVF) were one of the most significant health damaging

69 contaminants after the fire. Inhalation exposure to airborne SVFs is a public health concern

70 because like other particulate matter, fibres that are released in fires can be suspended in air

71 (as dust or ash), inhaled and deposited in the lung (ATSDR 2018c). Lippmann (2014) identified

72 the minimum critical fibre lengths for asbestosis (interstitial fibrosis), mesothelioma and lung

73 cancer to be ~2 μm, ~5 μm and ~15 μm, respectively. With regard to fibre diameter for

74 asbestosis and lung cancer, fibres with diameters >0.15 µm appear to be of predominant

75 significance (as thinner fibres can be more readily cleared via the lymphatic system) whilst for

76 mesothelioma (and other lesions of the mesothelium), fibre diameters <0.1 µm seem to be the

77 most pathogenic.

1.2 Environmental Pathways

79 The interaction between a fire and its surroundings or environment proceeds via direct

80 gaseous and particulate emissions to the atmosphere and localised deposition to soil and

81 water. Subsequent dispersion and deposition of atmospheric emissions results in widespread,

82 low level contamination of soil, ground and surface water, as shown Figure 1. Van Loon and

83 Duffy (2000) reported that particles with diameters less than 10 µm will have a deposition rate

84 of around 3 mm s^{-1} and will tend to remain airborne, travelling with the smoke plume. Particles

85 with diameters greater than 100 µm will have a settling velocity of 0.3 m s^{-1} and are likely to

86 be deposited close to the fire.
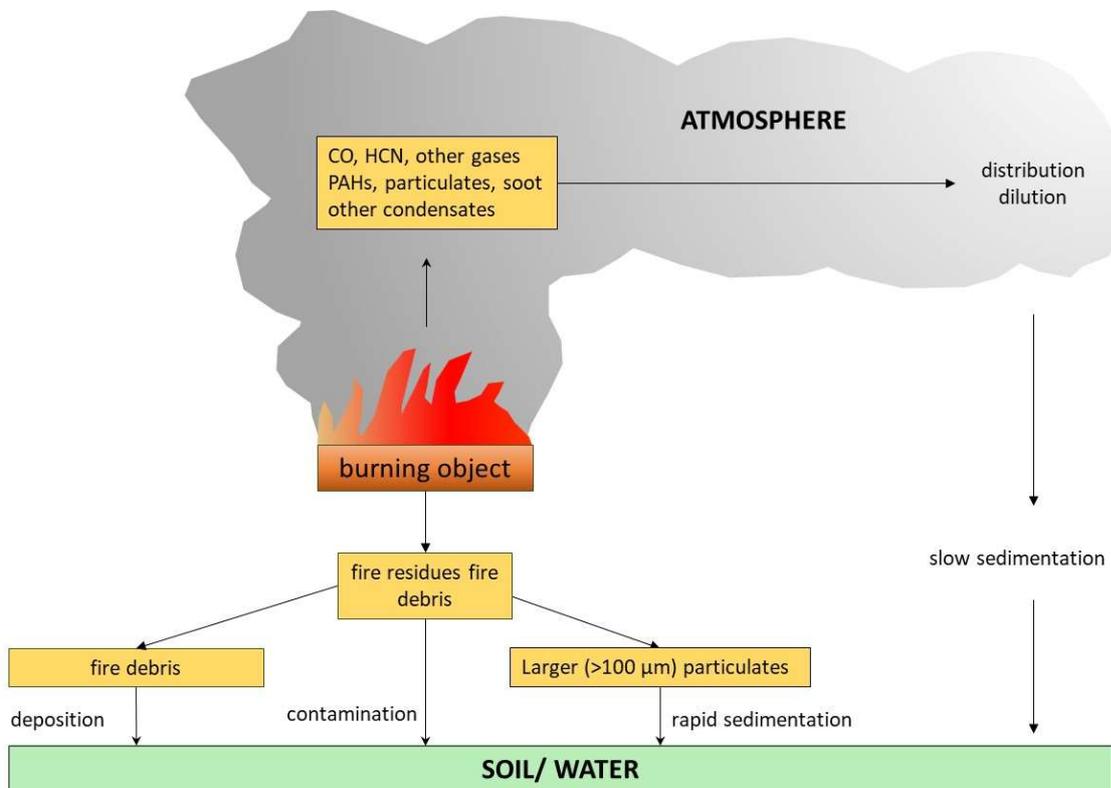
87

88 **Figure 1.** Emission pathways from fires (adapted from ISO 26367-1 (2011).

4

The degree to which fire species are partitioned between different phases (gaseous, aqueous, solid etc.) also depends on their physical characteristics and weather conditions (temperature, rain, wind speed etc.). For example, PAHs will agglomerate eventually leading to soot formation. The agglomerating species will initially travel as airborne particulates, but may grow large enough to sediment into water or soil, while CO will remain in the gas phase. Cyanide is released into air as a gas and to a lesser extent as particulate bound cyanides (ATSDR 2006). Cyanide can be transported over long distances before decomposition by reaction with hydroxyl radicals. In soil, HCN co-exists with alkali metal salts where it volatilises or degrades rapidly. Alternatively, HCN may be immobilised into metallo-cyanide complexes such as ferricyanides or ferrocyanides (ATSDR 2006). MIC will only persist in the atmosphere from a few hours to a few days, while in soil it will be broken down into other compounds upon contact with moisture (ATSDR 2014). PAHs and VOCs are comprised of species that partition differently according to their mass, with lighter species remaining primarily in the gaseous phase and heavier species tending to deposit on surface water or soil when absorbed on particulates (>2.5 μm) such as fly ash and soot (Van Loon and Duffy 2000). Humans can also be exposed to PAHs through inhalation or dermal contact with re-suspended soil and dust (Stec *et al.* 2018). While human-soil contact generally occurs outdoors, inhalation is also identified as a source of PAHs indoors, where people spent 80–93% of their time (WHO 2010). SVFs with smaller diameters become airborne more readily than fibres with larger diameters. SVFs remain unchanged in air, soil or sediment over long periods (Bernstein *et al.* 2005).

The UK's Public Health England (PHE) provides specialist advice on health including health advice on air quality, smoke exposure, asbestos, and the clean-up process (PHE 2018a). The data from the air quality monitoring in the area surrounding Grenfell Tower, since the start of the fire on 14 June, has shown that the risk to people's health from air pollution around the Grenfell Tower site was consistently low. Levels of gas particulate matter (PM_{10}) remained low and monitoring results for dioxins, furans, PCBs and PAHs were broadly equivalent to background levels for London. No asbestos was reported as found, despite being present in

116 the Grenfell tower. There are no reports of contamination measurements being taken from the

117 soil or water run-off. No measurements appear to have been carried out by UK's

118 Environmental Agency or the local authority (the Royal Borough of Kensington and Chelsea

119 (RBKC). RBKC are legally responsible for assessing and quantifying contaminated land within

120 their community (PHE 2018b). The rationale for the current study was to address concerns

121 from the Grenfell community related to the potential soil contamination and establish whether

122 more detailed investigation is required.

2. Materials and Methods

124 Two char samples were collected from balconies 50 and 100 m from the Tower 1 month after

125 the fire and analysed (Char1 and Char2). Based on the findings soil samples, together with

126 fallen fire debris and more charred soot samples (Res and Char3) were collected 6 months

127 after the fire at different distances from the Tower. Sampling was limited by locations where

128 there was permission to collect soil and aimed to follow the direction of the prevailing wind at

129 the time of the fire (South Easterly), with location shown in Figure 2a and wind on the day of

130 fire Figure 2b (TimeandDate 2018). 17 months after the fire char from a balcony (Char4),

131 indoor dust and a yellow oily deposit on a vertical fabric window blind (described by the

132 occupier as "contaminated by the fire") were collected from a flat 160 m from the Tower. Table

133 1 shows the details of the char and soil samples. A standard soil sample, Kettering loam soil,

134 was obtained from Boughton Loam Ltd (containing clay 24%, silt 18%, sand 58%, organic

135 content 6.72%). It is a preferred natural soil used as a standard in contamination analyses.

136 Quantitative analyses for PCDD/Fs, PAHs, benzene and metals were carried out on the char

137 and soil samples. Gas chromatography-mass spectrometry (GC-MS) was used for

138 SVOC/VOCs. Qualitative screening (thermogravimetric analysis coupled with gas phase

139 Fourier Transform Infrared Spectroscopy, (TGA-FTIR)) was used to check for the presence of

140 common fire effluents on all samples. Finally, the contaminated window blind was extracted

141 and analysed for the presence of isocyanates, in order to characterise the yellow oily deposits.

2.1 Sample Collection

Soil samples (approximately 2 kg) were collected from the ground at depths of up to 200 mm. A fresh pair of gloves was used for each sample collection and the trowel was cleaned before and after each collection. The samples were stored in airtight 1 L dark glass jars covered in aluminium foil and kept at 4°C.

Approximately 60 pieces of what appeared to be char from insulation foam (the largest being 300 mm in width and 460 mm in length, with an approximate density of 18 kg/m^3) were collected from the ground within 90 m of the Tower. A semi-burnt piece of fire debris, recognisable as a sheet of insulation material (Res), was also found and collected. Samples were stored in dark polyethylene bags.

Char samples were also collected from three balconies (Char 1, 2 and 4) between 50 and 160 m from the Tower. Dust samples were collected from five different locations within one apartment, 160 m from the Tower, and combined. Two pieces of the window blind, one with visible soot and yellow oily deposits and the other without, were also collected from the same apartment.
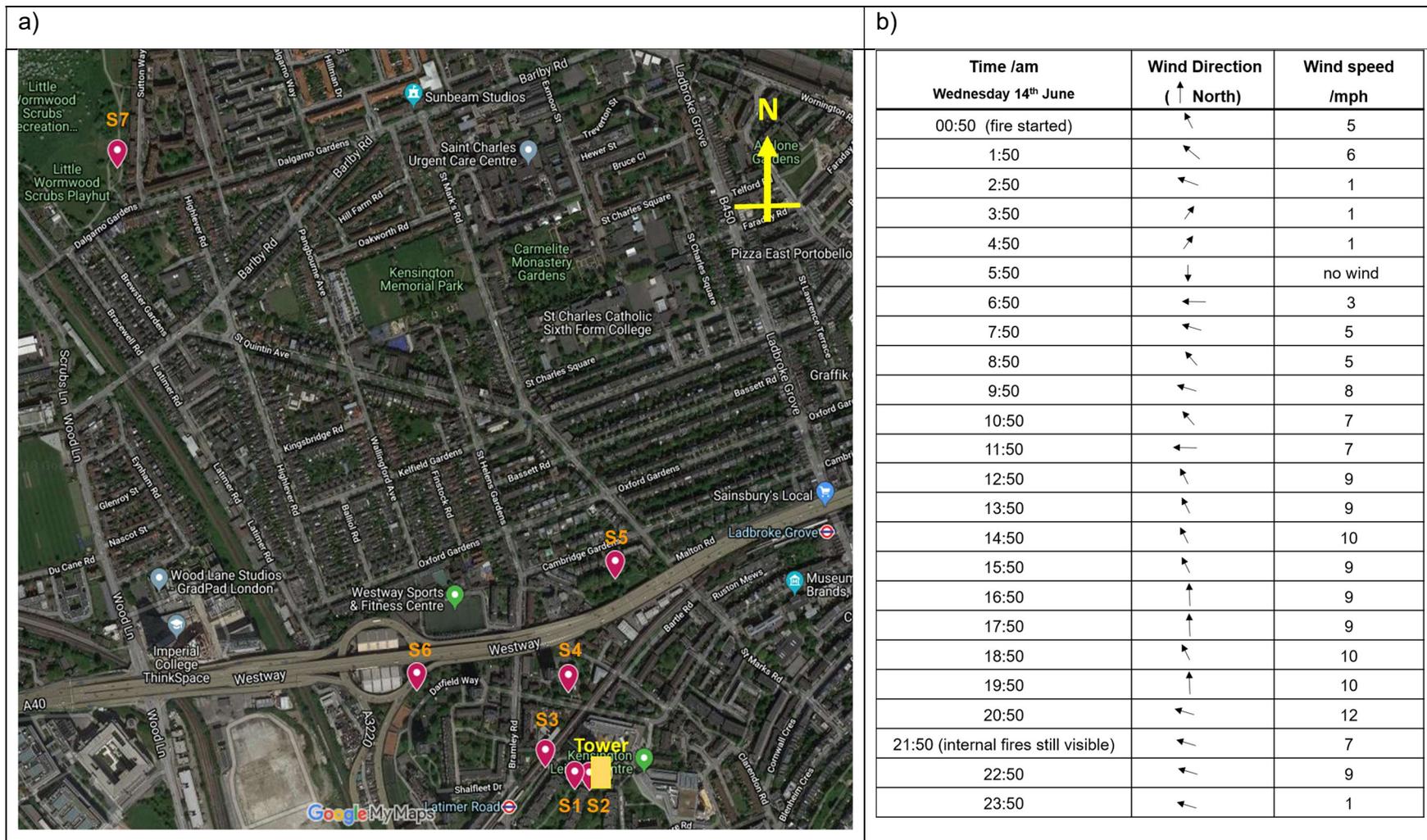
2.2 Sample preparation

Up to 5 g of each soil sample was then dried to a constant weight on a watch glass in an oven (VWR Dry-Line 115) at 60 °C to determine the moisture content, then sieved (5 mm) and ground to ensure a homogenous sample (the smell of fire smoke was observed for the soil samples 1 to 3). The moisture content, based on triplicate analyses, is reported in Table 1. Non-dried samples were used for TGA-FTIR analysis in order to avoid volatile losses.

163   **Table 1.** Sample descriptions, locations, moisture, pH and nitrogen content.

Sample Type	Abbreviation	Sample location* /(m)	Collection data**/ (months)	Average Moisture/ %	pH	Nitrogen content %
Kettering loam soil (control)	Ref			0.2	7.2	0.7
Soil	S1	27	6	34.9	5.4	1.9
	S2	50	6	35.7	6.1	1.7
	S3	90	6	26.2	8.5	1.2
	S4	142	6	24.2	4.2	1.2
	S5	316	6	23.6	6.7	1.2
	S6	332	6	14.9	6.9	1.2
	S7	1260	6	18.3	8.3	1.0
Fire debris	Res	90	6		6.4	UB: 2.1 B: 1.1
Char from balconies	Char1	50	1		-	6.1
	Char2	90	1		-	6.3
Charred samples from the ground	Char3	90	6		5.3	6.2
Char from balconies	Char4	160	17		5.5	4.9
Dust samples from the flat	Dust	160	17		-	-
Oily residue from window blind from the flat	WB	160	17		-	-

164   Notes: UB, Unburnt; B, Burnt; -, None detected; *Sample location in respect to distance from Grenfell Tower; **Data collection carried out months
165   after the fire; "Fire debris refers to semi-burnt insulation material.

a)

b)

Time /am Wednesday 14th June	Wind Direction (↑ North)	Wind speed /mph
00:50 (fire started)	↙	5
1:50	↙	6
2:50	←	1
3:50	↗	1
4:50	↗	1
5:50	↓	no wind
6:50	←	3
7:50	↙	5
8:50	↙	5
9:50	←	8
10:50	↙	7
11:50	←	7
12:50	↙	9
13:50	↙	9
14:50	↙	10
15:50	↙	9
16:50	↑	9
17:50	↑	9
18:50	↙	10
19:50	↑	10
20:50	←	12
21:50 (internal fires still visible)	←	7
22:50	←	9
23:50	←	1

Figure 2. Samples locations and meteorological reports of wind speed and direction during the fire (TimeandDate.com 2018).

2.2.1 Chemical analysis

All glassware was baked at 300 °C and rinsed with the appropriate solvent before use. Laboratory blanks were run alongside samples (intervals specified in individual sections below). All water was distilled. All samples were kept at 4 °C in a locked enclosure prior to analysis. All analyses were conducted in the analytical laboratories of the University of Central Lancashire except for the dioxins and furans which were quantified in a private UKAS accredited laboratory. The limits of detection (LOD) and limits of quantification (LOQ) for analysed fire effluents together with the dioxins and furans recoveries can be found in the supplementary material (Tables S1-S8).

2.2.1.1 pH

Approximately 20 g of each soil was mixed with 20 mL of deionised water and the water pH measured using a glass electrode in triplicate (Jenway 3540).

2.2.1.2 CHNS analysis

Approximately 2 mg of dried sample was placed into a tin capsule and run on a ThermoScientific Flash 2000 CHNS/O analyser (detection sensitivity within ±1%), in order to determine the presence of nitrogen. Each sample was analysed in triplicate with a blank run as part of the initial CHNS calibration daily. The instrument was calibrated with BBOT (2,5-Bis (5-tertbutylbenzoxazol-2-yl) thiopene) (Elemental Microanalysis, B2135) (6.51 N%, 72.53 C%, 6.09 H%, 7.44 S%) using the K-factor calibration method. In place of laboratory blanks between samples, BBOT standard was run every 15 samples in order to check the response of the CHNS analyser.

2.2.1.3 ICP-OES screening

The method used was based on EPA 6010D (U.S. EPA 2014). 0.1 g of the sample was digested in 10 mL of concentrated nitric acid (Fisherbrand) in a microwave digester (Milestone Ethos EZ SR12) at 200 °C for 45 min. 0.1 mL of the digested sample was added to 9.9 mL of

192 water, which was then analysed by Inductively Coupled Plasma-Optical Emission

193 Spectrometry (Thermo Scientific iCAP 7000 ICP-OES) for elemental composition. Samples

194 were run in quadruplicate with each individual sample tested three times for consistency. The

195 RSD for all final results was less than 5%. Blanks prepared from digested acid were run after

196 every fifteen samples, and were all below the limits of detection (LOD) for all elements

197 analysed. The LOD and LOQ were calculated as three and ten times the standard deviation

198 from the analysis of the standards and the blanks (Table S1). The standards used for

199 comparison were the TraceCERT® 1000 mg/L P in water and the multi-element standard 5

200 TraceCERT® in 10% nitric acid (Sigma Aldrich).

201 2.2.2 Fire effluent analysis

202 2.2.2.1 Benzene quantification

203 3.5 g of soil sample, or 1 g of residue or char material, was added to 3 mL of a 3:1

204 hexane:acetone mixture (Sigma Aldrich) and the sample was sonicated (Sonicor SC52-H) for

205 40 min. 1.5 mL of the solution was extracted, centrifuged at 15 000 rpm for 30 min (Sanyo

206 MSE Micro Centaur MSB010.CX2.5) and 2 µL of the extracted solution was injected into the

207 GC-MS (Agilent HP 6890 coupled to Agilent MS 5973) with the software: Agilent MSD

208 Chemstation version F.01.00.1903). All analyses were run in quadruplicate. Laboratory blanks

209 run every ten samples. The chromatograms used for analysis were blank subtracted. The LOD

210 was calculated using three times the signal to noise ratio of the analyte, while the LOQ was

211 calculated using ten times the signal to noise ratio. The LOD and LOQ were 0.11 and

212 0.54 ppm respectively.

213 2.2.2.2 PAHs and phosphorus flame retardants

214 5 g of soil was passed through a 5 mm sieve and added to 40 mL of a 1:1 ratio of

215 dichloromethane:acetone mixture (Sigma Aldrich) and sonicated (Sonicor SC52-H) for 2 h.

216 For the next 6 h the samples were sonicated for 10 min each hour. Once sonication was

217 complete, 2 mL of the liquid was centrifuged at 15 000 rpm for 30 min (Sanyo MSE Micro

218   Centaur MSB010.CX2.5) and 2 µL of the centrifuged extracted solution was injected into the

219   GC-MS (Agilent HP6890 coupled to Agilent MS 5973). Approximately 1 g of residue or char

220   sample was added to 3 mL of a 3:1 hexane:acetone mixture (Sigma Aldrich) and the samples

221   sonicated for 40 min. 1.5 mL of the solution was extracted, centrifuged at 15 000 rpm for 30

222   min and 2 µL of the extracted solvent was injected into the GC-MS. Each analysis was

223   repeated five times.

224   Quantification of PAHs was based on the method described by Guerin (1999). Analysis was

225   performed for PAHs using a HP 6890 Series GC System equipped with a 5973 Mass Selective

226   Detector (Hewlett Packard) and a TraceGOLD TG-5MS column with the dimensions

227   30 m x 0.25 mm x 0.1 µm (Thermo Scientific). An injection volume of 2 µL was used with a

228   splitless injection with a flow rate of 35 mL/min. Samples were analysed in SIM mode. The GC

229   was set to a start temperature of 100 °C with a 2 min hold, then with 8 °C/min to 210 °C, with

230   2 °C/min to 280 °C and was held at 280 °C for 3 min. The results were then processed using

231   Agilent MSD Chemstation version F.01.00.1903. Calibration standards were obtained from

232   Sigma Aldrich. Laboratory blanks were analysed with every ten samples. The PAHs were

233   quantified using external standard calibrations. The LOD was based on three times the signal-

234   to-noise ratio of each analyte (related to the 5g samples) while the LOQ was based on ten

235   times the signal-to-noise ratio, as shown in Table S2. Responses below the LOQ were not

236   included in this analysis. The average blank levels were below the LOD for all PAHs.

237   2.2.2.3 Polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofuran analysis

238   Quantification of PCDD/Fs was based on EPA1613 (US EPA 1994). The analysis was

239   undertaken in a UKAS accredited laboratory, approved to quantify dioxins. This includes a

240   spiked sample and a reference material analysed alongside the samples on a weekly basis.

241   The LOD and recoveries for each sample are shown in the supplementary document

242   (Table S3-S8). Approximately 1 g of sample was fortified with ^{13}C dioxin/furan standards

243   (Wellington) at 1 ng for each congener. Samples were then extracted in a Soxhlet apparatus

244   in toluene (Rathburn), for 16 h. Samples were solvent extracted with hexane (Rathburn)

245 followed by rotary evaporation (Buchi 310). Sample clean-up was achieved using a Miura

246 system (GO-HT) with silica, alumina and carbon columns - eluting with hexane and then

247 toluene. The final volume of samples was reduced to 20 µL and fortified with recovery

248 standards ((Wellington). Analysis was carried out by using 60 m DB5 capillary column (Agilent)

249 and Waters NT Ultima high resolution mass spectrometer operating at 10000 resolving power,

250 which was quantified against isotope dilution calibration curve. Analysis was done using

251 Masslynx Software.

252 2.2.2.4 Isocyanate analysis

253 0.5 g of each sample was added to 1 mL of a 0.01 M di-n-butylamine in toluene solution (Sigma

254 Aldrich) and sonicated (Sonicor SC52-H) for 30 min. Post-sonication 500 µL of a 500 ng/mL

255 standard solution was added to 500 µL of extract and the samples were evaporated to dryness

256 under a stream of nitrogen (Energas). 0.5 mL of UPLCMS grade acetonitrile (Fisherbrand)

257 was then added to the vial which was gently swirled for 30 s before the solution was transferred

258 to the UPLCMS system (Bengtström *et al.* 2018). The results were compared to a standard

259 solution containing a number of isocyanates (Sigma Aldrich, DBA Isocyanate Standard

260 Mixture). The UPLCMS was purged before testing with the UPLCMS grade solvents, and three

261 blanks were run immediately prior to the samples. Due to the low quantity of the samples, they

262 were treated as qualitative samples and the MS spectra compared to spectra obtained from a

263 purchased calibration standard mixture used as a reference. The detailed analytical settings

264 are presented in Table 2.

265

266   **Table 2.** UPLCMS settings for the isocyanate analysis.

UPLCMS settings	
Equipment specifications	Waters Acquity UPLC coupled to a Waters TQD MS Software: Mass lynx version V4.1 SCN714
Column	Waters BEH C18 column (130Å, 1.7 µm, 2.1 mm X 50 mm)
Mobile Phases	A) 95:5 *v/v* water (VWR, 83645.320) and acetonitrile (VWR, 84865.260) and 0.05% formic acid (VWR, 20318.297) B) Acetonitrile and 0.05% formic acid
Flow rate	0.25 ml/min
Gradient program (time/min - %A)	Start – 40, 5 – 2, 6 – 40, 9 – 40
Total program length (min)	10
Column temperature (°C)	40

267

268   ### 2.2.2.5 TGA-FTIR analysis

269   Thermogravimetric analysis coupled to gas phase Fourier Transform Infrared Spectroscopy

270   (TGA-FTIR) was used to qualitatively assess the presence of other fire effluents as a function

271   of sample's temperature. Additional to analyses of the soil samples, cyanide may be present

272   in soil as ferricyanide ($Fe(CN)_6{}^{3-}$) or ferrocyanide ($Fe(CN)_6{}^{4-}$), both analysed by TGA-FTIR in

273   order to determine the HCN release temperatures from the iron complexes. Samples were

274   analysed in a Mettler Toledo TGA/DSC2 connected directly to a Thermo Nicolet iS50 FTIR via

275   a heated line held at 250 °C. 100 mg of soil and 5 mg of residue were heated at 10 °C/min

276   from ambient to 700 °C in nitrogen. The FTIR was set to a resolution of 1 cm^{-1} with a DGTS

277   detector and a scan rate of 10 averaged spectra in a 10 cm pathlength gas cell. The FTIR

278   spectra were compared with the HR Nicolet Vapour Phase and TGA Vapour Phase libraries

279   using OMNIC 9.3.32 software. The wavelength range used for HCN profiles was 3278-3292

280   cm^{-1}. Each sample was analysed in triplicate in both air and nitrogen. The sample crucibles

281   were cleaned after each run. TGA-FTIR instrument was cleaned by and an isotherm run after

282   five tests. In addition, the gas phase FTIR was run using automatic atmospheric suppression.

283 ### 2.2.2.6 Synthetic vitreous fibre analysis

284 SVFs were found in samples of soil, char and residue by manual searching and optical

285 microscopy (Nikon Eclipse E200). Composition of SVF was estimated using a Jeol JCM-6000

286 with Scanning Electron Microscope (SEM) using BED-C COMPO with an integrated JED-2300

287 Energy Dispersive X-Ray Spectroscopy module (EDX). The software programs used for

288 analyses were JCM-6000 Plus version 1.4.0 and Analysis Station version 3.8.0.59. The fibres

289 were prepared on carbon stickers which were placed on SEM stubs for the analyses.

290 ## 3. Results

291 ### 3.1 ICP-OES analysis

292 Aluminium, zinc, copper, lead and other metals were present in soil within UK Environment

293 Agency baseline pollutant levels in soil (EA 2007a). Phosphorus, occurring naturally in the

294 soil, was present at higher levels for soils S1-S3 collected near the Tower (within the range of

295 140-170 mg/kg) than for S4 to S7 with values between 85 and 35 mg/kg, respectively.

296 ### 3.2 Benzene analysis

297 Data in Figure 3 shows elevated benzene concentrations for the first 4 soil samples when

298 compared to the residential soils (EA 2007b). Benzene concentrations decrease with

299 increasing distance from the Tower.

300 ### 3.3 PAHs quantification

301 The sum of the six main PAH concentrations (BaP, fluoranthene, benzo(a)anthracene,

302 benzo(b)fluoranthene, benzo(k)fluoranthene, and benzo(ghi)perylene) in London's urban

303 soils, sampled in nearby Hyde Park (3.9 km away from the Tower), is estimated at 4512 µg/kg

304 (as an average from three locations) (EA 2007b). Similarly to benzene, PAH concentrations -

305 Figure 3 (c and d), show decrease with increasing distance from the Tower.

a)   b)
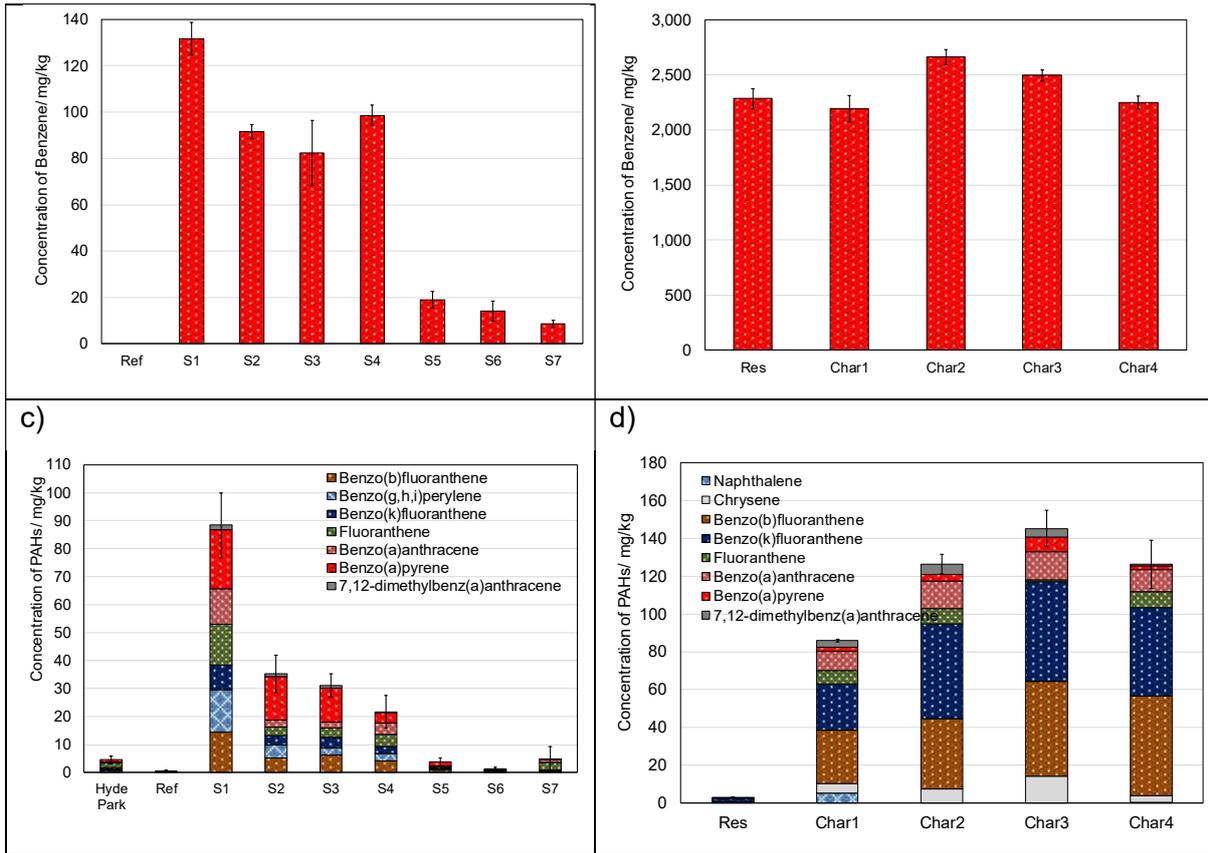
Figure 3. Benzene (a and b) and PAHs (c and d) concentrations showing errors bar for total concentrations in soil samples and fire debris in mg/kg.

3.4 PCDDs and PCDFs analysis

Table 3 shows median soil concentrations of different PCDDs and PCDFs found in soil samples around Grenfell Tower compared to values in urban UK locations and nearby Hyde Park (EA 2009a). PCDD/Fs concentrations are higher for the soil samples collected closer to the Tower, appearing to peak around 100 m from it.

313   **Table 3.** PCDD/Fs levels in soil samples and Char3.

	UK urban/ ng/kg	Hyde Park/ ng/kg	Ref/ ng/kg	S1/ ng/kg	S2/ ng/kg	S3/ ng/kg	S4/ ng/kg	Char3/ ng/kg
Dioxins								
2,3,7,8-TCDD	0.4	0.5	-	1.05	1.3	1.6	-	-
1,2,3,7,8-PeCDD	1.4	1.6	-	8.7	6.7	9.2	1.3	1.8
1,2,3,4,7,8-HxCDD	1.6	1.5	0.3	14.9	14	16.8	1.3	1.5
1,2,3,6,7,8-HxCDD	2.9	3.5	0.7	39.8	36.8	45.7	2.9	2.9
1,2,3,7,8,9-HxCDD	2.6	3.0	0.5	30.2	31.4	34.9	2. 5	2.5
1,2,3,4,6,7,8-HpCDD	25.2	27.5	7.3	889	965	1120	54.8	15.7
OCDD	104	88.8	25.3	6450	7370	8730	356	27.8
Furans								
2,3,7,8-TCDF	2.5	4.4	-	8.3	5.5	11	3.8	22.5
1,2,3,7,8-PeCDF	2.8	3.8	-	5.7	3.0	3.6	2.4	8.8
2,3,4,7,8-PeCDF	4.1	6.9	-	8.4	6.6	5.2	3.2	17.3
1,2,3,4,7,8-HxCDF	3.6	3.3	0.7	8.7	6.7	7.4	3.5	11.9
1,2,3,6,7,8-HxCDF	2.6	2.5	0.4	6.4	6.2	4.5	2.4	14.5
2,3,4,6,7,8-HxCDF	3.8	4.5	0.6	9.8	11.2	9.0	3.1	19.3
1,2,3,7,8,9-HxCDF	1.1	0.9	-	3.1	2.7	0.7	-	5.2
1,2,3,4,6,7,8-HpCDF	24.2	23.6	3.7	83.6	103	116	21.5	52.0
1,2,3,4,7,8,9-HpCDF	1.4	1.0	-	8.9	9.5	12.5	1.8	7.6
OCDF	26.0	19.4	3.7	202	222	239	23.6	19.6
∑PCDDs	138	126.5	34.1	7434	8425	9958	416	52.2
∑PCDFs	72.1	70.3	9.1	345	376	409	65.3	179
Total PCDDs and PCDFs	**210**	**197**	**43**	**7779**	**8802**	**10367**	**482**	**231**
TEQ-WHO (mammals)	**6.48**	**8.65**	**1.39***	**36.4***	**34.6***	**40.6***	**5.63***	**16.4***

314   Notes: ∑, sum of; -, None detected; * concentration of non-detected congeners at detection
315   limit

3.5 Phosphorus flame retardants analysis

Tris(chloroisopropyl) phosphate (TCPP), tris(2-ethylhexyl) phosphate (TEHP) and tricresyl phosphate (TCP) were identified in samples S1 and S2, fire debris and Char3. These are commonly used in insulation foam and upholstered furniture foam and do not occur naturally in the soil (Hewitt *et al.* 2017).

3.6 Isocyanates analysis

MIC, isocyanic acid, ethyl isocyanate and propyl isocyanate were identified in the yellow deposit on the window blind.

3.7 TGA-FTIR analysis

TGA shows the mass loss as a function of temperature when the sample is heated in an inert atmosphere (nitrogen) while FTIR allows identification of volatiles as a function of temperature. Thus, the species observed at elevated temperatures may have been trapped or otherwise adsorbed particularly if they were released below 150 °C. At higher temperatures they are more likely to be decomposition products.

There are broad similarities in terms of released volatiles, shown in Figure 4a. Initial TGA mass losses, up to around 120 ºC, are largely assigned to water release followed by other volatiles. HCN and alkyl cyanides were evolved from over a temperature range of 210 °C. HCN release from soil samples (S1, S2, S4 and S5), fire debris and char collected from individuals balconies is observed from 280 to 310 °C, reaching a peak of around 350 °C. Ferrocyanide releases HCN between 250 and 450 °C, while ferricyanide have two distinguish HCN release maxima at 330 °C and 540 °C. Figure 4b shows the HCN profile of the iron cyanide complexes alongside S1 to S7.
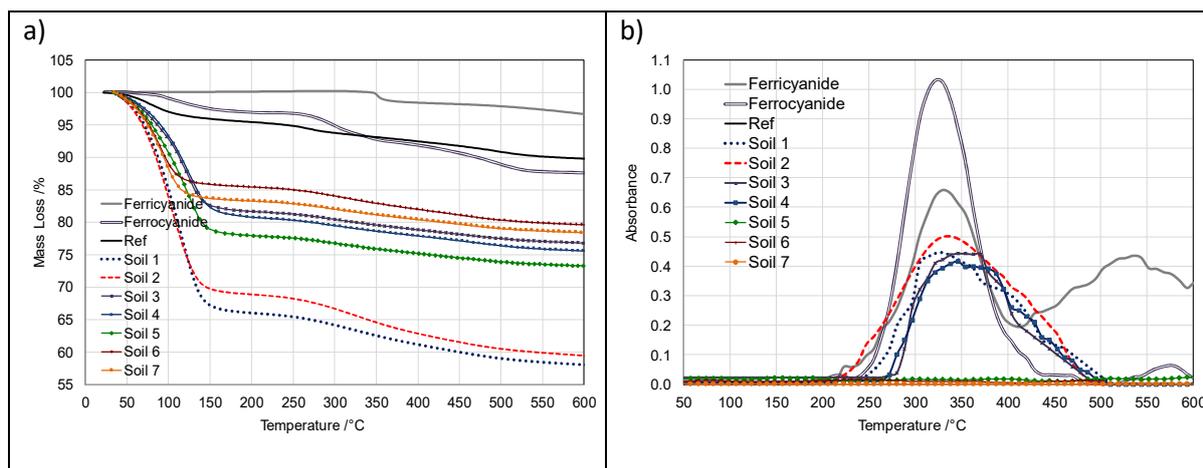
Figure 4. TGA mass loss curves of soil, Res and Char3 samples (a) and HCN release profiles for the soil samples (b).

3.8 Synthetic Vitreous Fibres analysis

SVFs were identified and isolated from soil samples S1 and S2 and were found attached to fallen debris and char samples. In order to identify the possible origins of the SVFs, samples of commercially available polyisocyanurate (PIR), phenolic foam (PhF) and stone wool (SW) were used as reference samples. The PIR sample had two layers of glass wool embedded at depths of approximately 25 and 55 mm within the foam. The phenolic foam sample had layers of glass wool embedded into the outer surface layers inside the foil covering. The foil covering was also reinforced with glass fibres. Reference samples were of the same manufacturer and product names as those reported to have been used on the Tower refurbishment (Grenfell Tower Inquiry 2018). An example of the SVF attached to the foam residue can be seen in Figure 5 and elemental composition in Table 4. Samples were run in quadruplicate.
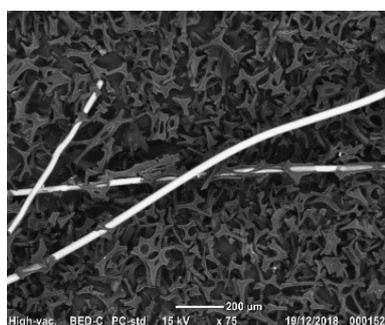
Figure 5. Picture of SVF in Char3.

353 **Table 4.** Elemental analysis of the fibres.

	Abbr.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	FeO	Diameter range /μm
Reference Materials	SW	3.7	9.7	19.4	39.5	0.7	1.6	0.9	17.8	1.8	6.0	8.4 – 11.1
	PIR	19.8	3.8	2.5	70.0		0.3	0.4	3.6			24.5-29.9
	PhF	1.7	3.4	17.0	59.7	2.5	8.2	0.8	15.3			9.7-14.6
Samples	Res	3.7	2.3	15.5	53.5		7.0	0.9	17.9	3.7	2.3	12.1 - 14.4
	Char2	15.2	4.3	2.2	72.3	1.0	0.4	0.5	4.8	15.2	4.3	28.8-31.7
	Char3	12.8	3.9	2.3	74.8	1.0	0.2	0.5	4.7	12.8	3.9	25.1-28.8
	S1	17.8	3.4	2.5	71.3		0.2	0.5	4.3	17.8	3.4	24.5 - 26.1
	S2	1.2	2.3	15.3	57.4	0.8	0.9	0.3	22.1	1.2	2.3	12.0 - 12.5

354 Note: Abbr, Abbreviation

4. Discussion and Conclusions

Soil guideline values provide a reliable baseline against which intensive local surveys and future national surveys can be assessed (EA 2009b). If representative soil concentrations are above the baseline values then further investigation is required to determine whether the substances pose a risk and to determine the scale and urgency of further action. The greater the exceedance of the assessment level, the greater the likelihood that the substance will pose a risk to human health and/or the environment (EA 2009b).

Soil guideline values for benzene for residential land are between 0.87 – 3.3 mg/kg and 95 mg/kg for commercial land use where contamination is expected (i.e. petrochemical and petroleum refining industries) (PHE 2014; EA 2009c). Values are based on a consideration of the oral, dermal and inhalation routes of exposure. Benzene is typically found in petrol and in vehicle emissions, therefore elevated levels may be expected at roadside locations. Data in Figure 3 shows benzene concentrations exceeded these values by factors between 25 and 40 for the four soil samples taken closest to the Tower when compared to the residential soils.

The British Geological Survey defined the normal background concentrations for BaP in England to be 3.6 mg/kg in urban areas and 0.5 mg/kg in all other areas. Guidance levels for BaP are set at 5.0 to 5.3 mg/kg for residential land and up to 77 mg/kg for commercial land (EA 2007b; PHE 2018c). BaP concentrations obtained from the first three soil samples exceed residential values (33, 24 and 17 mg/kg respectively). For soil S5 the value is 2.0 mg/kg, with S6 and S7 values at 0.3 mg/kg - showing the localised distribution of the contamination. The total sum of 6 PAH concentrations (S1), 45 m away from the Tower, is approximately 20 times higher than that reported in Hyde Park (or approximately 160 times greater than the reference soil). S2 to S4 exceeded these reference values by factors between 40 and 60. S5 to S7 are comparable to the reference soils. PCDD levels are around a factor of 70 greater than those collected in Hyde Park or a factor of 60 greater than the UK urban reference soil values. S4

380   contains lower concentrations than S1 to S3, but these are still three times higher than the UK

381   urban or Hyde Park concentrations.

382   Seventeen 2,3,7,8-substituted PCDD and PCDF congeners (Table 3) and 15 PAHs (BaP,

383   benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, indeno(1,2,3-cd)pyrene,

384   chrysene, acenaphthene, acenaphthylene, anthracene, benzo(g,h,i)perylene, fluoranthene,

385   fluorene, phenanthrene, pyrene and naphthalene) with their respective TEFs were used to

386   conduct non-cancer and cancer risks assessment using 2,3,7,8 – TeCDD and BaP toxicity

387   equivalence (PCDD/F WHO-TEQ and PAHs WHO-TEQ) (Van den Berg *et al.* 2013; U.S. EPA

388   2001; 2009; 2018). Results, as Non-Cancer Hazard Quotient (HQ of 1 for non-carcinogens)

389   and Cancer Risk (CR corresponding to a 10^{-6} risk level for carcinogens) are presented in Table

390   5. Reference doses, slope factors and other parameters for estimating human non-cancer and

391   cancer risks were taken from Regional Screening Levels Tables and EPA equations (U.S.

392   EPA 1989; 1991; 2001; 2009; 2018). In this study, the body weight was chosen 70 kg for

393   adults and 15 kg for children. Exposure duration of 25 years for adults and 6 years for children

394   was chosen with ingestion rates of soil 30 and 15 mg/day, respectively. Exposure frequency

395   was assumed to be 50 days/year and exposure time of 1 hr/day for inhalation, ingestion and

396   dermal pathway. Surface area of skin that contacts the soil was taken as 1500 and 500 cm^2

397   for adults and children, respectively (EA 2008). A life time average of 60 years was taken to

398   calculate the average time exposure for carcinogenic chemical exposure.

399   The Hazard Quotient (HQ) together with the lifetime cancer risk was calculated and is

400   presented in Table 5. HQ ≤ 1 indicates no adverse health effects, whereas HQ > 1 indicates

401   likely adverse health effects (NYS DOH 2007). An estimated increased excess lifetime cancer

402   risk is not a specific estimate of expected cancers (when values exceed the unity). Rather, it

403   is a plausible upper bound estimate of the probability that a person may develop cancer

404   sometime in his or her lifetime following exposure to that contaminant (Van den Berg *et al.*

405   1998).

406   **Table 5** Hazard quotient and cancer risk from exposure to residue, soil and char samples.

	Hazard quotient (HQ) of adult			Hazard quotient (HQ) of children			Cancer risk of human (10^{-6})		
	Ingestion	Dermal contact	Inhalation	Ingestion	Dermal contact	Inhalation	Ingestion	Dermal contact	Inhalation
Dioxins/Furans									
UK urban	6.43E-05	3.86E-05	3.86E-09	6.01E-04	6.01E-05	3.86E-09	5.86E-03	5.02E+06	5.87E-12
Hyde Park	6.02E-05	3.61E-05	1.45E-16	5.62E-04	5.62E-05	3.62E-09	5.48E-03	4.70E+06	1.45E-10
Ref	1.32E-05	7.93E-06	3.18E-17	1.23E-04	1.23E-05	7.94E-10	1.20E-03	1.03E+06	3.18E-11
S1	2.38E-03	1.43E-03	5.72E-15	2.22E-02	2.22E-03	1.43E-07	2.17E-01	**1.86E+08**	5.72E-09
S2	2.69E-03	1.62E-03	6.47E-15	2.51E-02	2.51E-03	1.62E-07	2.45E-01	**2.10E+08**	6.47E-09
S3	3.17E-03	1.90E-03	7.62E-15	2.96E-02	2.96E-03	1.91E-07	2.89E-01	**2.48E+08**	7.62E-09
S4	1.48E-04	8.89E-05	3.56E-16	1.38E-03	1.38E-04	8.90E-09	1.35E-02	**1.16E+07**	3.56E-10
Char3	7.07E-05	4.24E-05	1.70E-16	6.60E-04	6.60E-05	4.24E-09	6.43E-03	5.51E+06	1.70E-10
Polycyclic Aromatic Hydrocarbons									
Ref	9.55E-05	3.72E-02	2.46E-03	8.91E-04	5.79E-02	2.46E-03	2.86E-02	9.68E+03	2.47E-11
S1	1.95E-02	**7.61E+00**	5.02E-01	1.82E-01	**1.18E+01**	5.02E-01	5.85E+00	**1.98E+06**	5.05E-09
S2	1.23E-02	**4.80E+00**	3.17E-01	1.15E-01	**7.47E+00**	3.17E-01	3.69E+00	**1.25E+06**	3.19E-09
S3	9.76E-03	**3.81E+00**	2.51E-01	9.11E-02	**5.92E+00**	2.51E-01	2.93E+00	**9.89E+05**	2.53E-09
S4	3.47E-03	**1.35E+00**	8.92E-02	3.24E-02	**2.10E+00**	8.92E-02	1.04E+00	3.51E+05	8.98E-10
S5	1.03E-03	4.00E-01	2.64E-02	9.57E-03	6.22E-01	2.64E-02	3.08E-01	1.04E+05	2.66E-10
S6	2.42E-04	9.45E-02	6.23E-03	2.26E-03	1.47E-01	6.23E-03	7.27E-02	2.46E+04	6.28E-11
S7	2.92E-04	1.14E-01	7.51E-03	2.72E-03	1.77E-01	7.51E-03	8.75E-02	2.96E+04	7.56E-11
Res	1.09E-03	4.26E-01	2.81E-02	1.02E-02	6.63E-01	2.81E-02	3.28E-01	1.11E+05	2.83E-10
Char1	6.20E-03	**2.42E+00**	1.59E-01	5.78E-02	**3.76E+00**	1.59E-01	1.86E+00	6.28E+05	1.61E-09
Char2	9.89E-03	**3.86E+00**	2.55E-01	9.24E-02	**6.00E+00**	2.55E-01	2.97E+00	**1.00E+06**	2.56E-09
Char3	1.41E-02	**5.51E+00**	3.63E-01	1.32E-01	**8.57E+00**	3.63E-01	4.24E+00	**1.43E+06**	3.66E-09
Char4	9.29E-03	**3.62E+00**	2.39E-01	8.67E-02	**5.63E+00**	2.39E-01	2.79E+00	9.42E+05	2.41E-09

407   Note: Values correspond to a 10^{-6} risk level for carcinogens and an HQ of 1 for non-carcinogens.

408   The table shows the HQ for PAHs for dermal contact for both adults and children. The values

409   exceed one are shown in bold. They are for the char and the four soil samples collected

410   nearest to the Tower. This corresponds to an increased risk of any adverse health effects

411   from PAHs, but not from dioxins and furans. The table also shows the cancer risk to humans

412   multiplied by a factor of 10^6. Values exceeding 1×10^6 indicate an increased cancer risk. These

413   are also shown in bold in Table 5. The four soil samples (S1-S4) closest to the Tower indicate

414   significantly increased cancer risk from dioxin and furans, as well as for PAHs, via dermal

415   intake.

416   Soil samples, collected 6 months after the fire, show significant quantities of fire effluents. As

417   soil samples were dried at 60 ºC prior to analysis, reported levels of benzene, PAHs, and

418   dioxins may be lower than actually presented. The distributions of benzene, PAHs and

419   PCDD/Fs show very clearly that particulates/soot/char and fragments of fire debris were

420   distributed within the vicinity of the Tower. Concentrations of PAHs, PCDD/Fs and benzene in

421   the soils suggests that these particulates released toxic substances. Soil concentrations

422   exceed guideline values within 150 m of the Tower. HCN was also observed in TGA-FTIR.

423   Figure 6, shows the localisation of toxicant distribution following the fire. Results suggest that

424   the major sources of contamination for the toxicants analysed in this study are particulates of

425   diameter greater than 100 µm deposited up to 200 m away from the Tower and greater than

426   10 µm within 2000 m distance from the Tower.
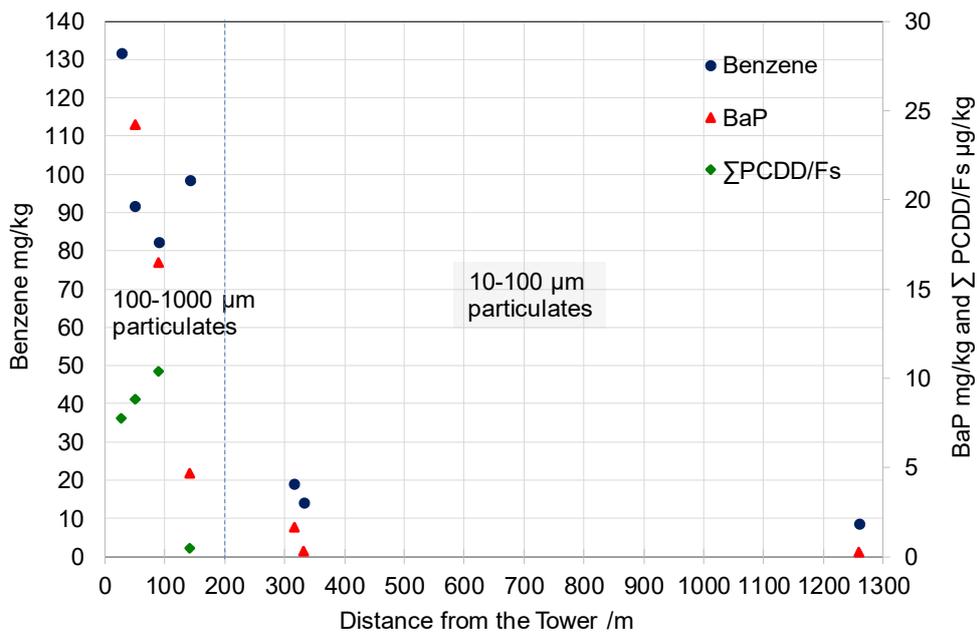
Figure 6. Concentrations of fire effluents in soil samples (Benzene and BaP in mg/kg, PCDD/Fs in µg/kg).

The elevated levels of dioxins and furans and PAHs found in soil samples is in stark contrast to the undetectable levels found during air monitoring by PHE (PHE 2018a). This is unsurprising since any gas phase PAHs or PCDD/Fs will have been dispersed prior to commenced of the PHE analysis (month after the fire) (PHE. 2018b).

The HCN evolution from the soil, mirrors the temperature range of release from ferri- and ferro-cyanides. This suggests that S1 to S4 were exposed to significant quantities of HCN, particularly as S5 –S7 show no such release. TGA-FTIR analysis showed release of MIC as a decomposition product of the fire debris and char samples. The yellow oil on the window blind has been previously characterised as a part polymerised product of isocyanates. Discovery of MIC deposition a volatile liquid (boiling point at 38 °C), on part of the window blind that was exposed to the outside air, is an obvious health concern particularly as it was found 17 months after the fire within a living space.

Analysis of the SVFs from the three insulation panels (PIR, PhF, SW) used on the Tower was compared to that of the SVFs found in soil, char and residue (see section 3.8). It was found that SVFs isolated from the soils are more likely to originate from PIR for S1 and PhF for S2.

445   The composition of the SVF from the fire debris corresponded to that of phenolic foam,

446   whereas the SVF on the chars (Char2 and Char3) displayed close similarities to the SVF from

447   the PIR foam.

448   Soon after the fire, there was little evidence of environmental, indoor or health surveillance to

449   identify the types of fire effluents or populations at risk. The Grenfell Tower fire released both

450   acute and chronic toxicants in the fire effluent which may have potential long-term adverse

451   health effects on emergency responders, clean-up workers and local residents.

452   The data needs to be interpreted with caution as soil is a complex matrix which can vary

453   significantly, even within a small area such as the Grenfell environments. A much more

454   valuable study could have been undertaken in the immediate aftermath after the fire. The

455   absorption and release of toxicants will depend both on their chemical nature and the

456   characteristics of the soil. Sampling from better controlled environments such as plant pots,

457   where a known potting compost has been used and the medium has been undisturbed since

458   the fire, have potential to identify fire contaminants more reliably. In addition, indoor

459   contaminants resulting from deposits within residents homes (dust) have greater potential for

460   positive identification and establishing their relationship to any long-term health effects.

461   From earlier study on the fire behaviour of façade materials, it has been found that brominated

462   flame retardants were not present in significant quantities on the exterior face of the building

463   (McKenna et al. 2019). It is acknowledged that furniture and other products in the Tower may

464   and will contain them, but less clear how much effluent would be released to the surrounding

465   environment.

466   The presence of chlorinated PCDD/Fs and the presence of brominated flame retardants in

467   furniture etc. suggests the likely presence of brominated and mixed brominated-chlorinated

468   dioxins and furans. Significant quantities of chlorinated, brominated and mixed dioxins and

469   furans were identified around the World Trade Centre (Landrigan et al. 2004). The presence

470   of both PAHs and halogenated PCDD/Fs also strongly indicates the likely presence of

471   halogenated PAHs, polychlorinated and polybrominated biphenyls (Xu *et al.* 2018). None of

472   these substances were analysed in this study. They have health risks associated with their

473   presence and should be quantified in any follow-up study.

474   Any health effects, together with long-term fire exposure monitoring, should also be carried

475   out and supervised by a multidisciplinary team with medical, environmental, fire and

476   combustion toxicology expertise. Public agencies need to be adequately prepared to provide

477   reliable guidance to the public on more appropriate means of exposure assessment, risk

478   assessment, and preventive measures - in the event of a recurrence such as this tragic fire.

5. Acknowledgments

6. References

483   Andersson, JT and Achten C. 2015. Time to Say Goodbye to the 16 EPA PAHs? Toward

484   an Up-to-Date Use of PACs for Environmental Purposes. Polycyclic Aromatic

485   Compounds 35(2-4): 330–354; DOI: 10.1080/10406638.2014.991042.

486   ATSDR (The Agency for Toxic Substances and Disease Registry). 2018a. Toxicological

487   Profile for Benzene, US department of Health and Human Services. Atlanta US. URL:

488   https://www.atsdr.cdc.gov/toxprofiles/tp3.pdf. Date accessed: Jan 2019.

489   ATSDR. 2006. Toxicological Profile for Cyanide, US department of Health and Human

490   Services. Atlanta US. URL: https://www.atsdr.cdc.gov/toxprofiles/tp8.pdf. Date accessed:

491   Jan 2019.

492   ATSDR. 2014. Medical Management Guidelines for Methyl Isocyanate, US department of

493   Health and Human Services. Atlanta US. URL:

494   https://www.atsdr.cdc.gov/substances/toxsubstance.asp?toxid=116. Date accessed: Jan

495   2019.

496 ATSDR. 2018b. Toxicological Profile for Chlorinated Dibenzo-p-dioxins (CDDs), US
497 department of Health and Human Services. Atlanta US. URL:
498 https://www.atsdr.cdc.gov/toxprofiles/tp104.pdf. Date accessed: Jan 2019.

499 ATSDR. 2018c. Toxicological profile for synthetic vitreous fibers, US Department Of Health
500 And Human Services Public Health Services. Atlanta US. Agency for Toxic Substances
501 and Disease Registry. URL: https://www.atsdr.cdc.gov/toxprofiles/tp161.pdf. Date
502 accessed: Jan 2019.

503 Bengtström L, Salden M and Stec AA. 2016. The role of isocyanates in fire toxicity. Fire
504 Science Reviews 5: 4; DOI: 10.1186/s40038-016-0013-2.

505 Bengtström L, Salden M and Stec AA. 2018. Stability of Isocyanates Sampled in Fire Smokes.
506 Annals of Work Exposures and Health 62(9): 1171–1175; DOI: 10.1093/annweh/wxy072.

507 Bernstein D, Castranova V, Donaldson K, Fubini B, Hadley J, Hesterberg T, Kane A, Lai D,
508 McConnell EE, Muhle H, Oberdorster G, Olin S, Warheit DB. 2005. Testing of fibrous
509 particles: short-term assays and strategies. Inhalation Toxicology 17(10): 497-537; DOI:
510 10.1080/08958370591001121.

511 Environment Agency (EA). 2007a. UK Soil and Herbage Pollutant Survey Report 7:
512 Environmental concentrations of heavy metals in UK soil and herbage. URL:
513 https://www.gov.uk/government/publications/uk-soil-and-herbage-pollutant-survey. Date
514 accessed: Dec 2018.

515 EA. 2007b. UK soil and herbage pollutant survey (UKSHS). URL:
516 https://www.gov.uk/government/publications/uk-soil-and-herbage-pollutant-survey. Date
517 accessed: Dec 2018.

518 EA. 2008. Updated technical background to the CLEA model, Science Report:
519 SC050021/SR3. URL:
520 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_
521 data/file/291014/scho0508bnqw-e-e.pdf. Date accessed: Jan 2019.

EA. 2009a. Soil Guideline Values for dioxins, furans and dioxin-like PCBs in soil Science Report SC050021 / Dioxins SGV. URL: https://webarchive.nationalarchives.gov.uk/20140328153735/http:/www.environment-agency.gov.uk/static/documents/Research/SCHO0909BQYQ-e-e.pdf. Date accessed: Jan 2019.

EA. 2009b. Using Soil Guideline Values Better Regulation Science Programme Science report: SC050021/SGV. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/297676/scho0309bpqm-e-e.pdf. Date accessed: Dec 2018.

EA. 2009c. Soil Guideline Values for benzene in soil, Science Report SC050021 / benzene SGV. URL: https://webarchive.nationalarchives.gov.uk/20140328153731/http:/www.environment-agency.gov.uk/static/documents/Research/SCHO0309BPQI-e-e.pdf. Date accessed: Dec 2018.

Grenfell Tower Inquiry, Dr Barbara Lane's expert report. URL: https://www.grenfelltowerinquiry.org.uk/evidence/dr-barbara-lanes-expert-report. Date accessed: Dec 2018.

Grenfell Tower Inquiry, Prof Luke Bisby's expert report. URL: https://www.grenfelltowerinquiry.org.uk/evidence/professor-luke-bisbys-expert-report. Date accessed: Dec 2018.

Guerin TF. 1999. The extraction of aged polycyclic aromatic hydrocarbon (PAH) residues from a clay soil using sonication and a Soxhlet procedure: a comparative study. Journal of Environmental Monitoring 1(1): 63-7; DOI: 10.1039/A807307D.

Hewitt F, Christou A, Dickens KE, Walker R and Stec AA. 2017. Release of volatile and semi-volatile toxicants during house fires. Chemosphere 173: 580-593; DOI: 10.1016/j.chemosphere.2016.12.079.

548 McKenna ST, Jones N, Peck G, Dickens K, Pawelec W, Oradei S, Harris S, Stec AA, Hull TR.
549 Fire behaviour of modern façade materials – Understanding the Grenfell Tower fire. 2019.
550 Journal of Hazardous Materials, 368: 115-123; DOI:
551 https://doi.org/10.1016/j.jhazmat.2018.12.077

552 International Organization for Standardization (ISO) ISO 26367-1:2011 Guidelines for
553 assessing the adverse environmental impact of fire effluents-Part 1: General. URL:
554 https://www.iso.org/standard/43529.html. Date accessed: Dec 2018.

555 Landrigan PJ, Lioy PJ, Thurston G, Berkowitz G, Chen LC, Chillrud SN, Gavett SH,
556 Georgopoulos PG, Geyh AS, Levin S, Perera F, Rappaport SM, Small C. 2004. Health
557 and environmental consequences of the world trade center disaster. Environmental Health
558 Perspectives 112(6): 731–739; DOI: 10.1289/ehp.6702. Lippmann M, Cohen MD and Chen
559 LC. 2015. Health effects of World Trade Center (WTC) Dust: An unprecedented disaster's
560 inadequate risk management. Critical Reviews in Toxicology 45(6): 492-530; DOI:
561 10.3109/10408444.2015.1044601.

562 Lippmann M. 2014. Toxicological and epidemiological studies on effects of airborne fibers:
563 Coherence and public health implications. Critical Reviews in Toxicology 44(8): 643-95;
564 DOI: 10.3109/10408444.2014.928266.

565 McGee JK, Chen LC, Cohen MD, Chee GR, Prophete CM, Haykal-Coates N, Wasson SJ,
566 Conner TL, Costa DL, and Gavett SH. 2003. Chemical analysis of World Trade Center fine
567 particulate matter for use in toxicologic assessment. Environmental Health Perspectives
568 111(7): 972-980; DOI: 10.1289/ehp.5930.

569 National Statistics. 2018. UK Government, Home Office. URL:
570 https://www.gov.uk/government/collections/fire-statistics-monitor. Date accessed: Jan
571 2019.

572 New York State Department of Health (NYS DOH). 2007. Hopewell precision area
573 contamination: appendix C – NYS DOH, in: Procedure for Evaluating Potential Health Risks

for Contaminants of Concern. URL: https://www.health.ny.gov/environmental/investigations/hopewell/docs/final_health_consult.pdf. Date accessed: Jan 2019.

Persson B and Simonson M. 1998. Fire emissions into the atmosphere. Fire Technology 34:266-278; DOI: 10.1023/A:1015350024118.

PHE. 2018a. Public health advice reports. URL: https://www.gov.uk/government/news/public-health-advice-following-the-grenfell-tower-fire. Date accessed: Dec 2018.

PHE. 2018b. Environmental monitoring following the Grenfell Tower fire. URL: https://webarchive.nationalarchives.gov.uk/20180608192719/https://www.gov.uk/government/publications/environmental-monitoring-following-the-grenfell-tower-fire. Date accessed: Jan 2019.

PHE. 2018c. Polycyclic aromatic hydrocarbons (Benzo[a]pyrene) Toxicological Overview. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/737017/PAH_TO_PHE_240818.pdf. Date accessed: Jan 2019.

Public Health England (PHE). 2014. Benzene: health effects, incident management, and toxicology. URL: https://www.gov.uk/government/publications/benzene-general-information-incident-management-and-toxicology. Date accessed: Dec 2018.

Stec AA and Hull TR. 2010. Fire Toxicity. Oxford, Oxfordshire, CRC Press; Woodhead Publishing.

Stec AA, Dickens KE, Salden M, Hewitt FE, Watts DP, Houldsworth PE and Martin FL. 2018. Occupational Exposure to Polycyclic Aromatic Hydrocarbons and Elevated Cancer Incidence in Firefighters. Scientific Reports 8(1): 2476; DOI:10.1038/s41598-018-20616-6.

Stec AA. 2017. Fire toxicity – The elephant in the room? Fire Safety Journal 91: 79-90; DOI: 10.1016/j.firesaf.2017.05.003.

599 TimeandDate.com. 2017. Past Weather in London, England, United Kingdom. URL:

600 https://www.timeanddate.com/weather/uk/london/historic?month=11&year=2017. Date

601 accessed: Jan 2019.

602 US Environmental Protection Agency (EPA). 1994. Method 1613 Tetra- through Octa-

603 Chlorinated Dioxins and Furans by Isotope Dilution HRGC/HRMS. URL:

604 https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=30002RIE.TXT. Date accessed: Dec

605 2018.

606 US EPA .2001. Supplemental guidance for developing soil screening levels for Superfund

607 sites. OSWER 9355.4-24. Office of Solid Waste and Emergency Response. Washington

608 DC. URL: https://rais.ornl.gov/documents/SSG_nonrad_supplemental.pdf. Date

609 accessed: Jan 2019.

610 US EPA. 1989. Risk assessment guidance for superfund, Vol. I: Human Health Evaluation

611 Manual. EPA/540/1–89/002. Office of Solid Waste and Emergency Response. Washington

612 DC. URL: https://www.epa.gov/sites/production/files/2015-09/documents/rags_a.pdf. Date

613 accessed: Jan 2019.

614 US EPA. 1991. Risk Assessment Guidance for Superfund (RAGS), Volume I: Human Health

615 Evaluation Manual (HHEM), Part B, Development of Risk-Based Preliminary Remediation

616 Goals. Publication 9285.7-01B. NTIS PB92-963333. Office of Solid Waste and Emergency

617 Response. Washington DC. URL: https://www.epa.gov/risk/risk-assessment-guidance-

618 superfund-rags-part-b. Date accessed: Dec 2018.

619 US EPA. 2009. Risk assessment guidance for superfund, Vol. I: Human Health Evaluation

620 Manual (F, Supplemental Guidance for Inhalation Risk Assessment) EPA/540/R/070/002.

621 Office of Superfund Remediation and Technology Innovation. Washington DC. URL:

622 https://www.epa.gov/sites/production/files/2015.../part_e_final_revision_10-03-07.pdf.

623 Date accessed: Dec 2018.

624 US EPA. 2014. "Method 6010D (SW-846): Inductively Coupled Plasma-Atomic Emission
625 Spectrometry," Revision 4. Washington, DC. URL: https://www.epa.gov/homeland-
626 security-research/epa-method-6010d-sw-846-inductively-coupled-plasma-atomic-
627 emission. Date accessed: Jan 2019.

628 US EPA. 2018. Regional Screening Levels (RSLs) - Generic Tables. URL:
629 https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables. Date accessed:
630 Jan 2019.

631 Van den Berg M, Birnbaum L, Bosveld ATC, Brunström B, Cook P, Feeley M, Giesy J P,
632 Hanberg A, Hasegawa R, Kennedy SW, Kubiak T, Larsen JC, van Leewen FXR, Liem AKD,
633 Nolt C, Peterson RE, Poellinger L, Safe S, Schrenk D, Tillitt D, Tysklind M, Younes M,
634 Waern F and Zacharewski T. 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs,
635 PCDFs for humans and wildlife. Environmental Health Perspectives 106(12): 775–792;
636 DOI: 10.1289/ehp.98106775.

637 Van den Berg M, Denison MS, Birnbaum LS, DeVito MJ, Fiedler H, Falandysz J, Rose M,
638 Schrenk D, Safe S, Tohyama C, Tritscher A, Tysklind M, Peterson RE. 2013.
639 Polybrominated Dibenzo-p-Dioxins, Dibenzofurans, and Biphenyls: Inclusion in the Toxicity
640 Equivalency Factor Concept for Dioxin-Like Compounds. Toxicological Sciences 133(2):
641 197–208; DOI: https://doi.org/10.1093/toxsci/kft070

642 Van Loon GW and Duffy SJ. 2000. Environmental chemistry. Oxford, Oxfordshire, Oxford
643 University Press.

644 Xu Y, Yang L, Zheng M, Jin R, Wu X, Li C, Liu G. 2018. Chlorinated and Brominated Polycyclic
645 Aromatic Hydrocarbons from Metallurgical Plants. Environmental Science and Technology
646 52(13): 7334-7342; DOI: 10.1021/acs.est.8b01638.

647 Wang LR, Wang Y, Chen JW and Guo LH. 2009. A structure-based investigation on the
648 binding interaction of hydroxylated polycyclic aromatic hydrocarbons with DNA. Toxicology
649 262(3): 250-257; DOI: 10.1016/j.tox.2009.06.015.

650   World Health Organisation (WHO). 2010. Guidelines for Indoor Air Quality: Selected

651   Pollutants. The WHO European Centre for Environment and Health. URL:

652   http://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf. Date accessed:

653   Dec 2018.