Safety Science 116 (2019) 287–294

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

# Firefighter and fire instructor's physiological responses and safety in various training fire environments

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## ARTICLE INFO

*Keywords:*
Firefighting
Heat stress
Hemostasis
Coagulation
Heart attack
Heart rate
Occupational safety

## ABSTRACT

For firefighters around the world, fire training is necessary to ensure operational readiness, but can be hazardous. Fire instructors routinely attempt to design safe but realistic scenarios and may do so in very different thermal environments. Yet, the physiological burden (and presumed physiological benefits) of different training has rarely been investigated. We studied the impact of three training fire environments: (a) pallets (Pallet), (b) oriented strand board (OSB) and simulated fire/smoke (Fog) on firefighters' and fire instructors' physiological responses. Peak ambient temperatures exceeded 420 °C in Pallet and OSB scenarios, but were less than 40 °C for Fog. Firefighters' peak core temperatures, heart rates and hemostatic responses were not statistically different among the training environments despite the large differences in ambient conditions. Instructors' heart rate and hemostatic responses were significantly blunted compared to the firefighters' despite similar peak core temperatures, suggesting instructors performed less work or were less stressed. It is important that physiological responses experienced by firefighters and instructors working in fully encapsulating personal protective equipment be considered based on intensity and duration of work, regardless of the apparent risk from ambient conditions.

## 1. Introduction

In an attempt to prepare firefighters for the situations they will encounter, and the occupational stressors and risks faced on the fireground, training is considered absolutely necessary in the fire service. However, not all training is conducted in the same way. In fact, training usually involves preparing for many different scenarios and training is conducted in a wide variety of environments. Some training instructors argue that it is important to expose trainees to a realistic (i.e. elevated) thermal burden during training scenarios. However, the environmental conditions associated with live-fire scenarios coupled with thermal burden and metabolic demands associated with working in fully encapsulated personal protective equipment may increase the risk for injuries and fatalities during training. Between 2001 and 2010, 108 firefighters in the United States died during training activities, which represents more than 11% of the firefighter line-of-duty deaths reported by the National Fire Protection Association, with sudden cardiac death accounting for 56 (52%) of those incidents (Fahy, 2012). In the years since this report (2011–2017), 73 firefighter line of duty deaths (representing between 7.1 and 16.7% of National Fire Protection Association reported fatalities each year) have died in training (NFPA, 2018a)

It has been proposed that conducting simulated training in a thermo-neutral environment, but with a "realistic" visual atmosphere that can be created by commercially available theatrical smoke ("fog") machines (oftentimes supplemented with a simulated flame using a lighted orange cone or commercial digital fire simulation system) may provide firefighters with the opportunity to learn and practice necessary skills more safely, with decreased physiological strain and reduced threat of injury during the training event itself. Some training centers favor such an approach while others insist that "live fire training" is necessary, in part, so that firefighters experience realistic heat

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https://doi.org/10.1016/j.ssci.2019.03.017
Received 7 November 2018; Received in revised form 25 February 2019; Accepted 19 March 2019

conditions. Thus, there is considerable variability in training fire environment based on the construction of the structure and fuels utilized to simulate fireground conditions. Although researchers have begun to characterize the risks posed by firefighting activities in training fires (Lannon and Milke, 2014, Madrzykowski, 2017, Willi et al., 2016), to date no studies have been conducted to assess the impact of different training fire environments on the physiological responses of firefighters undertaking the training or of instructors who provide the training.

The impact of the different fuels used in firefighter training must be evaluated to understand relative risk. While a wide variety of fire/smoke sources are currently used in training, some of the most common scenarios include: (a) traditional wood and straw fuels, (b) engineered wood products or (c) simulated fire and smoke. Traditionally, the most common firefighter training scenarios use wood (typically from pallets) and another light combustible material to ease ignition (straw or excelsior) as they easily generate fire, are easily stored and transported, are readily available in large quantities, and produce a controlled fire. These materials typically generate relatively light grey or white smoke. In recent years, some training academies have begun to utilize engineered wood products such as oriented strand board (OSB) in addition to pallets and straw because the materials produce fire conditions that more closely replicate fire environments encountered in 21st century structure fires (e.g. they typically result in increased smoke production and darker smoke obscuration). On the other hand, some fire training agencies have begun using simulation technologies to produce training environments with no live fire in an attempt to reduce physiological strain so that the firefighter can focus more cognitive attention on properly learning techniques and to reduce risk to the firefighter and training structure building. The most commonly available simulation technology use theatrical smoke or pepper fog for visual obscuration and a realistic visual display of fire glow. For some firefighters, training fires represent a major proportion of their firefighting experience. Therefore, it is important to investigate the training fire environments that are commonly used to better understand the physiological burden imposed by this training and evaluate differences among approaches.

The physiological responses and cardiovascular risks associated with firefighting activities have been reported by several research groups (Burgess et al., 2012; Colburn et al., 2011; Fernhall et al., 2012; Hostler et al., 2010; Kales et al., 2007; Kirk and Logan, 2015; Romet and Frim, 1987; Sothmann et al., 1992; Walker et al., 2015). These studies demonstrate that firefighting involves strenuous metabolic work, in part because of the nature of the work and in part because of the use of heavy, insulative gear. The gear worn adds to the metabolic work that is performed and interferes with heat dissipation, thus exacerbating the heat stress. Thus, firefighting can lead to maximal or near-maximal heart rates and in some cases, rapid changes in core temperature (Barr et al., 2010; Horn et al., 2013). Research has documented how different firefighting activities and job functions affect physiology (Romet and Frim, 1987; Horn et al., 2017; Smith et al., 1996), as well as the physiological impact of conducting fire service instruction (Eglin et al., 2004; Eglin and Tipton, 2005; Watkins and Richardson, 2018; Watkins et al., 2018; Watt et al., 2016). However, surprisingly little research has been conducted to investigate how different training fire environments affect physiological responses to firefighting activities or how these training fire environmental and related physiological responses compare to those on a realistic fireground.

Firefighting activities have been shown to alter hemoconcentration and disrupt hemostatic balance. It has been previously shown that firefighting increases platelet number and decreases platelet closure time (increased aggregation), and increases global coagulatory potential (Smith et al., 2011; Smith et al., 2014a). Furthermore, a procoagulatory state persisted even after 2 h of recovery whereas fibrinolysis was enhanced immediately post-firefighting, but returned to baseline values 2 h after firefighting (Smith et al., 2014a). While hemostatic changes associated with firefighting are not typically outside of values seen during high intensity physical activity, the firefighting-induced procoagulatory state may play a role in cardiovascular events triggered by plaque rupture. Thus, coagulatory variables are important physiological variables to investigate in training situations.

The purpose of this study was to evaluate physiological responses of firefighters and fire instructors in different training environments. This manuscript will focus on three main components: (1) characterizing the thermal environment in which firefighters may operate when using three common fuel loads, (2) evaluating core temperature and heart rate responses of firefighters and fire instructors working in different training scenarios and (3) assessing hemostatic response of firefighters and instructors during training exercises. To contextualize this new data from training fire environments, results are compared to literature from measurement collected in fireground response scenarios.

## 2. Methods

### 2.1. Participants

Participants were recruited through a nationwide multimedia effort along with a focused effort by a statewide network of firefighters who teach and train at the Illinois Fire Service Institute (IFSI) campus. Participants provided informed written consent indicating that they understood and voluntarily accepted the risks and benefits of participation. This study was approved by the University of Illinois at Urbana-Champaign and the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Boards. Twenty-four firefighters (22 male, 2 female) from departments in Georgia, Illinois, Indiana, Massachusetts, New York, South Dakota, Texas, Virginia and Wisconsin participated in this study. Ten fire instructors (9 male, 1 female) from IFSI also participated in this study. There was no statistically significant difference in the descriptive characteristics (Table 1) between these groups, although the firefighters were slightly older than instructors and this difference approached significance ($p = 0.082$).

All participants were required to have completed a medical evaluation consistent with the National Fire Protection Association 1582 standard in the past 12 months. Firefighters with any known cardiovascular disease, or who used tobacco, were younger than 18 or older than 55 years of age, had gastrointestinal complications, or pregnant were excluded from the study. Participants reported for testing following a standard meal (Ensure Original Shake (220 cal; 6 g (9%) fat, 33 g (11%) CHO, 10 g (20%) protein), Clif Bar (240 cal; 5 g (8%) fat, 43 g (14%) CHO, 9 g (18%) protein) that was ingested within 60 min of the trial. Firefighter crews reported at approximately the same time on each of the three days to control for diurnal variations in measurements.

We recruited relatively experienced firefighters who would complete the assigned tasks as directed and were familiar with live fire policies and procedures. Throughout the study protocol, all firefighters were required to wear their self-contained breathing apparatus prior to entering the structure. All firefighters were fit tested for the self-contained breathing apparatus mask which they used for this study within the past 12 months. The research team supplied all personal protective equipment for the participants to enhance standardization and to ensure that all protective equipment adhered to National Fire Protection

**Table 1**
Descriptive statistics for firefighter and fire instructor participants. Data are mean (SE).

| Measure | Firefighters (n = 24) | Fire instructors (n = 10) |
|---|---|---|
| Age (years) | 40.4 (1.8) | 34.7 (2.2) |
| Height (m) | 1.81 (0.01) | 1.78 (0.03) |
| Weight (kg) | 90.2 (3.4) | 87.1 (5.4) |
| BMI (kg/m$^2$) | 27.5 (0.9) | 27.2 (1.3) |
| Experience (years) | 16.6 (1.6) | 14.8 (2.5) |

Association standards.

### 2.2. Study design

The study used a repeated measures design in which firefighters (n = 24) participated in training scenarios in three different training fire environments commonly used to simulate fire training in residential structures. Within a given test day, three different groups of firefighters engaged in testing (at approximately 0900, 1200 and 1500 respectively). Three groups of four firefighters were tested in one test period ('Alpha' test days) with 48 h between tests. A different three groups of four firefighters were tested in a second test period ('Bravo' test days), with 48 h between tests. In addition, fire instructors (n = 10) were studied as they set up, instructed and cleaned up for all three training fire scenarios within a given test day (approximately 0800–1600). A cadre of 5 instructors worked with all the groups of firefighters on the 'Alpha' test days and a separate cadre of 5 instructors worked with the firefighters on 'Bravo' test days.

Firefighters performed the same firefighting scenario (suppress a two-room fire) in the three different training fire environments defined as follows:

- **Pallet** – Fires were ignited using three pine wooden pallets and one bale of straw in two separate bedrooms in a concrete and steel training structure. The traditional IFSI training structure was laid out similar to a mid-20th century single family dwelling (Fig. 1a).
- **OSB** – Fires ignited in burners using two pallets and one bale of straw along with a sheet and a half of OSB along the ceiling of two separate bedrooms in a T-shaped metal shipping container based prop (Fig. 1b).
- **Fog** – Theatrical smoke machines were utilized in conjunction with a commercially available fire simulation panel that provides digital flames and sound effects that reacts to a firefighter applying water through thermal sensors (Attack Digital Fire System, Bullex; Albany, NY) Two separate systems were utilized in a building constructed from metal shipping containers to have an identical layout to the IFSI mid-20th century single family dwelling (Fig. 1a).

The order in which the training fire environments were introduced was staggered. 'Alpha' firefighters and fire instructors started with the Fog scenario, then Pallet and ended with the OSB scenarios. 'Bravo' firefighters and instructors began with the OSB scenario, followed by Pallet, then Fog. It was not possible to counterbalance the design for the firefighters while ensuring that the instructors were exposed to a single training fire environment per day. This order was chosen in an attempt to partially balance the order within the constraints of the overall design.

For each firefighting scenario, firefighters were deployed in teams of four to suppress a two-room fire in the training structures. A team was composed of a two-person Fire Attack crew which advanced the fire hose from an engine and suppressed all active fires and a two-person Search and Rescue crew that performed a forcible entry task and then searched for and rescued two simulated victims (75 kg manikins). These tasks are commonly conducted in firefighter training operations and also represent typical fireground operations for single family home fires in the United States, patterned after the "Inside Attack" and "Inside Search" firefighter tasks performed in a related study focused on simulated residential structure fire responses (Horn et al., 2017).

Additionally, five instructors were deployed in each scenario following typical training protocols. All instructors helped set up the training structures (load fuel packages, move simulated victims to their location, load fire hose, set up apparatus, etc.) and performed clean up after each scenario. During each scenario, two of the instructors acted as 'stokers' to light the fires and control ventilation to ensure fire growth and smoke development as necessary. Two instructors worked with the Fire Attack team, while one instructor was assigned to the Search and Rescue firefighters. During these scenarios, the instructors acted as safety monitors as well as provided support as they normally would during a training fire scenario.

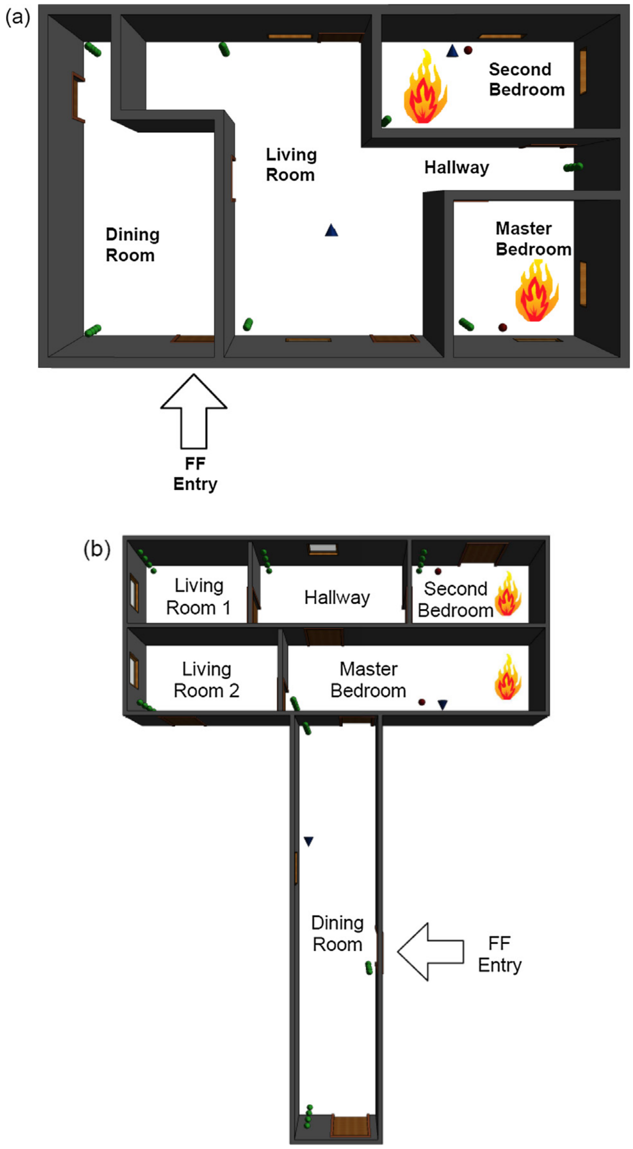


**Fig. 1.** Schematic of structural layout for the (a) Pallet and Fog scenarios and (b) OSB scenario including data acquisition instrumentation.

### 2.3. Study protocol

Following recruitment, participants completed informed consent and all required paperwork. Firefighters received a core temperature capsule (VitalSense Temperature Capsule, Phillips Respironics, Murrysville, PA) that they ingested 6–12 h prior to data collection. Upon arrival on each day, multiple pre- and post-firefighting cardiovascular measurements and chemical exposure samples were collected prior to the initiation of the fire training evaluation (these data will be reported elsewhere). The firefighter participants were then deployed to complete their firefighting work in the purpose-built test structures.

Fires were ignited (or smoke machines turned on for the Fog scenario) in the two simulated bedrooms on the opposite side of the structure from the entry point. The fire/smoke was allowed to grow until conditions in the fire rooms reached levels determined to be near peak values based on pilot studies. The two firefighters assigned to the Attack team pulled a fire hose from a waiting fire engine, advanced through the front door of the structure and the fires were completely suppressed. The two person Search team crawled through the structures to locate and rescue two simulated occupants of the structure (75 kg manikins).

## 2.4. Measures

### 2.4.1. Building thermal measurements

To assess fire dynamics throughout the fire scenarios, measurements included air temperature, gas concentrations, pressure, heat flux, thermal imaging, and video recording. Detailed measurement locations can be found in Fig. 1. This paper will only present the thermal measurements. Air temperature was measured with bare-bead, Chromel Alumel (type K) thermocouples with a 0.5 mm nominal diameter. Thermocouple arrays were located in every room with measurement locations of 0.3 m, 0.9 m, 1.5 m and 2.1 m above the floor.

### 2.4.2. Assessment of firefighter core temperature

Core body temperatures were continuously measured throughout all data collection sessions. Participants swallowed a small disposable core temperature sensor capsule (VitalSense Temperature Capsule, Phillips Respironics; Murrysville, PA) 6–12 h prior to activity. A monitor (MiniMitter Vital Sense, Phillips Respironics; Bend, OR) was clipped to the firefighters' belts before and after firefighting and carried in their bunker coat after donning their personal protective equipment. This unit communicated with and recorded data from the core temperature capsule.

### 2.4.3. Assessment of firefighter heart rate

Heart rate was monitored using a physiological status monitoring system integrated into the firefighter's base layer (Globe Manufacturing; Pittsfield, NH). The shirt system integrates a BioHarness 3 (Zephyr Technologies; Annapolis, MD) heart rate strap and software system to report heart rate at approximately one sample each second. Firefighters donned their shirts prior to firefighting data collection and wore them through each scenario until they were released from rehabilitation and showered.

### 2.4.4. Assessment of hemostatic function

Venous samples were drawn pre- and post-firefighting activity from the antecubital vein using a 21 gauge needle by a trained phlebotomist. For firefighters, blood was collected pre-firefighting, immediately post-firefighting and 2 h post-firefighting for all training exercises (n = 23 firefighters per scenario; as one firefighter was unable to be drawn). Blood was drawn from instructors before the first crew's training exercise (pre-firefighting), and immediately after the first and third crew's training exercise (n = 10 instructors per scenario). Platelet count was assessed from venous whole blood as part of a complete blood count analysis at a contract laboratory (LabCorp). Platelet function was assessed by epinephrine (EPI)-induced and adenosine 5′-diphosphate (ADP)-induced platelet aggregability using a platelet function analyzer (PFA-100; Dade Behring, Deerfield, IL) at the IFSI Research lab. Blood samples were collected in a Vacutainer containing 3.2% sodium citrate, maintained at room temperature and analyzed within 2 h of collection. Blood was pipetted (800 μL) into the disposable cartridges and then aspirated under high shear rates (5000–6000 $s^{-1}$) through an aperture cut into the membrane coated with collagen and adenosine 5′-diphosphate and a membrane coated with collagen and epinephrine. Time to occlusion was reported. Blood samples were collected in tubes containing 3.2% sodium citrate for measurements of activated partial thromboplastin time (aPTT), also at a contract laboratory (LabCorp).

## 2.5. Statistical analysis

All analyses were performed in SPSS (v23 IBM, Armonk, NY) with significance set at an alpha of 0.05. Results are expressed as mean ± standard error (SE). Variables were checked for normal distribution using Shapiro-Wilk tests, and those variables not normally distributed were log transformed (natural logarithm) prior to statistical analyses.

Data describing the environmental conditions within the three training fire environments at 0.9 m above the floor (approximate crawling heights) are reported in each of the rooms (Living Room, Dining Room, Hallway, Fire Bedrooms) during the times when firefighters were operating within the structure and compared with a one-way analysis of variance (ANOVA) framework across the training environments (Pallet, OSB, Fog).

Separate repeated measures ANOVA were conducted for peak heart rate, core temperature and each of the hemostatic variables across training ***environment*** (Pallet, OSB, Fog) for both firefighters and instructors, followed by post-hoc t-tests with Bonferroni corrections for multiple comparisons where appropriate. Unfortunately, due to some "lost" core temperature capsules and interruptions of communications with sensors during data collection, there was significant loss in the core temperature data set, limiting the numbers available for repeated measures analysis. In order to increase the power of the statistical analysis, the core temperature data was also analyzed using all valid core temperatures that were recorded for each training environment (14 firefighters and six instructors for Pallet scenarios; 21 firefighters and 10 instructors for OSB; 17 firefighters and seven instructors for Fog). Since the activities in one environment did not influence the next, each scenario was treated independently and an ANOVA was conducted assuming unequal variance. Finally, to compare the physiological responses of the different training roles (firefighters vs instructors) to a single bout of firefighting activity, a three way ANOVA was conducted to examine changes in activity by ***time*** (pre- to post-firefighting) for each ***training role*** (firefighter, instructor) and ***environment*** (Pallet, OSB, Fog).

# 3. Results

## 3.1. Building temperature profiles

The firefighting scenarios were designed to take approximately 8–9 min to complete (which is similar to the time required by Inside crews from Horn et al (2017) to complete suppression and rescue activities), though there was a significant range in completion time depending on abilities of each crew. On average (mean ± SE), firefighters completed the Pallet scenario in 7:38 ± 0:29 (min:sec), OSB in 8:04 ± 0:19 (min:sec) and Fog scenario in 9:21 ± 0:18 (min:sec). The Fog scenario resulted in significantly longer completion times than the Pallet ($p = 0.022$) and OSB ($p = 0.031$) scenarios, while there was no difference between Pallet and OSB. One crew was an outlier in the Pallet scenario, completing in 5:19. Without this group, the average for the Pallet scenario was 8:06 ± 0:11 s.

Table 2 provides a summary of average and peak temperatures at each of the measurement locations from the buildings during simulated firefighting activities (between the time of first firefighter entry up to completion of the scenario and firefighter exit) at 0.9 m which is taken as the height within the structure where firefighters were most commonly operating. Data from 1.5 m shows identical trends, but at higher magnitudes. There were statistically significant differences in ambient temperatures for each training environment in most of the measurement locations (outside of the burn rooms for the Pallet and OSB scenarios). Overall, the OSB scenario resulted in the most severe thermal environment followed by the Pallet scenario, then Fog. The magnitude of this difference varied from room to room, but the largest range in peak temperatures was measured in the Master Bedroom, which varied from 199.8 °C (OSB) to 145.1 °C (Pallet) to 35.9 °C (Fog). In contrast, the smallest differences in average room temperatures were for the Dining Room at 0.9 m from the floor, where values varied from 38.6 °C (OSB) to 32.8 °C (Pallet) to 22.6 °C (Fog). Temperatures changed very little throughout the Fog scenario (difference between peak and average

**Table 2**
Mean (SE) of the peak and average air temperatures (°C) inside the training structures at 0.9 m (approximate vertical plane that firefighters were operating) measured over the time when firefighters entered and exited the structure.

| | | Dining Room | Living Room | Hallway | Bedrooms | |
|---|---|---|---|---|---|---|
| | | | | | Master | Second |
| Peak | Pallet | 57.7 (2.5) | 38.5 (1.2) | 77.0 (9.1) | 199.8 (35.8) | 117.7 (24.3) |
| | OSB | 107.4 (9.9)$^{\#}$ | 110.9 (11.6)$^{\#}$ | 116.4 (6.5)$^{\#}$ | 145.1 (15.1) | 118.5 (8.8) |
| | Fog | 29.1 (1.3)$^{*}$ | 24.1 (1.8) | 26.9 (2.4)$^{*}$ | 35.9 (4.9)$^{\#}$ | 25.4 (1.9)$^{\#}$ |
| Average | Pallet | 43.1 (2.9) | 30.2 (0.9) | 38.1 (1.6) | 63.3 (4.0) | 53.6 (10.7) |
| | OSB | 65.4 (8.6) | 65.2 (4.2)$^{\#}$ | 69.4 (4.7)$^{\#}$ | 81.4 (7.0) | 65.3 (3.8) |
| | Fog | 25.0 (1.7)$^{*}$ | 20.5 (2.5) | 21.5 (2.0)$^{*}$ | 22.0 (2.3)$^{\#}$ | 20.5 (2.5)$^{\#}$ |

*Notes:*
All Fog vs OSB comparisons were significantly different with p ≤ 0.001 except Peak in Master Bedroom (p = 0.011) and Peak in Second Bedroom (p = 0.002).
* Significantly different than Pallet (p < 0.05).
\# Significantly different than Pallet (p ≤ 0.001).

temperatures was 6 °C), remaining similar to the outside ambient conditions. For the live fire scenarios, temperatures varied during the scenarios as the fire grew and then as water was applied to suppress the fires.

### 3.2. Heart rate & core temperature

Firefighters' core temperature and heart rate data are reported in Table 3. While a main effect of training fire environment on heart rate was observed ($p = 0.035$), post-hoc analysis for multiple comparisons revealed no statistical significance in repeated measure or independent samples analysis. A similar response was noted for core temperature where there was a borderline significant training fire environment effect ($p = 0.054$) with no differences observed following post-hoc analysis.

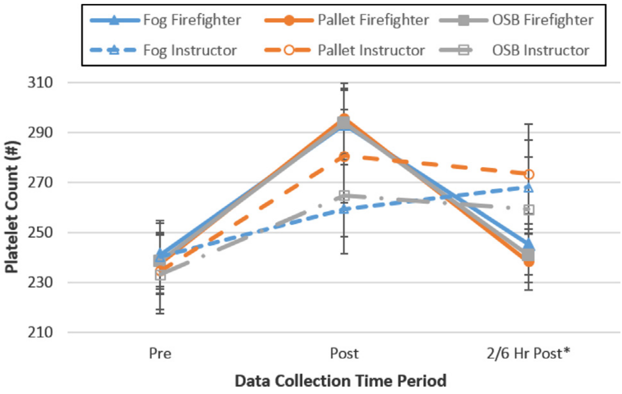
Fire instructors' core temperatures and heart rates are also reported in Table 3. There was no effect of training fire environment on core temperature ($p = 0.648$) for this group of participants; but we detected a significant environmental effect for peak heart rate ($p = 0.008$). Post-hoc analysis revealed that, compared to the Fog scenarios, instructors' peak heart rates were significantly higher in the Pallet ($p = 0.023$) and nearly significant for OSB ($p = 0.053$) scenarios. There were no significant differences between the Pallet and OSB scenarios for peak heart rates ($p = 1.000$).

Comparing firefighters to instructors, the training role had a significant influence on heart rate ($p < 0.001$), with nearly 17 bpm higher values recorded for firefighters than instructors. There was no significant effect of environment ($p = 0.063$) or interaction between training role and the environment ($p = 0.481$) in which they worked. Furthermore, there was no effect of training role ($p = 0.250$), environment ($p = 0.226$) or interaction ($p = 0.369$) on peak core temperatures between firefighters and instructors.

**Table 3**
Mean (SE) of peak core temperature and heart rate data for firefighters and instructors operating in different training fire environments.

| | Firefighter | | | Instructor | | |
|---|---|---|---|---|---|---|
| | Pallet | OSB | Fog | Pallet | OSB | Fog |
| Core Temp | 38.46 (0.10)$^{*}$ | 38.74 (0.10) | 38.47 (0.08)$^{*}$ | 38.53 (0.21) | 38.46 (0.15) | 38.31 (0.14) |
| Heart Rate | 180.3 (3.0) | 181.2 (3.6) | 176.9 (2.9) | 166.7 (8.1)$^{\#}$ | 169.4 (5.6)$^{\#}$ | 153.4 (7.8) |

*Note:* Core temperature data n = 14, 21, 17 for firefighters and n = 6, 10, 7 for instructors, Heart rate data, n = 22 and n = 10 for firefighters and instructors.
* Significantly different than OSB (p < 0.05).
\# Significantly different than Fog (p < 0.05).

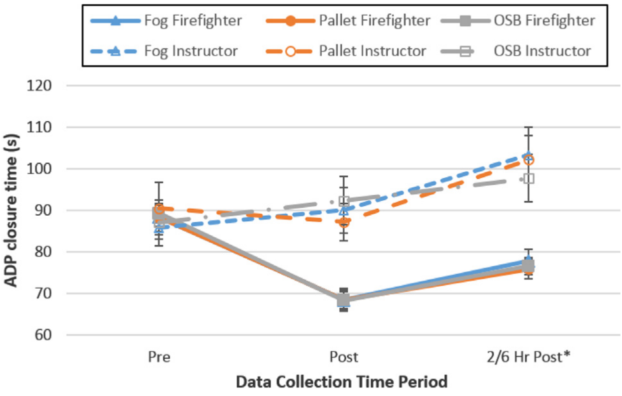


*Note: Instructor sample is collected immediately post final scenario, which is 6 hours after initial 'Post' blood draw

**Fig. 2.** Mean (SE) platelet number in firefighters pre-firefighting, immediately post-firefighting and 2 h post-firefighting and for instructors pre-firefighting, immediately post-firefighting first session and immediately post-firefighting last session (6 h post first session).

### 3.3. Hemostatic function

Firefighters' hemostatic response to the acute bout of fire training activities resulted in a significant time main effect ($p < 0.001$) for platelet count (Fig. 2, n = 20), platelet closure for blood stimulated with adenosine 5′-diphosphate (Fig. 3, n = 22) and epinephrine (Fig. 4, n = 22) as well as activated partial thromboplastin time (Fig. 5,



*Note: Instructor sample is collected immediately post final scenario, which is 6 hours after initial 'Post' blood draw

**Fig. 3.** Mean (SE) platelet closure time for blood stimulated with adenosine 5′-diphosphate (ADP) in firefighters pre-firefighting, immediately post-firefighting and 2 h post-firefighting and for instructors pre-firefighting, immediately post-firefighting first session and immediately post-firefighting last session (6 h post first session).

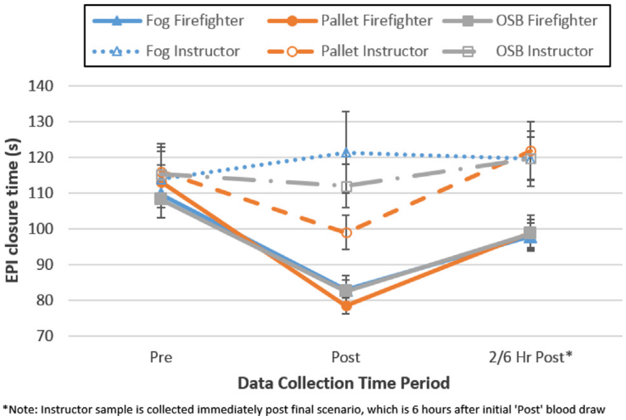


**Fig. 4.** Mean (SE) platelet closure time for blood stimulated with epinephrine (EPI) in firefighters pre-firefighting, immediately post-firefighting and 2 h post-firefighting and for instructors pre-firefighting, immediately post-firefighting first session and immediately post-firefighting last session (6 h post first session).

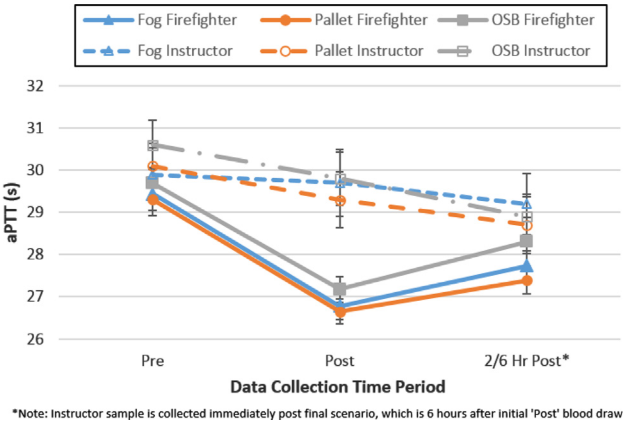


**Fig. 5.** Mean (SE) activated partial thromboplastin time (aPTT) in firefighters pre-firefighting, immediately post-firefighting and 2 h post-firefighting and for instructors pre-firefighting, immediately post-firefighting first session and immediately post-firefighting last session (6 h post first session).

n = 23), with no significant effect of training environment or interaction. Post-hoc testing revealed a significant increase in platelet count from pre-to-post firefighting ($p < 0.001$) that returned to baseline by 2 h post firefighting. For both measures of platelet closure time and activated partial thromboplastin time, post-hoc testing revealed significantly faster clotting times post firefighting compared to pre ($p < 0.001$) that by 2 h post firefighting has slowed slightly from immediate post firefighting levels ($p < 0.001$), but still remained faster than pre firefighting levels ($p < 0.001$).

Instructors' (n = 10) hemostatic responses to firefighting were generally less pronounced than firefighters, though we found a significant time main effect for platelet count ($p = 0.001$), platelet closure time for blood stimulated with adenosine 5′-diphosphate ($p = 0.005$) and activated partial thromboplastin time ($p < 0.001$). Post-hoc testing revealed a significant increase in platelet count from pre-to-post firefighting ($p = 0.001$) that remained elevated after the instructors completed the final training scenario of the day ($p = 0.013$). For platelet closure for blood stimulated with adenosine 5′-diphosphate, post-hoc testing revealed a significant decrease from post first-to-post final firefighting activity ($p = 0.030$) that was also significant pre-to-post final firefighting activity ($p = 0.014$). Finally, for activated partial thromboplastin time, post-hoc testing revealed a significant decrease from pre-to-post firefighting ($p = 0.004$) that continued to decrease immediately post-final activity ($p < 0.001$ compared to pre-firefighting, $p = 0.025$ compared to immediate post-firefighting).

The analysis of training role (firefighter vs fire instructor) on hemostatic response found a significant main effect of time for all four variables ($p < 0.001$), and a significant effect of training role on platelet closure for blood stimulated with adenosine 5′-diphosphate ($p = 0.016$) and epinephrine ($p = 0.005$) as well as activated partial thromboplastin time ($p = 0.004$). Significant interactions were detected for time × training role (platelet count, $p = 0.022$, others $p < 0.001$) and time × fuel for platelet count ($p = 0.008$) and platelet closure for blood stimulated with epinephrine ($p = 0.006$). In all cases changes from pre-to-post firefighting activity were larger for firefighters than instructors. Changes in hemostatic outcomes from pre-to-post firefighting activity were consistently larger after the pallet scenario followed by OSB, then Fog.

## 4. Discussion

This study provides a detailed characterization of the thermal environment and physiological responses of firefighters and fire instructors working in a broad range of common training fire environments. Our most important finding was that the dramatically different thermal environments in the training scenarios resulted in minimal differences in firefighters' physiological responses during the short duration training scenario in fully encapsulating bunker gear. Additionally, though fire instructors worked multiple scenarios throughout the day and reached equivalent peak core temperatures, their peak heart rates were slightly lower and hemostatic response was blunted compared to the firefighters.

### 4.1. *Building temperature profiles*

The environmental thermal data reported here complements the existing literature, with important additions. Traditionally, pallet and straw (or similar light combustible materials such as excelsior used to ignite the pallets) fuels have been the most commonly utilized training fuels due to their relatively low cost, ease of accessibility and ability to control thermal conditions. While environmental temperatures experienced during firefighting activities using pallet and straw fires in concrete and steel training structures have been reported for many years (e.g. Willi et al., 2016; Lannon and Milke, 2014), this study provides the first comparison of these conditions with 21st century training structures constructed from metal containers and using engineered wood products to produce more intense heat and smoke. Average and peak temperatures in the burn rooms (Master and Second Bedrooms) were fairly similar in the Pallet and OSB scenarios (except that average temperatures in the Master Bedroom were slightly higher in the OSB scenario; Table 2). However, most air temperatures throughout the rest of the structure were significantly higher for the OSB compared to the Pallet. This may be partially attributed to the slightly higher temperature in the Master Bedroom due to the glue in the OSB fuels, but is also likely due to the increased ability of the metal shipping container construction to conduct heat through the structure and into surrounding areas, which can then reradiate this energy to the firefighter. Additionally, the orientation of the OSB fuel provided flame across the ceiling in the OSB prop (to simulate common conditions in a structure fire where flames may roll over the firefighters' head), thus firefighters are likely to be exposed to increased radiant energy from these flames as they enter and approach the fire sets prior to suppression. Radiant heat transfer may not be fully accounted for by stationary thermocouples in training fire environments (Willi et al., 2016). In contrast, the concrete and steel structure provides a larger heat sink for the local fires. Heat transfer to the firefighter is largely due to convective heat transfer from the fire gas exposure, with a lower magnitude of radiant heat exposure. Thus, while peak temperatures in the burn rooms are not significantly different using these modern props, firefighters are likely to experience higher temperatures as they search for fires and simulated occupants inside the metal shipping containers.

Some fire instructors argue that it is important to expose trainees to realistic, elevated thermal burden during training to prepare firefighters for real world scenarios. As such, there is a belief among many instructors that changing fuel packages to OSB can result in firefighters being exposed to temperatures similar to what they would face on today's fireground. A similar "coordinated attack study" was recently conducted using a wood frame structure (drywall finish) containing typical household combustibles as the fuel (Horn et al., 2017). Comparing temperatures measured here to those from Horn et al (2017) in Table 2, it is apparent that temperatures were much higher throughout the residential structure compared with the training fire environments. Thus, while temperatures are increased using OSB, they are still not approaching those that may be encountered in a structure fire environment.

While these training scenarios were designed to replicate a "coordinated fire attack" that is common in training and were consistent with scenarios that have been published (Horn et al., 2017), it is important to acknowledge that a wide variety of training scenarios exist throughout North America. The National Fire Protection Association 1403 standard (NFPA, 2018b) provides guidance on fuel packages (4.13.1: "The fuels that are utilized in live fire training evolutions shall only be wood products." 4.13.7: "The fuel load shall be limited to avoid conditions that could cause an uncontrolled flashover or backdraft."), yet the standard does not specify safe thermal ranges during training evolutions or include discussion on engineered wood products such as OSB.

### 4.2. Heart rate & core temperatures

As in previous studies, heart rate and core temperature increased during the training scenarios. In all three scenarios, firefighters' peak heart rates reached approximately 180 bpm (the age-predicted maximal heart rate [220-age] for 40-year old firefighters). Average heart rates throughout the scenarios were approximately 160–165 bpm, reflecting strenuous work during the seven- to nine-minute response. Core temperatures increased from a baseline of approximately 37.5 °C to peak at 38.4–38.7 °C, values that are consistent with other published findings (Horn et al., 2013). While the scenarios and environments varied significantly among the studies reviewed by Horn et al. (2013), core temperature changes ranged from 0.3 to 1.4 °C over many types of firefighting scenarios, many of similar duration to those studied here. When firefighters respond to simulated residential structure fires, Horn et al. (2017) found that the core temperature change and rate of change of the interior firefighting crews was near the upper end of these ranges (1.04 °C). Interestingly, the peak core temperatures measured during these training fires (~38.5 °C) were slightly higher than those in the aforementioned residential structure fires study (~38.0 °C). However, the baseline temperatures of firefighters studied in this cohort were slightly higher, resulting in similar core temperature changes (1.09 °C) after the firefighters' response. According to the American Conference of Governmental Industrial Hygienists (ACGIH, 2016), a healthy, acclimatized, experienced worker's core temperature should not exceed 38.5 °C. Thus, our data suggests that ample rest should be provided between evolutions to ensure that core temperatures do not continue to rise from the levels measured after this single scenario lasting less than 10 min, regardless of the training environment utilized.

Despite significant differences in ambient conditions between the Fog and Pallet training scenarios, the peak core temperatures and heart rates (average and peak) of participants were not significantly different. These two structures were laid out with identical dimensions, locations of the fire and simulated trapped occupants and can be directly compared. This finding is inconsistent with an earlier study by Smith et al (1997) where 16 male firefighters were randomly assigned to perform a simulated ceiling overhaul task for 16 min in either a neutral (~14 °C) or hot (~90 °C) condition while wearing firefighting turnout gear. Significant increases were seen for heart rate and tympanic temperatures, with the increases being much greater following the hot condition. It is possible that the more prolonged firefighting activity investigated by Smith et al. (1997) accounted for the greater differences seen in that study when firefighters performed work in different ambient temperatures. Horn et al (2015) found no difference in physiological responses to simulated firefighting activities when conducted in a burn building (~85 °C at working height) or environmental chamber (~47 °C) when performing activities for 14 min on a two-minute work-rest cycle (for a total of eight minutes of physical activity). Since heart rate was very similar between environments in this scenario, it appears that the work firefighters do provides the near peak cardiovascular load that can be measured by heart rate, with only a small additional load provided by high temperature environments. However, heart rate may not completely reflect cardiovascular strain and load since this measure cannot go above maximal. It is possible that ventricular function may have been affected differentially as a result of heat load.

Interestingly, the peak core temperatures experienced by the instructors were similar to that of the firefighters even though the instructors do not participate in the same level of strenuous activity (as can be seen by the significantly lower heart rates). Instructors did spend more time conducting other activities such as reloading hose, moving simulated victims in the structure, setting up the fuel packages in the structures (for Pallet and OSB), and igniting fires. Significantly lower heart rates were seen for instructors during the Fog scenarios compared to the live fire scenarios (Pallet and OSB). Other than the short amount of time spent loading fuel for the fires in the Pallet and OSB scenarios, the tasks carried out by the instructors were fairly similar, regardless of the training environment, so these differences in heart rate may be explained by exposure to the higher ambient temperatures or greater stress levels when firefighters in their charge are exposed to more dangerous live fire conditions. Although the instructors typically experience less physiological strain during the training events, their responsibility to complete this job multiple times per day suggests that the insult may still be a concern and should be monitored.

### 4.3. Hemostatic responses

Firefighters' hemostatic responses pre- to post-fire training is similar to what has been previuosly reported in the literature (Smith et al., 2011, 2014a, 2014b). Significant increases in platlet count can be attributed to both the stress response and acute dehydration. Increased platelet closure time and function, coupled with reduced clotting time, have also been reported after training with a partial recovery up to two hours later. This study extends our understanding by reporting nearly identical hemostatic responses of firefighters during live-fire training scenarios as was found during the training in a thermoneutral environment (i.e., Fog scenario). These findings support the heart rate and core temperature data indicating that the physiological strain of firefighting is determined more by the activities that are performed than by the ambient temperatures in the room – at least during short term firefighting activities.

Instructors' hemostatic responses were generally similar to the firefighters, though with a consistently smaller magnitude of change. Platelet counts in instructors increased after the first activity, but to a lesser extent than they did for firefighters, particularly after the Fog scenario. Even after completing two additional scenarios throughout the day, peak values were lower than after a single training drill for the firefighters. However, firefighters' values returned to near baseline within two hours of activity, while the elevation in platelet count continued in the instructors six hours after the initial bout. Activated partial thromboplastin time continued to decline in instructors for all three scenarios, though there was a slightly lower response during the Fog scenario. Taken together, these measurements suggest less hemostatic disruption for the instructors than the firefighters which is consistent with lower work and less physiological disruption.

### 4.4. Limitations and future work

While this study provides a broad characterization of the thermal conditions and physiological responses associated with common firefighter training scenarios, important limitations are noted. Although this study used typical training structures and a common coordinated fireground scenario, we did not measure all possible training scenarios and specifically we did not collect data on the vast array of larger, multi-story structures which firefighters might encounter with larger fuel sets. We also did not measure longer, more complicated scenarios, or investigate repeated scenarios that would create greater physiological strain. Another potential limitation in the firefighter vs instructor comparison is that instructors' baseline values were always measured in the morning, so may be biased compared to firefighters' whose baseline core temperatures were measured prior to their scenarios that occurred either in the morning, approximately at noon or in the early afternoon. It should also be noted that physiological response is not the lone factor when making recommendations for training. Fire instructors should also consider how the environmental conditions (e.g. visibility, thermal conditions, flame rollover, etc) support the objectives of each training scenario conducted.

## 5. Conclusions

Firefighting training fire environment (fuel load and structure design) has a significant effect on ambient environmental conditions encountered by firefighters operating inside the structure and thus has the potential to influence physiological measures related to health and safety. However, the differences in ambient temperature did not translate to significant differences in firefighters' peak heart rate, core body temperature or hemostatic function when comparing the Fog training scenarios to the live fire scenarios. It is important that firefighters wearing fully encapsulating personal protective equipment and working on the training ground be provided rest, recovery, and rehab based on intensity and duration of work, regardless of the apparent safety risk from ambient conditions alone. The assumption that performing firefighting activity in ambient (or thermoneutral) conditions leads to lesser physiological strain compared to live-fire activity is not supported by our data.

Instructors in the Fog scenarios had significantly lower peak heart rates than during the Pallet or OSB scenarios, but their peak core temperatures were not significantly different across the training environments. Instructors experienced lower peak heart rates than firefighters, but similar peak core temperatures due to the prolonged nature of their response and repeated exposures. Despite the fact that instructors where involved in multiple evolutions during the day, they had a blunted hemostatic response compared to firefighters. These data suggest that hemostatic changes are sensitive to the intensity of work that is performed. Given the high heart rates and significant increase in core temperatures seen in this short-duration, coordinated fire attack drill as well as changes throughout the day for instructors with repeated responses, additional work should be conducted to better understand physiological strain and safety associated with firefighters who may be completing repeated high intensity evolutions or may be assigned to longer duration tasks.

## Acknowledgements

The authors would like to thank all of the firefighters and instructors who participated in this study along with support staff from the Illinois Fire Service Institute, in particular Chief Sean Burke who ran incident command for each of these scenarios. 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 & Health (NIOSH).

## Funding

This work was supported by the Department of Homeland Security Fire Prevention and Safety Grant program [EMW-2014-FP-00590].

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