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## French firefighters exposure to Benzo[a]pyrene after simulated structure fires

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### ABSTRACT

**Introduction:** Firefighters have occupational exposure to toxic compounds during firefighting, but not only. Surface contamination of equipment has never been studied in French firefighters.

**Materials and methods:** This study measured the surface load in benzo [a]pyrene (BaP), a carcinogenic polycyclic aromatic hydrocarbon, on the outer surface of fire jackets, personal protective equipment and tools used by firefighters after a live fire training in a closed environment. The effectiveness of a standard jacket washing procedure on BaP contamination was assessed.

**Results:** A single training session was responsible for a BaP deposit of  $113.75 \pm 45.03 \mu\text{g}/\text{m}^2$  on exposed fire jacket material. After a single session, the deposit of BaP found on PPE and tools was measured on different surfaces ranged from 12 to  $157 \mu\text{g}/\text{m}^2$ . After multiple training sessions, a cumulative effect was suspected. The current PPE cleaning and maintenance procedures does not appear to effectively reduce contamination.

**Conclusion:** French firefighters' exposure during in a live-fire training session in fire simulator is responsible for exposure to BaP. The estimated load of BaP on the outer surface of fire jackets could potentially have acute and chronic effects if absorbed in one's body. Further studies are needed to better understand individual French firefighters' exposure and determine appropriate measures to prevent contamination. It will be also necessary find maintenance procedures that significantly reduce the BaP load.

### 1. Introduction

The effect of fire exposure on firefighters is a major concern. Smoke from fires comprises suspended liquid and solid particulate matter, gases and vapors that result from the combustion or pyrolysis of material. The International Agency for Research on Cancer (IARC) reviewed the large number of toxic components in fire related smoke (IARC Working Group on the Evaluation of Carcinogenic Risks, 2010a). The focus has generally been on substances that cause acute toxicity, such as carbon monoxide (CO), hydrogen cyanide (HCN), sulfur dioxide (SO<sub>2</sub>); but it is also known that all types of fire produce carcinogenic substances, including benzene, 1,3-butadiene, and formaldehyde. Many of the identified carcinogenic products of combustion are volatile

organic compounds (VOCs). Thermal degradation of polymers found in building produce VOCs (such as methane, benzene, toluene, in addition to monomers like ethylene, styrene, phenol, formaldehyde, 1,3-butadiene, phenol, and isoprene). Burning of plastics typically also produce hydrogen cyanide and hydrochloric acid (HCl). In a study, Austin et al. showed that no new or unusual VOCs were identified in current structural fires compared to the combustion of wood. Polycyclic aromatic hydrocarbons (PAH) as naphthalene, pyrene, phenanthrene, fluoranthene, acenaphthylene, benzo [a]anthracene and benzo [a] pyrene are released during the incomplete combustion or pyrolysis of organic materials (Fent et al., 2014; Kirk and Logan, 2015a; Laitinen et al., 2010). The emission of combustion products for the same material depends on the conditions of combustion. Nonetheless, the

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relative amounts of various VOCs found in smoke in structural fires have been remarkably similar from fire to fire, namely with the same 14 of 144 target compounds, dominated by benzene (IARC Group 1), toluene and naphthalene (IARC Group 2B) (Austin et al., 2001a, 2001b). The International Agency for Research on Cancer (IARC Working Group on the Evaluation of Carcinogenic Risks, 2010a) states that firefighting exposes to possible carcinogens (IARC Group 2B). Firefighters are also exposed to fire-smoke containing heavy metals (Dobraca et al., 2015) and potent endocrine disrupting agents, possibly phthalates, that may lead to hormone-mediated adverse health outcomes (Stevenson et al., 2015).

The potential for personal protective equipment (PPE) to become contaminated by particulate and vapor-phase products of combustion during firefighting is well recognized. Various VOCs or PAHs have been found on PPE in multiple studies (Fent et al., 2015; Kirk and Logan, 2015a, 2015b).

Benzo [a]pyrene (BaP), is a 5 ring PAH compound, classified as a group 1 carcinogen to humans (IARC Working Group on the Evaluation of Carcinogenic Risks, 2010b). Literature shows that exposure could occur in phases considered as safe by firefighters (overhauling, cleaning, restoring equipment, training, or working at the fire station) (Fent et al., 2015; Kirk and Logan, 2015b; Oliveira et al., 2017). French data is scarce on this subject. Differences in equipment and procedures between countries could be responsible for significant geographical variations. Concerned by the topic, fire instructors wished to know the extent of surface contamination of their occupational environment and the effectiveness of current cleaning procedures.

## 2. Materials and methods

This study was conducted at the Departmental Fire and Rescue Services of Maine-et-Loire Fire Campus. It was supported by our institutional Health and Safety Committee (CHS). Experiments were conducted in a fire training simulator constructed from a 40-foot shipping container. Structural fire exposure was modeled by transit in a live-fire training session. Shipping container simulators enable us to reproduce realistic conditions that firefighters could find during a fire in a closed environment and also allow a good standardization and reproducibility of environmental conditions. The simulator was ignited from the bottom with the calorific equivalent of a bedroom. The simulator container was divided into two parts: A fire zone with a calibrated fireplace (3 boards of 0.5 m<sup>2</sup> and a “Tipi” of particle board and wooden pallet weighing approximately 4 kg) and a target firebox composed of 9 m<sup>2</sup> particle board planks (equivalent to an empty library). A standardized session lasted approximately 30 min: After preparation, firefighters entered the simulator with their PPE and breathing apparatus (Fig. 1). PPE include a fire-jacket, overtrousers and gloves constructed with an outer shell made of Nomex (BALSAN, Déols, France), boots, and fire helmet. The first phase consisted of observing thermal phenomena after ignition of the fuel. Hot fumes were evacuated by special ventilation openings. Participants were left in the container for 15 min, after which the second phase began. Each firefighter entered the container through the door using the safety procedure. The rotation was completed after 30 min.

Highest ambient temperature ( $\approx 400$  °C) was observed during the observation phase near the fire zone.

The Benzo [a]Pyrene was chosen as a marker to relate PAHs exposure for our study. Toxicological expertise was provided by the “Laboratoire Interregional de Chimie de l’Ouest”, a public health insurance fund laboratory.

Assessment of surface exposure of fire-ensembles and effectiveness of washing procedure was the end-point of this study. In our Fire Department, washing procedures are subcontracted to a private company. It includes a hot water washing cycle with the use of a non-ionic surfactant for the degreasing phase; a washing phase with a detergent containing surfactants, sequestering agents, additives, and enzymes;

and finally, a rinsing phase; and a fluorinated waterproofing treatment.

PPE were cleaned prior to the training period. They were used, like the rest of the equipment, for a dozen sessions. The number of sessions since the last washing was indicated.

Multiple surface specimens are collected:

- Cloth samples attached to the front of fire-ensemble (Fig. 2). The cloth samples were made of the same material as the outer surface of the jacket. They were new and had never been exposed to a fire. The samples were placed before sessions started and separated into 2 parts before the jacket was sent for washing (1 part was left on the jacket during the procedure, the other was immediately analyzed).
- Other samples were collected on the equipment used by firefighters during many sessions.
- Helmets and hoses used by firefighters during the session were tested by wiping the outer surface on an area measuring 10 × 10 cm with an impregnated heptane wipe. For negative control, helmets used in a gas simulator were also wiped.

After treatment with 20 mL dichloromethane in order to dissolve BaP, the analysis was carried out by high-performance liquid chromatography (HPLC) with on-line purification and fluorometric detection for the determination of BaP (Champmartin et al., 2007) with a Limit Of Quantification (LOQ) for BaP of 2 ng (0.1 ng/mL). The LOQ was adapted to surface of sample:  $LOQ = 2/surface$ . For samples collected by wiping of an area measuring 10 × 10 cm, the LOQ was 0.2 μg/m<sup>2</sup>.

All values are expressed as mean and standard deviations. The dose of BaP deposited over the outer surface of the PPE was artificially estimated by calculating the mass of BaP for 1.73 m<sup>2</sup> (average body surface area). Means (before/after washing procedure) were compared by Wilcoxon matched-pairs signed-rank test. The level of significance was conventionally selected at 5%.

## 3. Results

Results of the HPLC analyzes of the eluate (obtained after treatment of the samples with dichloromethane) are presented in Table 1. A single session was responsible for a  $113.75 \pm 45.03$  μg/m<sup>2</sup> deposit of BaP on exposed textile cloth samples. This load is equivalent to 196.79 μg for a cloth surface area of 1.73 m<sup>2</sup>. Depending on the surface, after a single session, the deposit of BaP measured on surfaces ranged from 12 to 157 μg/m<sup>2</sup> (Tables 1 and 2).

Samples exposed to more than a dozen sessions were significantly more contaminated with BaP, suggesting an accumulation effect. The minimum BaP load on the outer surface of PPE, in this group, was equivalent to 3325.06 μg for a cloth surface area of 1.73 m<sup>2</sup>.

Gas fires do not produce PAHs (Laitinen et al., 2010). As expected, helmets used in a gas fire simulator were not exposed to BaP (Table 2).

After the washing procedure, BaP concentration of the textile cloth sample increased by 44% (Table 1). This result was not statistically significant ( $p = 0.25$ ) because of the small sample size ( $n = 4$ ).

## 4. Discussion

In this study, we found a significant deposit of BaP on the outer PPE surface after a single live-fire training session using particle board planks. The increase of BaP load on increasingly exposed samples suggests a cumulative effect linked to successive sessions. The current PPE maintenance procedure does not appear to effectively reduce contamination. This protocol reproduces real conditions found in a structural closed environment fire. The frame of sessions is reproducible. The fire load is identical from one session to another and is equivalent to the contents of a bedroom.

The deposition of PAHs is in line with the finding of previous studies of occupational exposition of firefighter instructors in smoke diving simulators. Laitinen et al. (Laitinen et al., 2010) found PAHs



**Fig. 1. - Pictures of a session.** Trainees are in black, instructors in yellow. A: Simulator container during the observation phase. Trainees are confined in the container with two instructors. B: Moving of the instructors during the phases. C: Training phase for the entry procedure. D: Entry of trainees in the container during the second phase. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 2. Location of cloth samples attached on the front of fire jacket.** The two cloth samples are made of the same material as the jacket.

**Table 2**

Deposition concentration collected by wiping of BaP on surfaces (10 cm<sup>2</sup>) during one session.

Specimens	N	Number of session	BaP concentration
Helmet surface (Control: simulation course with gas fire)	2	0	0.5
Hose surface	1	1	0.8
Helmet surface	1	1	12

Values are expressed in µg/m<sup>2</sup>. Limit of Quantification for BaP of 0.2 µg/m<sup>2</sup>.

concentrations of up to 100 µg/m<sup>2</sup> on the surface of the whole body. We can hypothesize that the concentrations at the surface of the PPE were higher. However, the deposit concentrations of BaP in the current study are greater than those found by Kirk et al. (Kirk and Logan, 2015a) on the surface of cloth samples after five live fire training scenarios. The difference can be explained by the lower amount of fuel used in these sessions.

The accumulation of BaP on textile was strongly suspected because

**Table 1**

Concentration (µg/m<sup>2</sup>) of BaP on samples after one or more sessions and after maintenance.

Samples	N	Number of session	Before maintenance	After maintenance	Difference	p
Unexposed textile witness	1	0	< 8 (LOQ)	–	–	
Textile cloth samples	4	1	113.75 ± 45.03	164.00 ± 46.77	50.25 [-59.27; 159.77]	0.25
Helmet flap	1	≈ 15	3826	–	–	
Identification badge	1	≈ 12	6916	–	–	
Textile sample	1	≈ 12	1922	–	–	

For textile cloth samples values are expressed as mean value ± standard deviation. 95%CI: [ ]. LOQ: Limit of Quantification.

of the increase of BaP concentrations between textile cloth sample and textile sample after, respectively, one and one dozen of sessions (Table 1). We cannot, however, formally conclude this in absence of evidence of successive increments of BaP after each session. The literature is consistent with our results. The accumulation of contamination on PPE after multiple exposures to fire was demonstrated by Kirk et al. (Kirk and Logan, 2015b).

Our study did not address the question of whether the pollutant crossed through clothing onto the firefighter's skin, or rather stayed on the surface of the vest. Extrapolation of the exposure found on the specimens to the total body surface was made for estimate the dose of BaP deposited over the outer surface of PPE not the body burden. The homogeneity of exposure was not sought in our study. Firefighters may be frequently exposed to significant dermal doses of BaP because of contaminated PPE. The amount of pollutant on the surface of PPE is relevant because a portion is likely to reach the skin through the jacket. This passage through the clothing was found by Kirk et al. (Kirk and Logan, 2015a). We also did not collect data on the transcutaneous passage of BaP and on metabolites found in urine at the end of the session. Fent et al. (2014) have shown that skin PAH concentrations are correlated with measured metabolite concentrations in urine. PPE can generate a dermal exposure when handling without protection and also atmospheric exposure by VOCs and low molecular weight PAHs off-gassing (Fent et al., 2015; Kirk and Logan, 2015b). Thus, other routes of contamination are possible. The amount of BaP could be responsible for acute or chronic toxicity. Normative exposure limit values for surface or dermal exposure are not defined in France or abroad. A synergistic effect with other PAHs and VOCs is possible.

Firefighter exposure is demonstrated but the level of risk is more difficult to define. Many factors should be taken into account to understand exposure through PPE contamination. In the French rescue system, firefighters may have a different status. Military firefighters (12 000 in 2016) provide missions in two of the largest French cities (Paris and Marseille). Professional firefighters (full time activity) and volunteer firefighters (who have a different main professional activity) are spread over the rest of the country. The proportion of volunteers (193 700 in total in 2016) and professionals (41 000 in 2016) is geographically variable (Statistiques des Services d'Incendie et de Secours, 2016, 2016). We could believe that military and professional firefighters are more likely to have enhanced exposure to carcinogens because, in comparison to volunteer firefighters, they have increased workload. They are also at higher risk of wearing or frequently handling PPE and contaminated tools. There are other variables that need to be considered. Due to high technicality, the cost of the PPE usually extends their replacement cycle leading to a risk of repeated contamination. The maintenance and renewal cycle for PPE are probably longer for volunteers. Data showing increased contaminant concentrations between studies involving shorter (Fabian et al., 2014) and longer (Lacey et al., 2014) periods of use of PPE. Comparison of contaminant concentrations on PPE between professional and volunteer firefighters has not previously been investigated. Volunteer firefighters are mostly located in rural and peri-urban areas. The distribution between structural fire and wildfire fighting is therefore different. The exposure is also different because in the French procedures, a breathing apparatus is not worn during wildfire fighting. Fire emanations vary in concentration of contaminants depending on the fuel. Particle board plank are known to emit more benzene and PAH, when ignited, than for other fuels without glue (Laitinen et al., 2010).

Globally, there is a lack of data on individual fire exposure for French firefighters. The only French epidemiological study available could not find a dose-response relationship between the frequency of exposure to smoke and health risks (Amadeo et al., 2015). An Australian study by Glass et al. (2017) showed that a risk of cancer could not be excluded in volunteer firefighters. Exposure to carcinogens by fire instructors should be followed more attentively as they have an increased cancer risk compared to other firefighters (Glass et al., 2016).

In their study, mortality and cancer incidences were compared with probability of fire emanation exposure. The high-risk group (practical areas for drills operators and professional instructors) had an increased risk of cancer (overall, testicular and melanoma) relative to the state population. The link with risk factors such as prolonged exposure time, longer years of service or regular tasks for instructors is suspected but has not been actually proven in the literature.

Our results show that the current washing procedure of fire jackets does not remove the presence of BaP. According to the manufacturer's recommendations, washing procedures must include cycles with use of water and a detergent. Kirk et al. (Kirk and Logan, 2015b) showed that many of the smoke compounds return to preexposure levels after a washing procedure done according to manufacturer specifications. For some compounds, levels after washing remained at levels above pre-exposure levels. Some PAHs, in particular, the BaP, are probably more difficult to remove than others. BaP is not soluble in water (Pubchem, n.d.). It is possible that the washing procedure was not adapted to the physicochemical characteristics of this contaminant.

Precautionary measures seem justified concerning PPE related contamination. The wearing of gloves (Laitinen et al., 2010) and aerial protection could be proposed before handling of PPE and exposed tools. Exposed PPE should be exclusively used for firefighting, and use non-exposed PPE for other rescue missions. With the cumulative effect, PPEs should, therefore, be considered with caution especially after several expositions. Firefighters should be informed about the routes of contamination to understand the need for protection. They also should receive appropriate follow-up with medical consultations, especially those with a high fire exposure frequency. This follow-up should not end at retirement because of the latency of pathologies related to chronic exposure. The recently developed Swedish model "Skeffeltea" received the award of European innovation in workplace safety (Swedish Civil Contingencies Agency, 2005). It calls on important material means including changes in fire stations. Efficacy of this model is currently not proven.

The present study has several limitations. First, the low numbers of samples. Second, we cannot exclude that the jackets exposed to several sessions increased the BaP load of the cloth samples during the washing procedure through cross-contamination. The absence of a decrease in BaP load in the cloth samples during the washing procedure could be the consequence of this cross-contamination. We do not have samples of the other PPE and fluids from the washing machine to confirm the cross-contamination. Third, the washing procedure being subcontracted by our fire department, it cannot be excluded that the textile cloth samples were washed separately from the fire jackets. Fourth, the method for determination of BaP in our study is the reference method used by hygiene laboratories in France in many complex matrices as validated by Champmartin et al. (2007) (Bitumen, Grease, Coal tar, Creosote, Cream, Ink). The coefficients of variation (C.V.) were low (< 5–7%). Application of the method, as can be seen in our study, was not validated for extraction from substance samples. Since, no validation of the method has been carried out.

## 5. Conclusion

Firefighters' exposure during in a live-fire training session in fire simulator is responsible for benzo [a]pyrene exposure (BaP). BaP is found on the surfaces of fire jackets, PPE, and tools. The estimated load of BaP on fire jackets could have potential acute and chronic effects when absorbed by the body. A cumulative effect, related to the multiplication of sessions, is suspected. The current PPE washing procedure does not appear to effectively reduce the BaP contamination. Further studies are needed in order to achieve a better knowledge of individual French firefighters' exposure. It will also be necessary to find a maintenance procedure that significantly reduces the BaP load. In the meantime, it is necessary to suggest measures to prevent the firefighters' contamination by PPE and contaminated tools.

## Conflicts of interest

None.

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