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

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### 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)

### 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

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their procedures at the station, on the fireground and 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 closures. 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].

## The Fireground Exposure Simulator (FES)

### Prop construction and test protocol

The Fireground Exposure Simulator (FES) prop was developed in a 2.4 m wide, 2.9 m tall and 12.2m long intermodal shipping container which is commonly used for firefighter training around the world (Figure 1). The container is divided into three sections, where the middle 3.1m 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 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



firefighters walked a short distance to the exposure chamber and side roll-up doors were closed during the first two-minute 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 two minutes, 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 two-minute 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.

### 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].

## Environmental conditions in the FES

### 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 0.9m heights as firefighters crawl, crouch, kneel and then move to 1.5m 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 experienced by some firefighters throughout the firefight. At the 0.9m level, average temperatures in the left and right chambers were  $37.0\pm 5.5^{\circ}\text{C}$  and  $37.1\pm 5.1^{\circ}\text{C}$  respectively with peak values of  $54.9\pm 6.8^{\circ}\text{C}$  and  $60.9\pm 7.6^{\circ}\text{C}$ . These values are well aligned with data collected from the simulated Fireground study, where search firefighters in Interior Attack trials average helmet temperatures were  $39.7\pm 4.6^{\circ}\text{C}$  with peak values of  $63.2\pm 13.0^{\circ}\text{C}$  [23]. At the 1.5m level average temperatures were  $62.4\pm 8.5^{\circ}\text{C}$  and  $63.7\pm 8.7^{\circ}\text{C}$ , which compares well with the simulated Fireground study's Attack firefighters where average helmet temperatures of  $57.6\pm 7.0^{\circ}\text{C}$  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 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.

### 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  $45,800\ \mu\text{g}/\text{m}^3$  for the human subject trials where firefighters were crawling and staying lower in the structure, while median values were  $196,000\ \mu\text{g}/\text{m}^3$  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 ( $2,725\ \mu\text{g}/\text{m}^3$ ) [11]. However, the average sample collection time from Keir et al. [11] was 67 minutes (max= 420 minutes), nearly 6 times longer than the current

study. Overall, the sampling time for this study ranged from 4–11 minutes. 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 fire 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  $\mu\text{g}/\text{m}^3$  (7,460–78,200  $\mu\text{g}/\text{m}^3$ ) and 17,800  $\mu\text{g}/\text{m}^3$  (9,770–43,800  $\mu\text{g}/\text{m}^3$ ) 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 and quartz tube vs. OVS-XAD-7 tubes). Overall, Keir's analysis method did not appear to capture 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 ( $r=-0.303$ ) as the Pearson coefficient is 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 ( $118.2\pm 8.1$  °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 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 is also occurred during the data reported in [22], likely contribute to this high variability.

## Summary & 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.

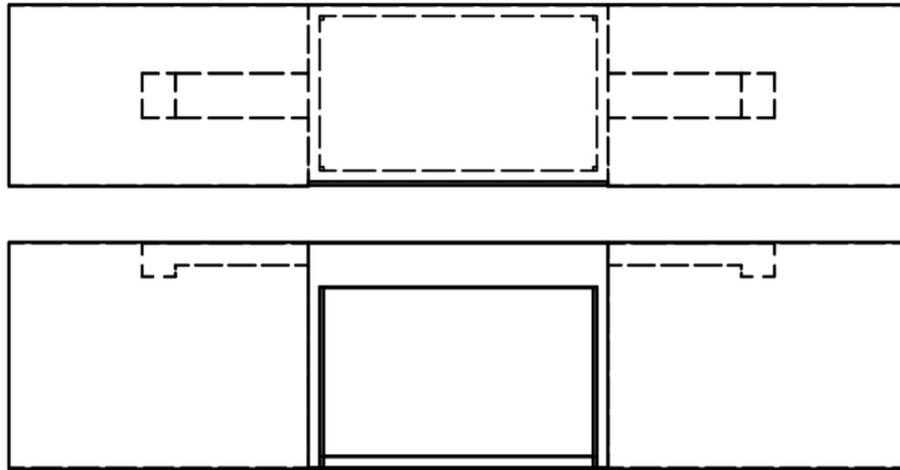
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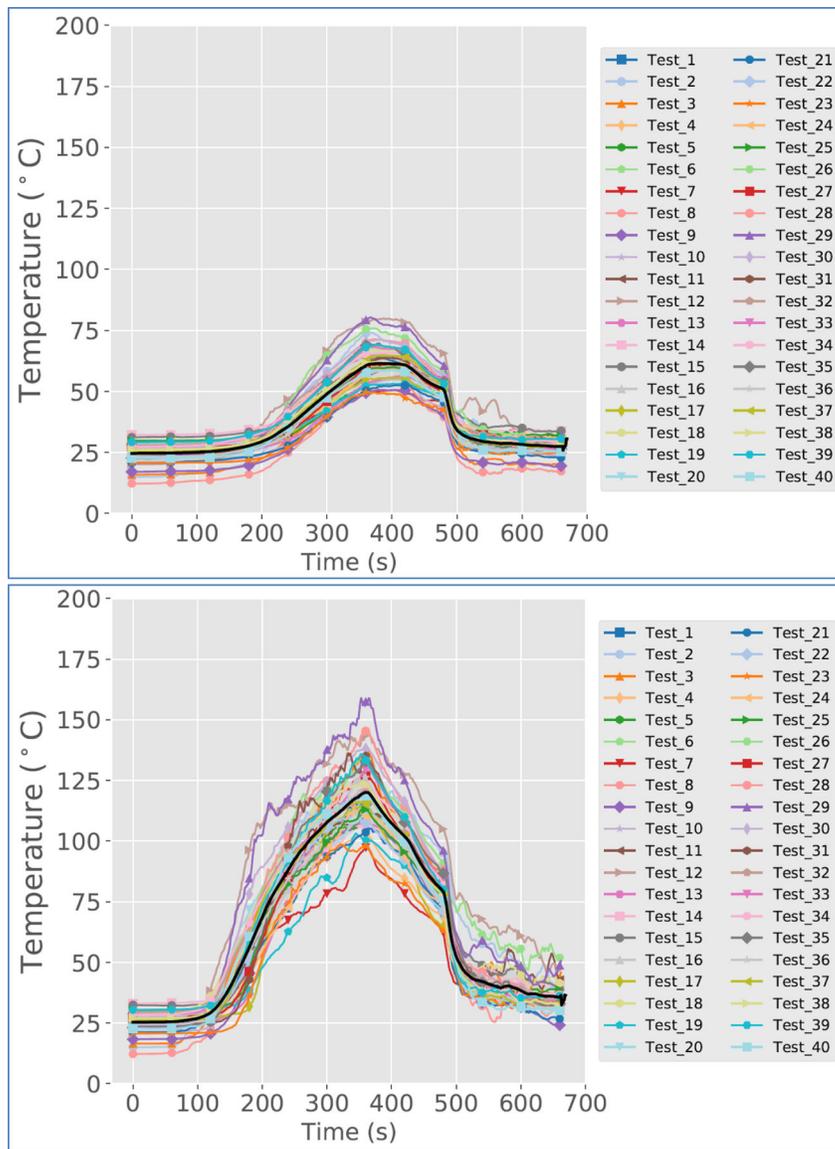
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**Figure 1.** Fireground Exposure Simulator (FES) prop. (top) Photo of prop being prepared for a mannequin exposure trial, (middle) overhead and (bottom) side perspectives of FES prop showing the combustion chamber in the middle and exposure chambers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



**Figure 2.** Temperature profiles from 40 separate burn trials at (top) 0.9m from the floor and (bottom) 1.5 m from the floor. Data collection begins upon ignition and the fire grows until suppression at 360 seconds followed by opening the exposure chamber doors at 480 seconds.

**Table 1.**

Average temperature profile in exposure chambers from sofa fueled fires during mannequin burns (n=40).

	Location (Height, Chamber)	Mean $\pm$ SD ( $^{\circ}$ C)	Peak $\pm$ SD ( $^{\circ}$ C)
<b>Fireground Exposure Simulator (FES)</b>	<i>0.3 m, Left</i>	30.5 $\pm$ 4.8	37.8 $\pm$ 5.1
	<i>0.3m, Right</i>	28.3 $\pm$ 4.0	36.8 $\pm$ 4.1
	<i>0.9 m, Left</i>	37.0 $\pm$ 5.5	54.9 $\pm$ 6.8
	<i>0.9 m, Right</i>	37.1 $\pm$ 5.1	60.9 $\pm$ 7.6
	<i>1.5 m, Left</i>	62.4 $\pm$ 8.5	114.2 $\pm$ 10.6
	<i>1.5 m, Right</i>	63.7 $\pm$ 8.7	119.7 $\pm$ 13.5
	<i>2.1 m, Left</i>	92.8 $\pm$ 9.9	154.9 $\pm$ 8.0
	<i>2.1 m, Right</i>	94.9 $\pm$ 10.5	161.2 $\pm$ 11.7
<b>Residential Fire Study <sup>A</sup></b>	Attack	57.6 $\pm$ 7.0	191.0 $\pm$ 48.6
	Search	39.7 $\pm$ 4.6	63.2 $\pm$ 13.0

<sup>A</sup>Results from [23] were provided for comparison.

**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
<b>Total PAHs<sup>B</sup> (<math>\mu\text{g}/\text{m}^3</math>)</b>							
<b>Fireground Exposure Simulator (FES)</b>	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
<b>Controlled Residential Fire Study<sup>A</sup></b>	Attack	19		23,800			7,460 – 78,200
	Search	16		17,800			9,770 – 43,800
<b>Benzene<sup>B</sup> (ppb)</b>							
<b>Fireground Exposure Simulator (FES)</b>	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
<b>Controlled Residential Fire Study<sup>A</sup></b>	Attack	17		40,300			12,400 – 322,000
	Search	22		37,900			12,000 – 306,000

<sup>A</sup>Results from [22] were provided for comparison.

<sup>B</sup>Most protective short-term occupational exposure limit for: Total PAHs ACGIH excursion limit for coal-tar pitch volatiles ( $1,000 \mu\text{g}/\text{m}^3$ ), and Benzene NIOSH STEL (1,000 ppb)

**Table 3.**

Partition of airborne PAH compounds into vapor and solid phase during sofa fueled fires (n=12). Filter amount may be underestimated as some PAHs will evaporate during sampling and collect on the sorbent.

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