



Development of Fireground Exposure Simulator (FES) Prop for PPE Testing and Evaluation

**Gavin P. Horn, Jeffery Lattz, Richard M. Kesler and Denise L. Smith, Illinois Fire Service Institute, University of Illinois at Urbana-Champaign, MC-675, 11 Gerty Drive, Champaign, IL 61820, USA*

Gavin P. Horn and Steve Kerber, UL Firefighter Safety Research Institute, Columbia, MD, USA

Denise L. Smith, Health and Human Physiological Sciences Department, Skidmore College, Saratoga Springs, NY, USA

Alex Mayer and Kenneth W. Fent, National Institute for Occupational Safety & Health, Cincinnati, OH, USA

Received: 26 November 2019/**Accepted:** 8 April 2020

Abstract. Research on the performance of personal protective equipment (PPE) for the Fire Service is challenged by the ability to repeatedly and feasibly test new designs, interventions and wear trials in realistic conditions that appropriately simulate end use environments. To support firefighter PPE research and firefighter PPE acclimation/training, a multidisciplinary team has developed a low cost, easily replicable approach for simulating conditions commonly encountered by firefighters operating on the interior of a residential structure fire. The testing enclosure can be used with either stationary mannequins or firefighters conducting typical fireground activities, providing a method to study a wide range of PPE and physiological studies as well as training activities that may support developing new technologies and standardized testing opportunities. Environmental gas concentrations and firefighters' local temperatures were measured during trials and compared to data collected from simulated fireground activities and fireground responses with good agreement.

Keywords: Firefighters, Fireground, Combustion products, Occupational exposure, Personal protective equipment (PPE)

1. Introduction

Firefighters are becoming increasingly aware of their chemical exposure risks on the fireground and the health risks associated with that exposure. In response, firefighting personal protective equipment (PPE) manufacturers are rapidly developing and marketing new solutions to address these concerns and fire departments are implementing changes in their procedures at the station, on the fireground and

*Correspondence should be addressed to: Gavin P. Horn, E-mail: ghorn@illinois.edu



after the firefight to reduce exposure risks. Fires with common household furnishings in today's residential structures can produce hundreds of compounds, including those that exist primarily in vapor phase (e.g., benzene, styrene, 1,3-butadiene, formaldehyde, vinyl chloride, dioxins) and those that exist primarily in solid phase (e.g., higher molecular weight polycyclic aromatic hydrocarbons (PAHs), phthalates, brominated flame retardants, and metals) [1–3]. Some of these compounds are known or probable human carcinogens including benzene and some PAHs [4, 5]. Firefighters are most commonly exposed to these compounds through inhalation when they are not wearing airway protection or through dermal absorption during and after the firefight.

Much of the research on firefighters' dermal exposure to contaminants has focused on the solid phase contamination, such as higher molecular weight PAHs [6–13]. Once these larger PAHs contact human skin, they will likely remain available for biological uptake. However, the lower molecular weight PAHs, like naphthalene, fluorene, phenanthrene, and anthracene are considered semi-volatile. These compounds, along with volatile organic compounds (VOCs), will exist primarily as vapor during interior firefighting, and may have much shorter residence time on skin thereby potentially affecting absorption rates. Firefighting PPE is rapidly evolving to better protect firefighters from this complex mixture of chemicals, while balancing protection requirements for other known hazards (thermal, abrasion, biomechanical, etc.).

While firefighting PPE is going through evolutionary changes, studies to determine the benefits of new PPE design features have largely been limited to simulated-contaminant testing as opposed to studying PPE under realistic and repeatable smoke conditions. Several laboratory-based tests exist to study effectiveness of PPE used for emergency responders; including the Man In Simulant Testing (MIST) [14], the shower test [15], and more recently, the Fluorescent Aerosol Screening Testing (FAST) [16]. These simulated contaminants typically represent a single type or class of compounds. Thus, interventions that may impact solids differently than gases cannot be directly compared within a single test.

The MIST method introduces first-responder protective garments to challenge vapors (commonly oil of wintergreen) that simulate harmful chemical agents. Protection factors are quantified for full garment ensembles by measuring penetration of vapors using pads placed underneath the clothing. This type of testing can be used with either mannequins or human subjects. The shower test provides a means to evaluate the ability of PPE to resist liquid penetration from spray nozzles onto a mannequin. Finally, FAST provides a means to document the aerosol penetration from the environment to a human subject's skin in a visual and, in some cases, quantifiable manner. The FAST aerosol is tagged with fluorescent dye to ease visualization under a black light, but the technique can also be made quantitative by tagging aerosol with other measurable chemicals. The concentration of simulants and forcing functions (such as air speed or shower volume and velocity) are often greater than those in realistic environments, which may provide the ability to identify a wide variety leakage paths such as at interfaces and clo-

tures. However, these leakage paths may not be present under more realistic conditions.

For MIST and FAST testing, physical movement and activities of human participants are standardized, but not necessarily representative of how firefighters move through the fireground or the work that is commonly conducted. For example, the common FAST motion routine includes standing, walking, bending, reaching, squatting, twisting, running in place and laying in the prone position. However, motions such as crawling for a search, advancing a hoseline from a crouched position, or performance of overhaul operations that are commonly conducted in fire conditions are not included. Thus, with FAST testing, it is not clear how the PPE interfaces may be stressed and potentially result in firefighter exposures during such realistic movements. Protocols such as the Firefighting Activities Station (FAS) [17, 18], have been developed from firefighter physiology-based studies over two decades [19–21]. The FAS involves firefighters conducting various activities similar to what they would perform on the fireground—climbing stairs, searching a room, advancing a hoseline and pulling down ceiling materials—in a manner that allows firefighters to develop proper technique under controlled conditions and allows quantification of the work completed.

This manuscript summarizes a new dual-purpose training/testing prop developed to provide researchers, equipment manufacturers, training organizations, standards organizations and firefighters with a means to produce a controlled environment with a repeatable and realistic thermal and smoke environment in order to characterize PPE performance or characterize firefighter responses to common fireground conditions that simulate the combined vapor, particulate and thermal threats firefighters face. The prop can be used to test up to 24 mannequins or six firefighters conducting training on typical fireground movements and activities at a given time. This manuscript also reports on gas concentration and temperatures obtained in the simulation prop and compares data from the new simulation prop to data from recent studies that have quantified exposures for firefighters operating in simulated fire attack and search & rescue operations [22, 23].

2. The Fireground Exposure Simulator (FES)

2.1. Prop Construction and Test Protocol

The Fireground Exposure Simulator (FES) prop was developed in a 2.4 m wide, 2.9 m tall and 12.2 m long intermodal shipping container which is commonly used for firefighter training around the world (Fig. 1). The container is divided into three sections, where the middle 3.1 m section is a controlled combustion chamber lined with concrete fiber board. Smoke generated by burning household furnishings is ducted in to two exposure chambers on each of the 4.6 m ends (labeled left and right when facing the combustion chamber doors). Fuel packages are loaded into a burner configured to protect the chamber ceiling from direct contact with flames. Sliding doors are used to adjust the availability of air into the combustion

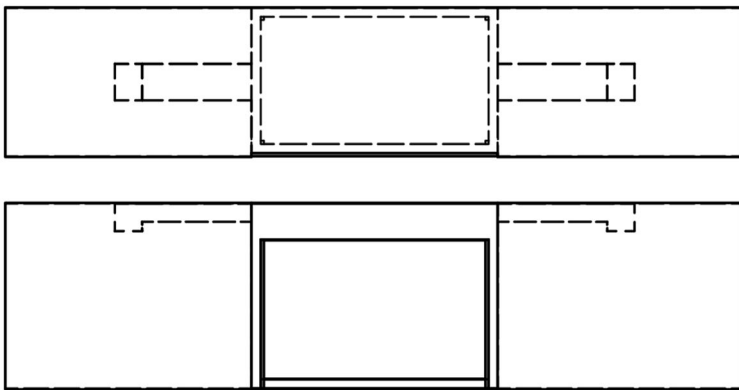


Figure 1. Fireground Exposure Simulator (FES) prop. (top) Photo of prop being prepared for a mannequin exposure trial, (middle) overhead and (bottom) side perspectives of FES prop showing the combustion chamber in the middle and exposure chambers on each end.

chamber as desired, while roll-up doors are used to enter/exit the exposure chambers.

While a wide variety of testing environments can be feasibly produced with this prop, fuel packages and ventilation conditions were iterated in a series of pilot tests in order to generate temperature and smoke levels in the exposure chambers that approximate the conditions experienced by the firefighting crews (fire attack, search and rescue) from previous work on simulating residential fires with household furnishings [22, 23]. In this manuscript we will refer to that prior effort as the “simulated Fireground” study and will report data from firefighters who performed the fire suppression and search and rescue operations. Results presented in this manuscript were from burns conducted using a popular, commercially available sofa and with the loading doors closed, utilizing only the existing leakage

paths in the combustion chamber for ventilation. The three-seat sofas (dimensions: 2.2 m \times 0.9 m \times 0.9 m H; weight: 47.5 kg) utilized as the fuel package were purchased new. The body and the cushions of the sofa were upholstered in 100% polyester fabric. The seat cushions were filled with 127 mm (5 in) thick polyurethane foam pads, with a layer of 25 mm (1 in) polyester batting on the top and bottom of the polyurethane pads. The back cushions were filled with polyester batting. Previous laboratory testing with these sofas has generated heat release rate (HRR) curves with key features that include a peak HRR of 4.2 MW and 650 MJ of total energy released [24]. To increase repeatability of positive ignition and reduce variability in fire growth, a road flare was ignited and placed in the center of the sofa at the intersection between the seat and back cushion. The timing of ignition, ventilation and suppression were based on common responses in the fire service and are patterned after previous research on exposures for interior attack crews during residential fire (simulated Fireground study) [23]. As the smoke fills each chamber from the top to the bottom, higher concentrations will be encountered near the top of the compartment as is common in residential room and contents fires. This aspect of the FAS test can be a unique and desirable phenomenon as it provides a realistic layering of heat and smoke in the chamber without direct exposure to flames. This exposure challenge complements the uniform conditions created in the MIST and FAST test.

The exposure chambers can be set up in two different configurations in order to study up to 24 mannequins or up to 6 firefighters (human subjects) undergoing training simultaneously. When configured for mannequin exposures, up to 12 individual full-sized mannequins were oriented around the duct outlet in each chamber (one side oriented facing clockwise, the other oriented counterclockwise). If so desired, fewer mannequins oriented in a crawling posture could also be incorporated. To ease loading and unloading of the mannequins, they are set up outside of the chamber on a rolling pallet, moved in prior to ignition, and then rolled out after each trial. Environmental condition data from mannequin trials reported in this manuscript were collected over a series of 40 separate burns conducted during a 90 day period through the summer months in Champaign, Illinois, USA.

For firefighter activity trials, three separate FAS stations were set up within each chamber along the wall connected to the combustion chamber. Activities, including stair climbing, crawling, hose advance and overhaul, were conducted on 2-min work/rest cycles for the FAS [17, 18]. Timing with the ignition of the sofa and ventilation of the exposure chambers was coordinated to create conditions that were similar to what is often experienced during firefighting operations. The activities included:

1. Firefighters began activity in an attached container with six sets of three steps (up and down) outside of any smoke exposure to simulate stair climbing activities in a smoke protected stairwell. Upon completion of the stair climb, firefighters walked a short distance to the exposure chamber and side roll-up doors were closed during the first 2-min rest.
2. For the second task, firefighters crawled around the exterior wall of the chamber simulating a search as the sofa was ignited and smoke began to fill the

structure. Firefighters searched in a clockwise direction for the first minute, then counterclockwise for the final minute.

3. After the second rest period, firefighters conducted a simulated hose advance for 2 min, after which the burning sofa in the combustion chamber was suppressed by staff members to end the combustion process and allow steam to flow into the exposure chambers as it would in a compartment.
4. After the final 2-min rest, firefighters stood up, grasped a pike pole, and simulated pulling down a ceiling to locate hidden/smoldering fires during overhaul. At this time, the roll-up doors on each end of the exposure chambers were opened and smoke was allowed to naturally vent out of the structure as is common during the overhaul process. At the end of the overhaul activity, the test protocol was completed.

In this manuscript, we report data collected from firefighters who completed training scenarios in the FES chamber in September or October. This protocol was approved by the University of Illinois at Urbana-Champaign Institutional Review Board through the Office for the Protection of Research Subjects.

2.2. Temperature and Smoke Sampling in FES

To characterize conditions in the FES, ambient air temperatures were monitored with bare-bead, Chromel Alumel (Type K) thermocouples with a 0.5 mm nominal diameter every 0.9 m from floor to ceiling at three locations in both of the exposure chambers. Thermocouple data was collected at a frequency of 1 Hz. Live thermal imaging and visible light camera feeds from each exposure chamber allow monitoring of the conditions and human subject activities.

Area air samples (charcoal tubes and OVS-XAD-7 tubes) were mounted on the outside of the PPE at chest height during the mannequin and human subjects testing to determine the magnitude of combustion byproducts (VOCs and PAHs) in the atmosphere. After each trial, the samples were collected, capped, and stored in a freezer. The charcoal tubes, operated at 0.1 L/min, were analyzed using NIOSH Method 1501 for benzene, toluene, ethylbenzene, xylenes, and styrene (BTEXS) [25]. The OVS-XAD-7 tubes, operated at 1 L/min, were analyzed separately for particulate (captured on the filter) and vapor-phase PAHs (captured on the sorbent) using NIOSH Method 5528 [25]. Total PAHs were calculated by summing the 15 quantified PAHs including acenaphthene, anthracene, benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[g,h,i]perylene, benzo[k]fluoranthene, chrysene, dibenzo[a,h]anthracene, fluoranthene, fluorene, indeno[1,2,3-cd]pyrene, naphthalene, phenanthrene, and pyrene. Zero was used for non-detectable concentrations. Data are reported as time averaged values, dividing the Total PAH concentration measured on the OVS-XAD-7 tubes by the time spent in the structure after ignition. This approach allows direct comparison to the sample data collected on simulating residential fires with household furnishings [22].

Table 1
Average Temperature Profile in Exposure Chambers from Sofa Fueled Fires During Mannequin Burns (n = 40)

| | Location (Height, Chamber) | Mean ± SD (°C) | Peak ± SD (°C) |
|-------------------------------------|----------------------------|----------------|----------------|
| Fireground exposure simulator (FES) | 0.3 m, Left | 30.5 ± 4.8 | 37.8 ± 5.1 |
| | 0.3 m, Right | 28.3 ± 4.0 | 36.8 ± 4.1 |
| | 0.9 m, Left | 37.0 ± 5.5 | 54.9 ± 6.8 |
| | 0.9 m, Right | 37.1 ± 5.1 | 60.9 ± 7.6 |
| | 1.5 m, Left | 62.4 ± 8.5 | 114.2 ± 10.6 |
| | 1.5 m, Right | 63.7 ± 8.7 | 119.7 ± 13.5 |
| | 2.1 m, Left | 92.8 ± 9.9 | 154.9 ± 8.0 |
| | 2.1 m, Right | 94.9 ± 10.5 | 161.2 ± 11.7 |
| Residential fire study ^a | Attack | 57.6 ± 7.0 | 191.0 ± 48.6 |
| | Search | 39.7 ± 4.6 | 63.2 ± 13.0 |

^aResults from [23] were provided for comparison

3. Environmental Conditions in the FES

3.1. Ambient Air Temperatures

While ambient temperatures were measured from floor to ceilings (Table 1), most firefighter activities on a fire ground take place between the 0.3 to 0.9 m heights as firefighters crawl, crouch, kneel and then move to 1.5 m as firefighters eventually stand during overhaul. However, some fire departments’ tactics dictate walking in the structure during the firefight to allow more efficient movements, so conditions at the higher levels may be experience by some firefighters throughout the fire-fight. At the 0.9 m level, average temperatures in the left and right chambers were 37.0 ± 5.5 °C and 37.1 ± 5.1 °C respectively with peak values of 54.9 ± 6.8 °C and 60.9 ± 7.6 °C. These values are well aligned with data collected from the simulated Fireground study, where search firefighters in Interior Attack trials average helmet temperatures were 39.7 ± 4.6°C with peak values of 63.2 ± 13.0°C [23]. At the 1.5 m level average temperatures were 62.4 ± 8.5°C and 63.7 ± 8.7°C, which compares well with the simulated Fireground study’s Attack firefighters where average helmet temperatures of 57.6 ± 7.0°C were recorded when conducting Interior attack [23].

Figure 2 depicts the variability in the temperatures over the 40 mannequin test trials. This variability in test conditions can be both a benefit and a limitation of the technique. Due to the ability to test multiple mannequins (with 24 independent sets of PPE) in a given trial, the tool provides the ability to compare many different iterations at one time with excellent repeatability within that group of samples. However, there is some day to day variability in FES ambient conditions due to wind and environmental conditions as a result of the prop’s location outdoors. A portion of this variability may be reduced by utilizing the prop inside a large environmental enclosure or test laboratory such as that present at UL, NIST or other large fire laboratories around the world. However, it is important to note

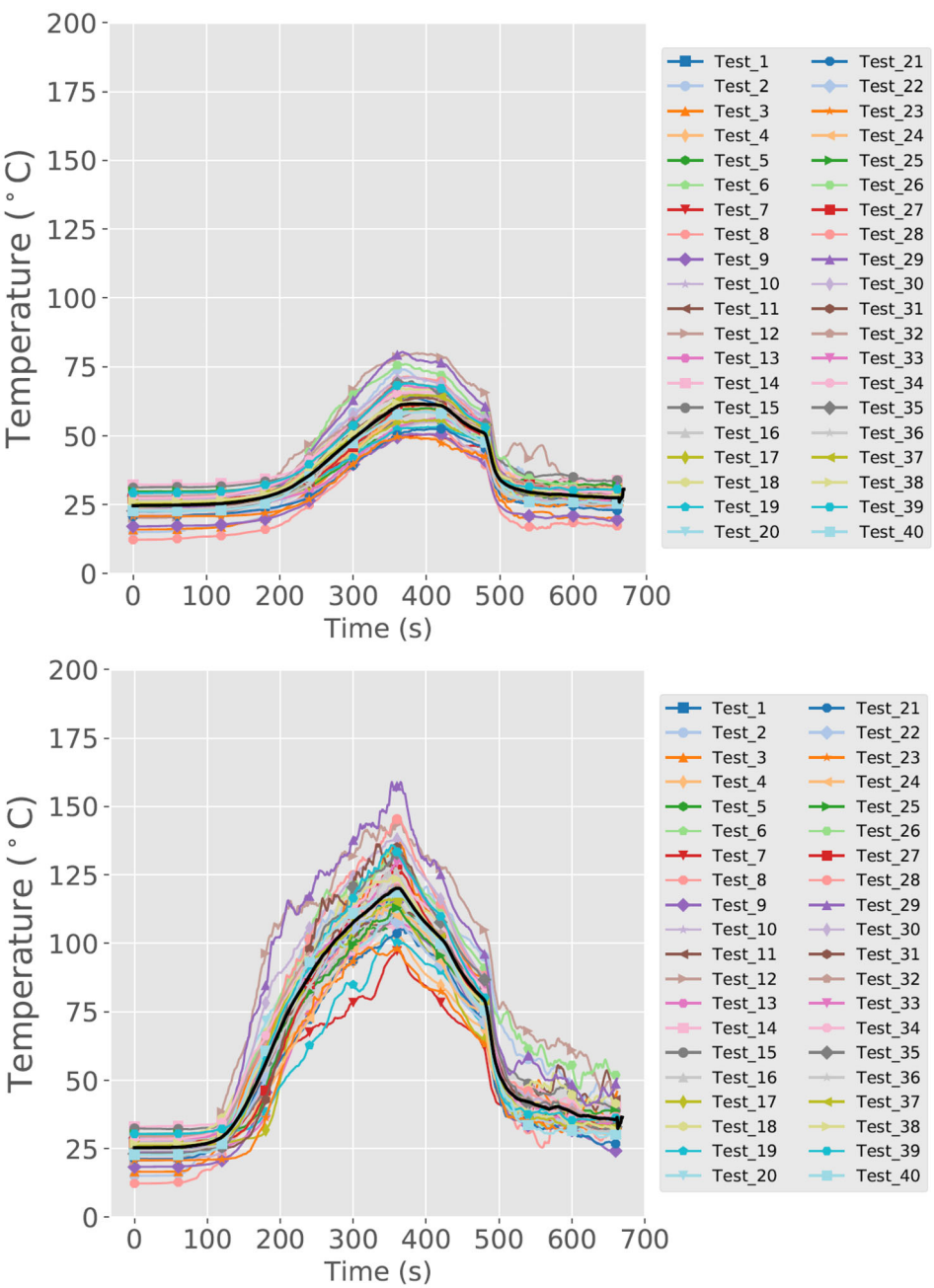


Figure 2. Temperature profiles from 40 separate burn trials at (top) 0.9 m from the floor and (bottom) 1.5 m from the floor. Data collection begins upon ignition and the fire grows until suppression at 360 s followed by opening the exposure chamber doors at 480 s. The black line without markers represents the average of all 40 trials.

Table 2
Summary of Airborne Concentrations of Total PAHs and Benzene for Measurements Taken from Pumps Affixed to Turnout Jackets in the Chest Region from Standing Mannequin and Mobile Firefighter Measurements

| Analytes | Measured on | N | Mean | Median | Standard deviation | 95% Confidence interval | Range |
|--|--------------------|----|---------|---------|--------------------|-------------------------|-----------------|
| Total PAHs ^b (µg/m ³) | | | | | | | |
| Fireground exposure simulator (FES) | Standing mannequin | 12 | 189,000 | 196,000 | 86,200 | 134,000–244,000 | 40,400–315,000 |
| | Mobile firefighter | 48 | 53,200 | 45,800 | 33,400 | 43,500–62,900 | 11,100–152,000 |
| Controlled residential fire study ^a | Attack | 19 | | 23,800 | | | 7460–78,200 |
| | Search | 16 | | 17,800 | | | 9770–43,800 |
| Benzene ^b (ppb) | | | | | | | |
| Fireground exposure simulator (FES) | Standing mannequin | 8 | 233,000 | 234,000 | 52,900 | 188,000–277,000 | 152,000–314,000 |
| | Mobile firefighter | 72 | 84,000 | 72,200 | 44,500 | 73,100–94,000 | 17,700–251,000 |
| Controlled residential fire study ^a | Attack | 17 | | 40,300 | | | 12,400–322,000 |
| | Search | 22 | | 37,900 | | | 12,000–306,000 |

^aResults from [22] were provided for comparison

^bMost protective short-term occupational exposure limit for: Total PAHs ACGIH excursion limit for coal-tar pitch volatiles (1000 µg/m³), and Benzene NIOSH STEL (1000 ppb)

that any live-fire scenario can have important variability in conditions even when using identical fuel packages [26, 27]. Thus, conducting serial trials using the FES prop can expose PPE samples a range of conditions that may be present during live fire events.

3.2. PAHs and VOCs in the Air

Of the 40 mannequin trials, measurements of airborne PAHs ($n = 12$) and VOCs ($n = 8$) were collected during 4 trials. PAH and VOC data from a subset of firefighters completing the FAS protocol were collected during 12 separate trials with 6 participants in each. As expected, both total PAHs and benzene concentrations in the environment were higher on the standing mannequins. Time-averaged median total PAH concentration in the environment (Table 2) was 45,800 µg/m³ for the human subject trials where firefighters were crawling and staying lower in the structure, while median values were 196,000 µg/m³ for the standing mannequins. A recent study by Keir et al. (2020) collected personal air samples from firefighters during emergency fire suppression and found much lower mean total PAH

concentrations ($2725 \mu\text{g}/\text{m}^3$) [11]. However, the average sample collection time from Keir et al. [11] was 67 min (max = 420 min), nearly 6 times longer than the current study. Overall, the sampling time for this study ranged from 4 to 11 min. In general, sample times were lower for the mannequin portion as pump faults were more prevalent, limiting how long the pumps ran. Data from Keir et al. were likely influenced by the sampling pumps running on the way to the firefight and possibly after suppression was completed, including time outside of the burning structure that are common in response scenarios [11]. The FES prop timing was designed to focus on simulating the short exposure time typical with fire suppression timeframes. From the simulated Fireground study [22], median personal concentrations of total PAHs for the attack firefighters were $23,800 \mu\text{g}/\text{m}^3$ (7460 – $78,200 \mu\text{g}/\text{m}^3$) and $17,800 \mu\text{g}/\text{m}^3$ (9770 – $43,800 \mu\text{g}/\text{m}^3$) for the search firefighters. Thus, firefighters conducting the FAS protocol in the FES prop resulted in PAH concentrations that are within the upper ranges measured in the simulated Fireground study. At the standing level, PAH concentrations are nearly an order of magnitude higher than the measurements from the simulated Fireground study. Consequently, contamination on the upper portions of the jacket for stationary mannequins will be much higher than what might be experienced for firefighters operating in a typical manner. However, this may also provide a high-concentration challenge to identify possible leakage paths in the PPE, which is similar to some traditional laboratory simulant tests.

VOC concentrations in the FES exposure chamber were dominated by benzene, which is similar to the results in the simulated Fireground study [22]. The median air concentration of benzene in the environment (Table 2) was 72,200 ppb for the trials where firefighters were crawling and staying lower in the structure during these simulated firefighting activities, while the median concentration was 234,000 ppb for the stationary, standing mannequins. These median values are within the ranges measured from attack firefighters (12,400–322,000 ppb) and search firefighters (12,000–306,200 ppb) in the simulated Fireground study [22], but higher than benzene concentrations reported by Austin et al. (11,000 ppb) [2] and Jankovic et al. (22,000 ppb) [3].

Some PAH measurements from the trials with human subjects were stratified by specific compound (Table 3). Four PAH compounds—the lower molecular weight PAHs, like naphthalene, fluorene, phenanthrene, and anthracene—were heavily partitioned into the vapor phase (> 75%). Naphthalene was the predominant PAH compound in air (48% of the total PAHs). From the simulated Fireground study [22], naphthalene was also the predominant PAH species accounting for 50% of the total. The relative ratio of the other PAH compounds and partition into vapor and solid phase in the exposure chamber appears to match that of a typical structure fire quite closely. Keir et al. (2020) also found that naphthalene was the most abundant PAH in the air in their study, with this compound accounting for 72% of all PAHs [11]. Furthermore, probable and possible carcinogens (IARC Class 2A and 2B) accounted for 77% of the total PAHs compared to 62% here, while benzo(a)pyrene (IARC Class 1) was typically around 1% in the Keir et al. study [11]. Some of these discrepancies may be attributed to the use of different analysis methods, including the type of sampling media (PUF

Table 3
Partition of Airborne PAH Compounds Into Vapor and Solid Phase
During Sofa Fueled Fires (n = 12)

| Compound | Vapor phase (%) | Solid phase (%) | % of total PAH |
|------------------------|-----------------|-----------------|----------------|
| Anthracene | 76.4 | 23.6 | 2.2% |
| Acenaphthene | 0 | 100 | < 1.0% |
| Benzo(a)anthracene | 15.4 | 84.6 | 2.2% |
| Benzo(a)pyrene | 14.8 | 85.2 | 2.1% |
| Benzo(b)fluoranthene | 14.8 | 85.2 | 2.0% |
| Benzo(g,h,i)perylene | 15.5 | 84.5 | 1.1% |
| Fluorene | 95.8 | 4.17 | 4.4% |
| Fluoranthene | 23.6 | 76.4 | 7.8% |
| Benzo(k)fluoranthene | 14.8 | 85.2 | < 1.0% |
| Chrysene | 14.5 | 85.5 | 1.8% |
| Dibenzo(a,h)anthracene | 14.5 | 85.4 | 6.4% |
| Indeno(1,2,3-cd)pyrene | 15.0 | 85.0 | 1.9% |
| Phenanthrene | 80.5 | 19.5 | 14.6% |
| Pyrene | 22.2 | 77.8 | 5.1% |
| Naphthalene | 97.5 | 2.53 | 47.7% |

Filter amount may be underestimated as some PAHs will evaporate during sampling and collect on the sorbent

and quartz tube vs. OVS-XAD-7 tubes). Overall, Keir's analysis did not result in solid-phase PAHs at the same level reported in the current study. For example, in the current study, fluoranthene and dibenzo(a,h)anthracene accounted for over 14% of the total PAHs and were mostly captured in solid phase on the filter (Table 3). These two analytes only made up about 2.5% of the total PAHs reported in Keir et al. Overall, the trends in PAH distribution from the FES prop were similar to fireground conditions.

The variability in thermal and area air samples (Total PAHs and Benzene) were analyzed for the mannequin scenarios where measurements were conducted at a similar height throughout each scenario (1.5 m from the floor). Independent correlation analyses that included temperature, Total PAHs and Benzene suggested a weak relationship between each measurement. Benzene had a negative weak correlation with both Temperature ($r = -0.303$) and Total PAH ($r = -0.230$), while Total PAH and Temperature comparison showed a weak, positive correlation ($r = 0.315$). The peak temperatures measured in the exposure chambers for these scenarios were quite tightly grouped ($118.2 \pm 8.1^\circ\text{C}$) resulting in a coefficient of variation (CV) of 6.8%. However, the Benzene (CV = 22.5%) and Total PAH (CV = 45.6%) were significantly more variable. While this variability is quite high, it is similar to Total PAH measurements made during the Controlled Residential Fire Study where CV for Attack and Search groups were 65% and 45% respectively. It is important to note that different pump fault times for PAH and Benzene measurements, which also occurred during the data reported in [22], likely contribute to this high variability.

4. Summary and Future Work

To support firefighter research, including PPE research and development, we have developed a new approach for simulating conditions commonly encountered by firefighters operating on the interior of a residential structure fire. The multimodal shipping container prop can be utilized with up to 24 mannequins in order to test multiple replicates at a single time or be configured for up to 6 firefighters performing simulated firefighting activities. The latter configuration provides the ability to conduct realistic firefighting activities and allow for investigating the impact of interventions on heat stress or systemic exposure. Environmental gas concentration and temperature measurements at crawling level were in good agreement with the same measurements in previous fireground research investigating firefighters working in residential fires. Chemical exposures were higher for standing stationary mannequins, which can allow for the ability to locate gaps in PPE in a high-challenge environment.

Future studies could utilize the FES to identify PPE features that may reduce chemical breakthrough and investigate how these features relate to heat stress and biological absorption of contaminants. By including the same instrumentation outlined in the Methods section (thermocouples and area air samples (charcoal tubes and OVS-XAD-7 tubes)) mounted under firefighter PPE and/or base layers (on mannequins or human subjects), the different temperatures and concentrations measured outside the PPE and inside the PPE can be directly compared to calculate protection factors. Such testing may be useful for iterating PPE design features with mannequins, while also studying how changes in garment design may impact heat stress generation with firefighter trials. Additionally, the prop may be employed to study the wide variety of PPE cleaning methods or skin cleaning tools that are being brought to the fire service marketplace.

Acknowledgements

This work was supported by the Department of Homeland Security Fire Prevention and Safety Grant #EMW-2015-FP-00646. The findings and conclusions are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

Compliance with Ethical Standards

Conflict of interest There are no conflicts of interest regarding this work.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original

author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Austin CC, Wang D, Ecobichon DJ, Dussault G (2001) Characterization of volatile organic compounds in smoke at experimental fires. *J Toxicol Environ Health A* 63:191–206
2. Austin CC, Wang D, Ecobichon DJ, Dussault G (2001) Characterization of volatile organic compounds in smoke at municipal structural fires. *J Toxicol Environ Health A* 63:437–458
3. Jankovic J, Jones W, Burkhart J, Noonan G (1991) Environmental study of firefighters. *Ann Occup Hyg* 35:581–602
4. IARC (2002) Monographs on the evaluation of the carcinogenic risks to humans: some traditional herbal medicines, some mycotoxins, naphthalene, and styrene, 82World Health Organization, International Agency for Research on Cancer, Lyon, France
5. IARC (2010) Monographs on the evaluation of the carcinogenic risks to humans: some non-heterocyclic polycyclic aromatic hydrocarbons and some related exposures, 92World Health Organization International Agency for Research on Cancer, Lyon, France
6. Baxter CS, Hoffman JD, Knipp MJ, Reponen T, Haynes EN (2014) Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons. *J Occup Environ Hyg* 11:D85–91
7. Fent KW, Eisenberg J, Snawder J, Sammons D, Pleil JD, Stiegel MA, Mueller C, Horn GP, Dalton J (2014) Systemic exposure to PAHs and benzene in firefighters suppressing controlled structure fires. *Ann Occup Hyg* 58:830–845
8. Fent KW, Alexander B, Roberts J, Robertson S, Toennis C, Sammons D, Bertke S, Kerber S, Smith D, Horn G (2017) Contamination of firefighter personal protective equipment and skin and the effectiveness of decontamination procedures. *J Occup Environ Hyg* 14:801–814
9. Fernando S, Shaw L, Shaw D, Gallea M, VandenEnden L, House R, Verma DK, Britz-McKibbin P, McCarry BE (2016) Evaluation of firefighter exposure to wood smoke during training exercises at burn houses. *Environ Sci Technol* 50:1536–1543
10. Keir JLA, Akhtar US, Matschke DMJ, Kirkham TL, Chan HM, Ayotte P, White PA, Blais JM (2017) Elevated exposures to polycyclic aromatic hydrocarbons and other organic mutagens in Ottawa firefighters participating in emergency, on-shift fire suppression. *Environ Sci Technol* 51:12745–12755
11. Keir JLA, Akhtar US, Matschke DMJ, White PA, Kirkham TL, Chan HM, Blais JM (2020) Polycyclic aromatic hydrocarbon (PAH) and metal contamination of air and surfaces exposed to combustion emissions during emergency fire suppression: implications for firefighters exposures. *Sci Total Environ* 698:134211. <https://doi.org/10.1016/j.scitotenv.2019.134211>

12. Stec AA, Dickens KE, Salden M, Hewitt FE, Watts DP, Houldsworth PE, Martin FL (2018) Occupational exposure to polycyclic aromatic hydrocarbons and elevated cancer incidence in firefighters. *Sci Rep* 8:2476
13. Wingfors H, Nyholm JR, Magnusson R, Wijkmark CH (2018) Impact of fire suit ensembles on firefighter PAH exposures as assessed by skin deposition and urinary biomarkers. *Ann Work Expos Health* 62(2):221–231
14. ASTM F2588-12 (2012) Standard test method for man-in-simulant test (MIST) for protective ensembles, ASTM International, West Conshohocken, PA
15. ASTM F1359/F1359M-16a (2016) Standard test method for liquid penetration resistance of protective clothing or protective ensembles under a shower spray while on a Manikin, ASTM International, West Conshohocken, PA
16. Hill J, Hanley J (2015) *Fluorescent Aerosol Screening Test (FAST) Test Report*. RTI Project Number: 0212534.112. Prepared for Jeffrey O. Stull, sponsored by International Association of Fire Fighters. RTI International, Research Triangle Park, NC
17. Ensari I, Motl RW, Klaren RE, Fernhall B, Smith DL, Horn GP (2017) Firefighter exercise protocols conducted in an environmental chamber: developing a laboratory based simulated firefighting protocol. *Ergonomics* 60(5):657–668
18. Horn GP, Kesler RM, Motl RW, Hsiao-Weckler ET, Klaren RE, Ensari I, Petrucci MN, Fernhall B, Rosengren KS (2015) Physiological responses to simulated firefighter exercise protocols in varying environments. *Ergonomics* 58(6):1012–1021
19. Smith DL, Petruzzello SJ (1998) Selected physiological and psychological responses to live-fire drills in different configurations of firefighting gear. *Ergonomics* 41(8):1141–1154
20. Smith DL, Manning TS, Petruzzello SJ (2001) Effect of strenuous live-fire drills on cardiovascular and psychological responses of recruit firefighters. *Ergonomics* 44(3):244–254
21. Horn GP, Gutzmer S, Fahs CA, Petruzzello SJ, Goldstein E, Fahey GC, Fernhall B, Smith DL (2011) Physiological recovery from firefighting activities in rehabilitation and beyond. *Prehosp Emerg Care* 15(2):214–225
22. Fent KW, Evans DE, Babik K, Striley C, Bertke S, Kerber S, Smith D, Horn GP (2018) Airborne contaminants during controlled residential fires. *J Occup Environ Hyg* 15(5):399–412
23. Horn GP, Kesler RM, Kerber S, Fent KW, Schroeder TJ, Scott WS, Fehling PC, Fernhall B, Smith DL (2018) Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic. *Ergonomics* 61(3):404–419
24. Weinschenk C, Madrzykowski D, Courtney P (2019) Impact of flashover fire conditions on exposed energized electrical cords and cables. Underwriters Laboratories Inc, Columbia, MD https://ulfirefightersafety.org/docs/Exposed_Energized_Cords.pdf
25. National Institute for Occupational Safety and Health (NIOSH) (2013) *Manual of analytical methods*. 4th ed. Publication No. 94–113 (August 1994); 1st Supplement Publication 96–135, 2nd Supplement Publication 98–119, 3rd Supplement Publication 2003–154. P.C. Schlech, and P.F. O'Connor (eds). Cincinnati, OH: U.S. Department of Health and Human Services
26. Kerber S (2013) Analysis of one and two-story single family home fire dynamics and the impact of firefighter horizontal ventilation. *Fire Technol* 49(4):857–889
27. Traina N, Kerber S, Kyritsis DC, Horn GP (2017) Occupant tenability in single family homes: part I—Impact of structure type, fire location and interior doors prior to fire department arrival. *Fire Technol* 53(4):1589–1610