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Characterizing a Firefighter's Immediate Thermal Environment in Live-Fire Training Scenarios

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Abstract. Detailed characterization of a firefighter's typical thermal exposures during live-fire training and responses can provide important insights into the risks faced and the necessary protections, protocols, and standards required. In order to gather data on representative thermal conditions from a firefighter's continually varying local environment in a live-fire training exercise, a portable heat flux and gas temperature measurement system was created, calibrated, and integrated into firefighter personal protective equipment (PPE). Data were collected from 25 live-fire training exposures during seven different types of scenarios. Based on the collected data, mild training environments generally exposed firefighters to temperatures around 50°C and heat fluxes around 1 kW/m^2, while severe training conditions generally resulted in temperatures between 150°C and 200°C with heat fluxes between 3 kW/m^2 and 6 kW/m^2. For every scenario investigated, the heat flux data portrayed a more severe environment than the temperature data when interpreted using established thermal classes developed by the National Institute for Standards and Technology for electronic equipment used by first responders. Local temperatures from the portable measurement system were compared with temperatures measured by stationary thermocouples installed in the training structure for 14 different exposures. It was determined the stationary temperatures represented only a rough approximate bound of the actual temperature of the immediate training environment due to the typically coarse distribution of these sensors throughout the structure and their relative (fixed) distance from the fire sets. The portable thermal measurement system has provided new insights into the integration of electronic sensors with firefighter PPE and the conditions experienced by firefighters in live-fire training scenarios, which has promise to improve the safety and health of the fire service.

Keywords: Firefighters, Heat flux, Thermal environment, Thermal class, Live-fire training, Flashover simulator

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1. Introduction

A firefighter's thermal exposure on the fire ground or training ground has a significant contribution to the risk faced in their job. Measuring this exposure can provide a means to quantify the risk and guide standards development to improve training, personal protective equipment (PPE), technology, and overall firefighter health and wellness. According to the National Fire Protection Association (NFPA), over 7500 firefighters were injured during training related activities in the United States in 2013 [1]. Instructors throughout the fire service follow the *NFPA 1403 Standard on Live Fire Training Evolutions* [2] in an attempt to minimize the risk involved with this type of training. However, many believe there are additional ways to increase the safety of such activities. For example, thermocouples have been integrated into some training structures to allow monitoring of room temperatures during training exercises. There is concern that gas temperature alone may not be a sufficient measure of the risk to which the firefighters are exposed as these stationary thermocouples may be either partially shielded from some portion of the fuel or installed in areas distant from where the firefighters would be exposed. Fatalities that have occurred during live-fire training have led to discussions about what the future of live-fire training should be [3–9].

In addition to instrumenting training buildings, the response environment has recently been augmented through electronic technologies that have potential to enhance fire fighting response capabilities and to acquire vast amounts of potentially useful data from different areas of the fire service [10]. Data streams are available from permanent installed temperature sensors within structures to which firefighters respond, though the utility of these temperature sensors to identify risks for firefighters has not been studied [10]. Additionally, portable measurement and data acquisition systems are being researched and developed for integration with firefighter PPE [10]. Local temperature measurement and display systems are relatively inexpensive, compact, and mobile. Heat flux measurements can also provide important additional information, particularly when being used to monitor a fire environment, but are more costly in terms of equipment and investment. The ability to study thermal sensor capabilities in a training environment can provide a first step towards improved utilization on the fire ground.

While thermal data acquisition capabilities are improving and their applications increasing in scale, there exists limited guidance for fire and training officers on the thermal and time limits that would ensure a safe live-fire response and training exposure. Over the years, a variety of thermal environment classification systems have been developed by researchers that may be useful to provide such insight with appropriate instrumentation [11–13]. Many of these systems define three or four different thermal classes based on temperature and heat flux. In 2006, the National Institute of Standards and Technology (NIST) reviewed existing thermal environment classification data and proposed four thermal classes, defined in Table 1, for use in defining standardized test criteria for electronic safety equipment used by firefighters [14].

While the NIST Thermal Classes have been established for evaluation of fire fighting electronic equipment, limited experimental time-resolved data exist from

Table 1
National Institute of Standards and Technology Thermal Classes

Thermal class	Maximum time (min)	Maximum temperature (°C)	Maximum heat flux (kW/m^2)
I	25	100	1
II	15	160	2
III	5	260	10
IV	<1	>260	>10

the perspective of a firefighter's typical exposure. Previous studies [15, 16] concerning firefighter PPE and thermal exposures in a fire environment have described pre-flashover fire fighting environments with temperatures ranging from 100°C (212°F) to 300°C (572°F) and maximum heat fluxes between 5 kW/m^2 and 12 kW/m^2. However, these studies did not specifically focus on the firefighter's local environment in live-fire training scenarios, and the studied environments often contained fuel loads that were different than the wood-based products and straw often used in *NFPA 1403* compliant training exercises. For example, Krasny et al. conducted seven room fire scenarios using fuel loads prohibited for live-fire training by *NFPA 1403* (mattresses, sofas, typical residential structure fuels) and compared the results to the protection level required for firefighter turnout coats by *NFPA 1971 Protective Clothing for Structural Fire Fighting* [17]. Similarly, thermal exposures during live-fire training were studied by Rossi [16]. However, in both cases, the instrumentation used to gather data remained stationary throughout the experiments. Firefighters typically move throughout a structure during training scenarios, so data collected from a single fixed position for the duration of a live-fire training exercise are unable to accurately define the firefighters' local thermal environment. By gathering experimental time-resolved data from the local environment of a firefighter moving throughout live-fire training scenarios, the live-fire training environment can be better understood and compared to current descriptions of pre-flashover fire fighting thermal conditions. Foster and Roberts have previously developed a mobile firefighter carried data acquisition system [12]. However, this system was limited by the physical size and the firefighter's mobility. Furthermore, the available analysis does not interpret the time-resolved effects of typical fire training conditions.

Additionally, there exists a legacy of research to study the effects of fire fighting PPE and activities on a firefighter's physiology and biomechanics, which has been conducted in a variety of testing environments. Some studies have utilized training drills with environmental temperatures less than 100°C in a live-fire burn structure to simulate fire ground activities [18–22]. More commonly, research groups have used a treadmill protocol in a temperature-controlled (~25°C to 50°C) room [23–28]. While Selkirk and McLellan have shown that the physiological responses to activity in fire fighting PPE is affected by the ambient temperature of the testing environment, there are limited data available upon which to base the representative thermal conditions.

The purpose of this project is to characterize a firefighter's typical thermal exposures as a firefighter participates in *NFPA 1403* compliant live-fire training exercises in order to study risks associated with training as well as establish a baseline for response exposure scenarios and data acquisition systems. To accomplish this task, a portable measurement and data acquisition system was created and integrated into firefighter PPE. Laboratory experiments were conducted at NIST to test and calibrate the custom system. This tool was then used to collect temperature and heat flux measurements from a firefighter's immediate surroundings in numerous live-fire training scenarios at the Illinois Fire Service Institute (IFSI). The live-fire exposure data were then interpreted with the NIST Thermal Class system and compared to data from stationary thermocouple arrays installed in the walls of the fire room.

2. Portable Measurement and Data Acquisition System

2.1. System Components and Design

To characterize a firefighter's continuously changing local thermal exposure during live-fire training, the data acquisition system shown in Figure 1 was designed to be used with standard firefighter PPE to allow for portability with minimal impact on mobility. Neither the thermal protection of the PPE nor the user's range of motion were significantly compromised by the utilization of the system. The measurement and data acquisition system is composed of two main parts: the helmet and the pack.

The helmet portion of the system (Figure 2) consists of a fire helmet (Cairns 880, MSA, Cranberry Township, PA, USA) equipped with a 0.25 mm (0.01 in) bare bead type K thermocouple (Type K, Omega Engineering Inc., Stamford, CT), a heat flux microsensor (HFM) [29], and a custom cooling block for the sensor that is attached to an aluminum helmet shield. The thermocouple bead is located approximately 6 cm (2.4 in) in front of the helmet shield.

In order to mount the thermocouple and HFM to the front of the helmet, four holes are fabricated along the vertical centerline of the aluminum shield. The thermocouple wire passes through the top hole and is located approximately 6 cm (2.4 in) in front of the shield. The three remaining holes are used to mount the cooling block for the HFM to the back of the shield and to mount the HFM to the front of the shield. The aluminum cooling block is designed specifically for the HFM and contains counterbore holes machined to the HFM's specifications. A 1/2-20 THD nut is used to hold the HFM in the block. Additionally, a 1/8 in diameter "pipeline" is machined around the counterbore holes for the cooling water to flow through. Two 1/8-NPT pipe fittings are used to connect 1/8 in diameter rubber tubing from the cooling block to the miniature water pump and water reservoir in the hydration backpack.

A data logger [30], water reservoir, and miniature water pump [31] are contained in various pockets of the hydration backpack (Figure 3). The data logger rests in the front pocket of the pack and is used to collect and store data from the heat flux microsensor and the thermocouple. The water reservoir, located in the

Figure 1. Customized portable measurement and data acquisition system used for all experiments.

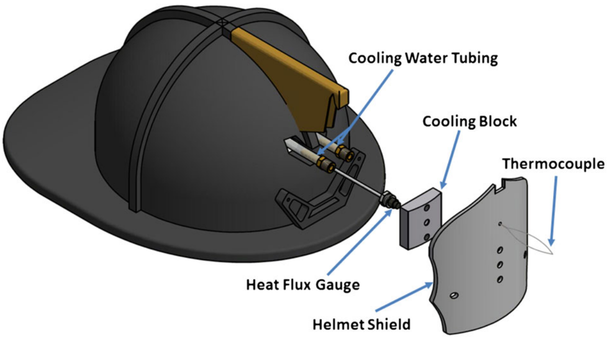


Figure 2. Exploded CAD model of the helmet portion of the portable measurement and data acquisition system.

rear pocket of the pack, serves as the storage unit for the cooling water. Finally, the water pump used to circulate water from the reservoir through the cooling block and its battery pack are located in a side pocket of the pack. The low-profile pack is worn under the firefighter's bunker coat on the chest to avoid interference with the SCBA pack on the back. While this system is designed to work with fire fighting PPE, it's intended for use as a research instrument at this point. It can be advanced for use in the response environment in future efforts.

Figure 3. Contents of the pack portion of the portable measurement and data acquisition system.

2.2. Laboratory Calibration

All laboratory calibration experiments were performed at NIST in Gaithersburg, MD using a natural gas-fired radiant panel apparatus described in detail in *ASTM E162 Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source* [32]. The apparatus was modified to provide for a range of heat flux exposures from 1 kW/m^2 to 20 kW/m^2 for testing firefighter protective equipment [33–35].

For each experiment, a NIST-calibrated, water-cooled Schmidt–Boelter total heat flux gauge (SBG) [36] was moved along a horizontal track to locate the distance from the panel with the desired level of heat flux. The distance from the panel was recorded, and the incident heat flux at this position was measured by the SBG and collected by a data acquisition system (SCB-100, National Instruments Corporation, Austin, TX, USA) for 60 s at a rate of one sample per second. The entire helmet portion of the portable measurement and data acquisition system with the HFM installed as it would be in the field (Figure 2) was moved along the horizontal track to the marked position, and the system's HFM measured the incident heat flux for 60 s at a rate of one sample per second.

Table 2
Heat Flux Microsensor (HFM) and Schmidt–Boelter Gauge (SBG) Laboratory Calibration Results

Approximate incident heat flux (kW/m^2)	Average SBG heat flux (kW/m^2)	Average HFM heat flux (kW/m^2)
1	1.08 ± 0.02	1.28 ± 0.09
3	3.26 ± 0.02	3.24 ± 0.10
5	5.27 ± 0.03	5.23 ± 0.10

Data are presented as mean ± standard deviation

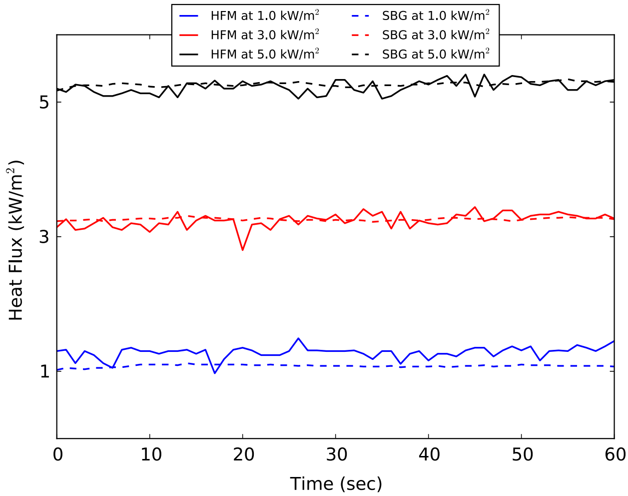


Figure 4. Heat flux microsensor (HFM) and Schmidt–Boelter gauge (SBG) data at each incident heat flux for each 60 s calibration exposure.

The procedure was performed for incident heat flux values of approximately 1 kW/m^2, 3 kW/m^2, and 5 kW/m^2 (Table 2; Figure 4). Firefighter PPE and thermal exposures [15, 16] have described pre-flashover fire fighting environments with maximum heat fluxes between 5 kW/m^2 and 12 kW/m^2. It was decided that laboratory experiments would be conducted at heat fluxes up to the lower end of the maximum range to ensure that the data collected from the helmet mounted HFM can be generalized to other similar training scenarios. The average and standard deviation of each experimental data set were calculated and used to generate a calibration curve for the portable system's HFM module compared to the NIST-traceable SBG (Figure 5).

It is apparent from Figure 4 that the field-deployable HFM module and data acquisition system has a higher sample-to-sample variation within the 60 s data interval compared to the laboratory-based SBG sensor and data acquisition system. The average coefficient of variation (standard deviation/mean) for the three heat flux levels measured with the SBG sensor was 1.0%, while the HFM of the portable system resulted in a 4.0% variation. Furthermore, the relative variability of the HFM module was the largest at the 1 kW/m^2 heat flux (6.8%) and reduced for larger heat fluxes (3.2% and 1.9% for 3 kW/m^2 and 5 kW/m^2, respectively). The calibration curve in Figure 5 confirms a slope of very near 1 with a high Pearson correlation coefficient (R = 0.997). The plot does suggest a slight bias towards over predicting the lowest end of the calibration range, though agreement at 3 kW/m^2 and 5 kW/m^2 is better than 1%. Together, these results suggest the HFM of the portable measurement and data acquisition system will provide a reliable assessment of the moderate to high heat flux values of interest in the Class

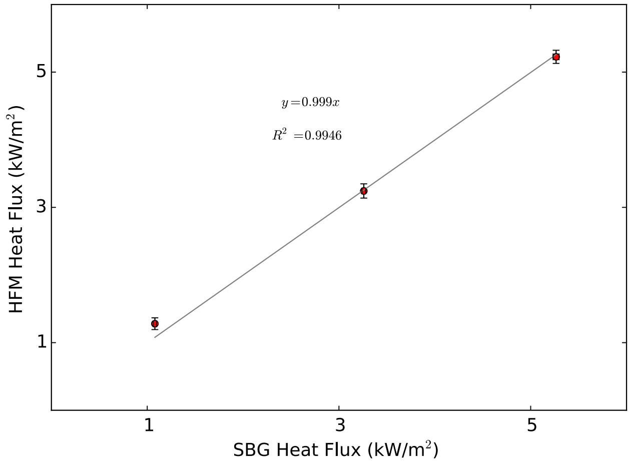


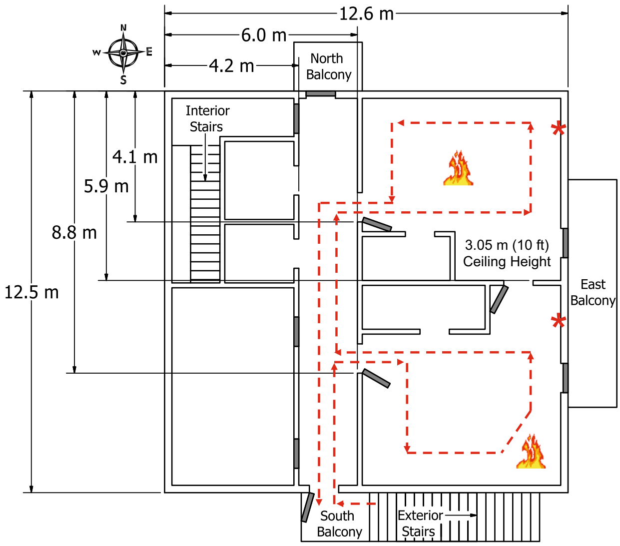
Figure 5. Heat flux microsensor (HFM) calibration with the Schmidt–Boelter gauge (SBG).

II–IV levels (Table 1) expected in the training environments. At lower heat flux values (Class I), the HFM's data will be more significantly affected by A/D conversion noise and result in slightly higher variability. Future iterations of this device may be improved with increased sensor sensitivity (currently 150 μV/W/cm^2) or reduction in the noise floor of the data acquisition system.

3. Live-Fire Scenarios

Experimental data were collected from a variety of live-fire scenarios including multiple coordinated fire ground training exercises and two different fire behavior demonstrations: (1) in a concrete-and-steel burn structure and (2) in a metal container based training prop known as a "flashover simulator". A wide variety of scenarios—from fuel loads, conditions, and activities commonly used for training firefighters from new recruit to highly experienced veterans—were studied. Prior to entering any structure, a steel plate coated with high emissivity ultra flat black paint ($\epsilon = 0.97$) [37] that was acclimatized to the outside ambient temperature was placed in front of the HFM module for 30 s to estimate black body emission at the current environmental conditions and establish background flux. Upon entry into the structure, the firefighter equipped with the portable measurement and data acquisition system followed the company of firefighters throughout the training exercise as the temperature and incident heat flux measurements from the immediate thermal environment were being recorded. This study involved human subject research, and its methods were approved by the University of Illinois Institutional Review Board.

(a) North side of Structure A



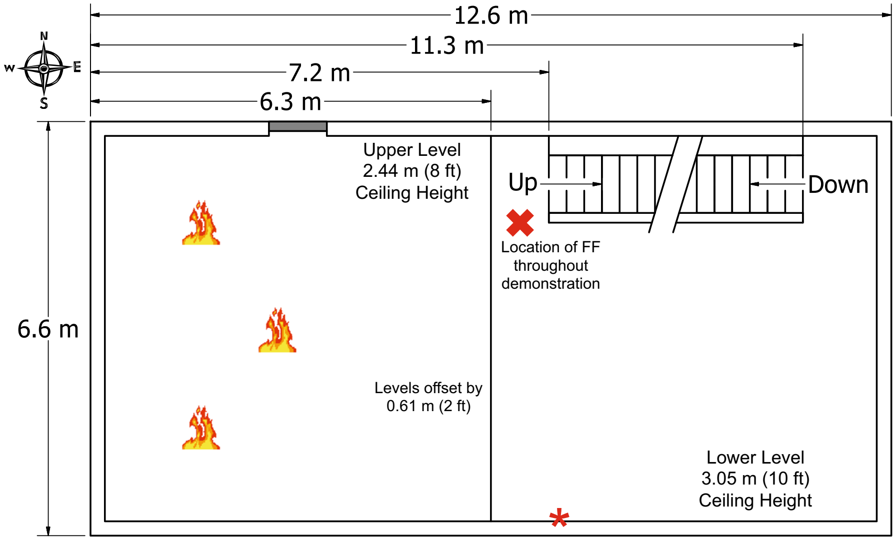
(b) Exercise 5 layout on second floor of Structure A

Figure 6. (a) Image of Structure A and (b) the approximate path taken by the training company (*red dashed lines*) and approximate locations of the fire sets (*flame*) and stationary thermocouple arrays (*red '*'*) on the second floor of Structure A during Exercise 5 (Color figure online).

3.1. Live-Fire Training Exercises

Data were collected from a total of five different *NFPA 1403* compliant coordinated fire ground training exercises (denoted as Exercises 1–5), all of which were conducted in a concrete-and-steel live-fire training structure (Structures A and B) located at IFSI in Champaign, IL (Figures 6a, 7a). The coordinated attack scenar-

(a) Northeast corner of Structure B



(b) Fire behavior demonstration layout on second floor of Structure B

Figure 7. (a) Image of Structure B and (b) approximate locations of the firefighter equipped with portable measurement and data acquisition system (*red 'X'*), fire sets (*flame*), and stationary thermocouple array (*red '*'*) on the second floor of Structure B during the fire behavior demonstration (Color figure online).

ios all followed a similar procedure: the fire was ignited and allowed to develop for a duration determined by the instructor depending on heat and smoke levels that were appropriate for each scenario, and then the training company would enter the structure, perform their assigned task(s), and exit the structure once the task was complete. Assigned tasks included searching the structure, advancing a hose line into the structure to extinguish the fire, and forcing entry through doors and other barriers. The fuel loads for the five exercises consisted of wooden pallets and straw. Fire sizes varied widely within and between each scenario, depending on when the firefighters arrived to the room location (which depended on exterior operations, such as forcible entry, and hose movement time within the structure) as well as throughout the time they were working in the room (water is applied, but may not completely suppress the fires). Based upon previous experiments conducted by NIST to characterize the heat release rate of various wooden pallet and excelsior fuel load configurations [38], it can be estimated that the fire size never exceeded 3 MW for any of the studied scenarios. Characteristics of the five different exercises, such as the number of repeats, the structure in which it was conducted, and the average duration of an exposure for each exercise, are listed in Table 3. The same firefighter wore the portable data measurement and acquisition system for every exposure encountered during Exercises 1–4, and the system was rotated between two different firefighters during Exercise 5. The firefighter wearing the system closely followed the path of the firefighters in the training exercise for all exposures. However, for some of the exercises (see Table 3), the path taken by the firefighters was different for each exposure.

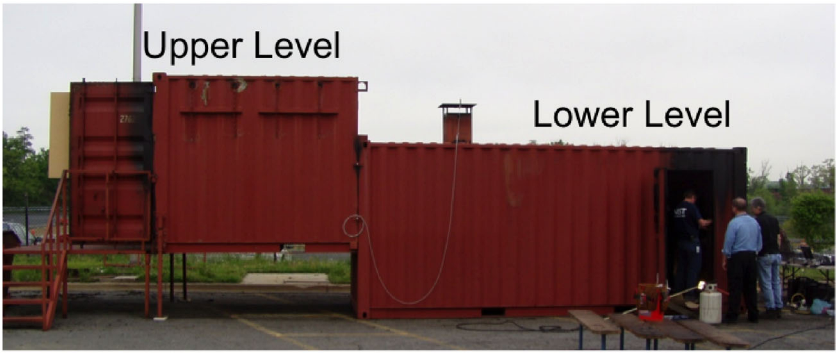
As an example of a typical scenario, Figure 6b shows the path taken by firefighters during Exercise 5 on a floor plan schematic of the second story of Structure A, including the approximate locations of the fire sets and the thermocouples installed in the structure walls. During Exercise 5, the training company was assigned to search the second floor of the structure, so a consistent path was followed during each exposure. Data were collected from the height of the crawling firefighters, approximately 0.9 m (3 ft) to 1.4 m (4.5 ft) above the floor.

During 14 of the live-fire experiments, the firefighter's local temperature measurements were compared to temperature data from stationary thermocouples extending 0.2 m (0.5 ft) into the rooms from the training structure walls. Thermocouples are located near the walls of the structure to cause minimal interference with the firefighters involved in the training exercise as is typical for this type of application. The 0.5 mm (0.02 in) bare bead thermocouples were located at heights of 0.2 m (0.5 ft), 1.2 m (4 ft), and 2.4 m (8 ft) above the floor near the wall of each room or hallway of the structure, and the data were acquired and recorded using a stationary logger [30]. This sparse distribution of thermocouples within the structure is typical of that found in the few structures that do characterize temperatures during live-fire training. While research grade instrumentation is typically employed, the ability to deploy these sensors is limited by the firefighters' need to move through the structure while using and deploying fire fighting tools.

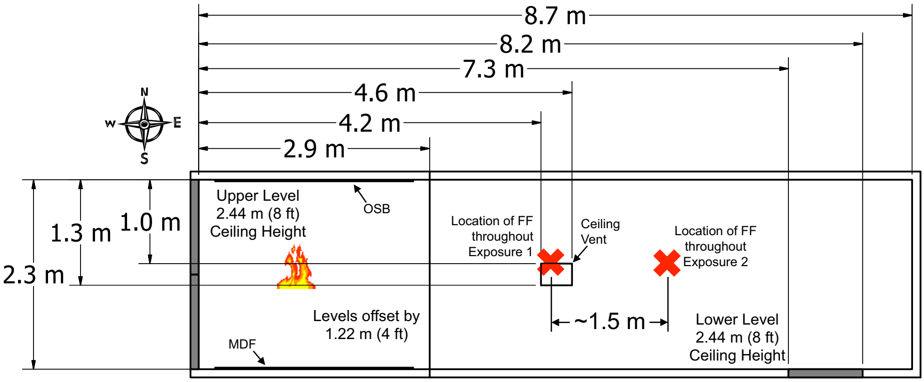
Table 3
Summary of All Scenarios

Exercise	Repeats	Structure	Average duration $\pm$ StdDev (min)	Brief description
Live-fire training exercises				
1	4	A	11 ± 2	1st floor of structure; same general path around one room; one fuel package in middle of room
2	3	A	9 ± 4	1st floor of structure; different paths through 2–3 rooms; three fuel packages
3	2	B	15 ± 1	2nd to 4th floors of structure; different path during each exposure; fuel packages on 2nd and 3rd floors
4	6	A	11 ± 3	2nd floor of structure; same general path around one room; one fuel package in middle of room
5	7	A	13 ± 5	2nd floor of structure; path and fuel package locations shown in Figure 6b

Label	Repeats	Structure	Average duration (min)	Brief description
Fire behavior demonstrations				
FB	1	B	14	Firefighter on 2nd floor of structure; three fuel packages close together; firefighter stationary throughout
FL	2	C	19 ± 2	Firefighter on lower level; fire on upper level; firefighter stationary throughout



(a) Image of typical "flashover simulator"



(b) Fire behavior demonstration layout for Structure C

Figure 8. (a) Image of ''flashover simulator'' and (b) approximate locations of the firefighter equipped with portable measurement and data acquisition system (*red 'X'*) and location of fire set (*flame*) in Structure C during the ''flashover simulator'' fire behavior demonstration (Color figure online).

3.2. Fire Behavior Demonstrations

Two different, but common, fire behavior demonstrations were studied using Structure B in Figure 7 (using only the second floor of the simulated six-story high-rise structure) and Structure C, a typical steel-container-based "flashover simulator" (Figure 8). In both scenarios, firefighters remained stationary for the majority of the demonstration. The firefighter wearing the portable measurement and data acquisition system was in a position such that data were collected from heights of approximately 0.9 m (3 ft) to 1.2 m (4 ft) above the floor.

Figure 7b shows the approximate location of the fire sets and the area from which data were collected during the fire behavior demonstration in Structure B. The demonstration lasted approximately 15 min and involved igniting the fuel load (wooden pallets and straw); letting the fire develop and allowing "rollover" to occur; suppressing the fire with a water stream from a smooth bore nozzle; and then repeating the process using a combination nozzle set to the wide fog stream pattern.

Two exposures using Structure C, the "flashover simulator", were studied during a training exercise at an IFSI Regional Training Site in Frankfort, IL. The "flashover simulator" contains two levels: the lower level where the training company was located throughout the duration of each exposure and the upper level where the fuel load was located. Both exposures used identical fuel loads: two wooden pallets and straw in a fire set located in the middle of the upper level; one 1.9 cm × 1.2 m × 2.4 m (0.75 in × 4 ft × 8 ft) sheet of oriented strand board (OSB) against a side wall of the upper level; and one 1.9 cm × 1.2 m × 2.4 m (0.75 in × 4 ft × 8 ft) sheet of medium density fiberboard (MDF) against the adjacent wall of the upper level. Each experiment began by igniting the middle fire set and allowing the fire to develop and rollover to the lower level. Ventilation conditions were varied and small amounts of water were applied to the fire several times to demonstrate the impact of changing these parameters. During Exposure 1, data were collected from the perspective of a firefighter near the front of the training company (closer to the source) and during Exposure 2, data were collected from the perspective of a firefighter located towards the back of the training company.

4. Results and Discussion

4.1. Live-Fire Training Exercises

Data collected from the five different typical live-fire training exercises are summarized in Tables 4 and 5.

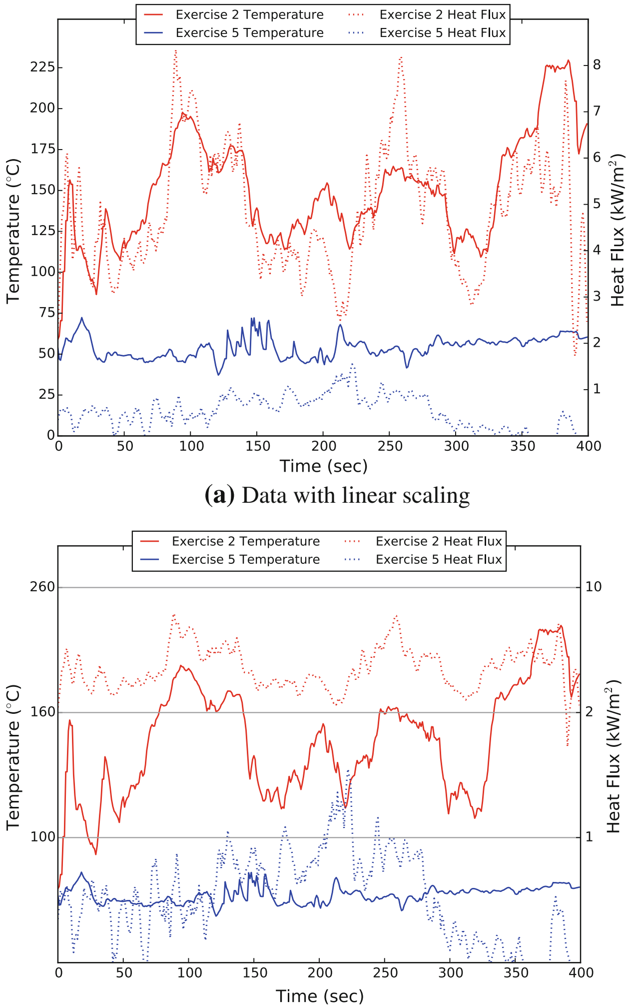
Throughout Exercises 1–5, more severe thermal exposures were characterized by ambient temperatures generally between 150°C and 200°C (Class II and III) and incident heat fluxes between 3 kW/m^2 and 6 kW/m^2 (Class III), while moderate exposures consisted of ambient temperatures around 50°C (Class I) and incident heat fluxes less than 1 kW/m^2 (Class I). These values were determined based on the average and standard deviation of the top and bottom 10% of the heat flux and temperature measurements collected from Exercises 1–5. To provide a visual comparison of the range of different exposure conditions, data collected during a more severe exposure (Exercise 2) and data from a moderate exposure (Exercise 5) were plotted against time, as shown in Figure 9. These data provide the first time-resolved picture of a firefighter's typical thermal exposure while moving through a structure and conducting live-fire training. Qualitatively, there exists a positive correlation between the heat flux and temperature variations with time. However, the temperature data peaks and valleys tend to lag behind the peaks in heat flux and are not as severe. Furthermore, the ratio between these measures is not consistent between each training scenario. Even though the same types of fuels are used in all of these scenarios (straw and wood pallets), the varying quantity of fuel involvement (due to different levels of fuel consumption and water application) throughout each scenario will affect direct radiant load and smoke production.

Table 4
Local Heat Flux Data for Exercises 1–5

			NIST Thermal Class averages duration [mm:ss] (heat flux ± StdDev [kW/m^2])			
Exercise	Average ± StdDev (kW/m^2)	Maximum (kW/m^2)	I	II	III	IV
1	2.4 ± 1.4	11.1	01:33 (0.6 ± 0.3)	02:50 (1.5 ± 0.3)	06:07 (3.2 ± 1.2)	00:01 (10.8 ± 0.3)
2	2.5 ± 1.7	10.0	00:31 (0.6 ± 0.5)	04:16 (1.5 ± 0.2)	04:05 (3.9 ± 1.6)	00:00 (–)
3	1.4 ± 1.3	12.7	05:28 (0.2 ± 0.7)	05:03 (1.5 ± 0.3)	03:43 (2.8 ± 0.9)	00:01 (12.7 ± 0.0)
4	1.0 ± 1.1	6.9	05:32 (0.2 ± 0.7)	03:10 (1.5 ± 0.3)	01:39 (2.8 ± 0.6)	00:00 (–)
5	1.0 ± 0.7	8.8	07:55 (0.5 ± 0.3)	03:43 (1.4 ± 0.3)	01:10 (2.9 ± 1.2)	00:00 (–)

Table 5
Local Temperature Data for Exercises 1–5

			NIST Thermal Class averages duration [mm:ss] (temperature ± StdDev [°C])			
Exercise	Average ± StdDev (°C)	Maximum (°C)	I	II	III	IV
1	119 ± 28	180	03:32 (90 ± 8)	05:41 (126 ± 19)	01:18 (167 ± 4)	00:00 (–)
2	113 ± 45	230	03:41 (68 ± 16)	03:37 (130 ± 17)	01:34 (181 ± 16)	00:00 (–)
3	115 ± 47	238	06:38 (69 ± 13)	04:36 (138 ± 17)	03:01 (180 ± 17)	00:00 (–)
4	92 ± 20	162	07:44 (84 ± 14)	02:33 (116 ± 12)	00:03 (161 ± 1)	00:00 (–)
5	59 ± 12	137	12:33 (53 ± 16)	00:14 (116 ± 11)	00:00 (–)	00:00 (–)



(a) Data with linear scaling

(b) Data scaled to different thermal classes

Figure 9. Local temperature and heat flux (moving average of 5 s) of a more severe thermal environment (Exercise 2) and a moderate thermal environment (Exercise 5) encountered during the various typical response live-fire training exercises.

It has been reported that surface cracking of a firefighter's SCBA facepiece can begin to occur at temperatures around 180°C and at an exposure to a heat flux of 5 kW/m^2 for a minimum of 12 min [35]. Firefighter radios begin to experience performance problems (drift of signal frequency, failure to transmit, etc.) when exposed to Class II/III conditions at 160°C for 15 min [39]. While some environments encountered during Exercises 1–5 contained temperatures and heat fluxes that exceeded these values, exposure levels varied throughout each training evolution and were not maintained at these levels continuously for the stated durations. Intermittent cooling occurred as the firefighter moved through the training evolution to areas with lower intensity heat flux exposure. So, no degradation of the firefighter's PPE or radio was observed during the exposures.

In Tables 4 and 5, the exposure duration is parsed into the average time spent in each of the NIST Thermal Classes for Exercises 1–5. Based on the temperature criteria in Table 1, no evolution exposed the firefighters to thermal conditions that exceed the maximum times associated with each NIST Thermal Class. Using the heat flux criteria, however, firefighters were exposed to Class III conditions longer than the suggested maximum time (5 min) for 7 of the 22 exposures encountered during Exercises 1–5. The longest exposure for a Class III thermal environment based on heat flux criteria was 8 min and 18 sec at an average heat flux of 4.1 kW/m^2. It is important to note that the durations listed for each class do not typically represent a continuous amount of time at that level; as firefighters moved throughout the structure, exposure to varying levels of thermal environments occurred. For example, considering only the temperature data from Exercise 2 in Figure 9b, Class III conditions were encountered between 79 s and 143 s; 248 s and 251 s; 253 s and 262 s; and 335 s and 400 s, for a total time of 141 s in Class III conditions. However, the longest amount of continuous time in Class III conditions was 65 s (the period from 335 s to 400 s). So, for all environments studied during Exercises 1–5, the longest *continuous* exposure to conditions at or above Class III during Exercises 1–5 was 2 min and 55 s. The intermittent thermal exposure conditions studied here may have allowed the firefighter's SCBA facepeice and other PPE to dissipate some built up heat due to the interior air movement which prevented any visual damage to the firefighter's PPE to occur.

As these results and the tabulated average NIST Thermal Class durations suggest, classifying an exposure using the heat flux criteria portrays a more severe exposure than if the temperature criteria were used to characterize the same environment. In fact, for every exposure encountered during Exercises 1–5, using the heat flux criteria suggested longer exposures to Class II–IV conditions than when using the temperature criteria. This result indicates that solely using temperature measurements to monitor a thermal environment in live-fire training scenarios may not be sufficient to predict risk to firefighters and that other measurements, such as heat flux, should be considered.

4.1.1. Comparison of Structure Temperatures to Immediate Environment Temperatures For 14 of the live-fire experiments conducted during Exercises 1–4, stationary temperatures were measured at the structure walls as described in Sect. 3.1. For each experiment, the fire was approximately located in the middle of the room. The temperatures measured by the thermocouples in the stationary array were compared to the ambient temperature data collected from the firefighter's immediate thermal environment. The firefighters participating in the training exercises were crawling for the majority of the exposure, so the thermocouple used to measure the ambient temperature of the firefighter's immediate environment was generally 0.9 m (3 ft) to 1.4 m (4.5 ft) above the floor.

Table 6
Average Ambient Temperature of Firefighter's Local Thermal Environment and Average Temperatures Measured by the Wall-Mounted Thermocouples at Heights of 1.2 m (4 ft) and 2.4 m (8 ft) for 14 Exposures

	Average temperature ± StdDev (°C) at		
Training exercise • exposure number	Firefighter local	Room at 1.2 m	Room at 2.4 m
1.1	119 ± 27	42 ± 10	150 ± 31
1.2	121 ± 30	22 ± 5	115 ± 40
1.4	95 ± 11	53 ± 5	65 ± 12
2.1	143 ± 35	54 ± 25	273 ± 58
2.2	101 ± 47	17 ± 3	143 ± 56
2.3	87 ± 20	24 ± 3	92 ± 20
3.1	103 ± 47	41 ± 4	88 ± 30
3.2	127 ± 45	47 ± 7	101 ± 27
4.2	96 ± 15	99 ± 16	160 ± 48
4.3	89 ± 25	116 ± 9	198 ± 18
4.4	84 ± 16	64 ± 1	142 ± 13
4.6	78 ± 21	69 ± 2	79 ± 3
4.7	121 ± 19	76 ± 10	118 ± 21
4.8	96 ± 8	73 ± 4	103 ± 7

Table 6 contains the average ambient temperature measured by the portable measurement system and the average temperatures measured by the wall-mounted thermocouple array at heights of 1.2 m (4 ft) and 2.4 m (8 ft) above the floor during the 14 exposures. Based on the local measurement position, one would expect the thermocouple at the 1.2 m location to provide the most likely estimate for the firefighter operating location. However, for 12 of the 14 exposures, the temperature of the firefighter's local environment was greater than the temperature measured at 1.2 m (4 ft) above the floor for at least 89% of the duration of the exposure. For 5 of these 12 exposures (2.1, 2.2, 2.3, 4.4, and 4.8), the temperature of the firefighter's local environment was between the temperatures at 1.2 m (4 ft) and 2.4 m (8 ft) above the floor for over 75% of the time, and for 3 of the 12 exposures (1.4, 4.6, and 4.7), the local environment temperature was greater than the temperature at the 2.4 m (8 ft) level for more than 75% of the duration.

Correlations between the temperature data sets collected during the 14 exposures were calculated. In general, the correlations between the fixed thermocouples and local temperatures were poor, though the data from the 2.4 m temperatures averaged a higher positive correlation with the temperature data from the firefighter's local environment (0.387) than the data from 1.2 m above the floor (0.280). However, the range of calculated correlation coefficients is quite large (−0.618 to 0.943) for both temperature data sets, suggesting that changes in the local temperature measured by fixed building thermocouples does not provide a reliable indication of the changes in a firefighter's local temperature.

For all the exposures considered, the fire was located approximately in the middle of the room, while the stationary thermocouples were near the walls. The concrete structure can act as a local heat sink and the distance from the fire source provides an opportunity for significant mixing of the plume gases with ambient air. Thus, local readings when the firefighter is closer to the fire are expected to be significantly higher than the stationary sensor readings. The temperatures measured by the thermocouple array at the 1.2 m level appear to represent, at best, a lower bound of the temperature of the immediate environment of firefighters in the studied training exercises. For the majority of the exposures considered, the firefighter's local ambient temperature was between the temperatures measured at 1.2 m (4 ft) and 2.4 m (8 ft) levels, or at heights greater than the approximate height of the firefighter's immediate environment in the training scenario (e.g., Figure 10). The firefighter's local temperatures measured here were within the 100°C to 190°C range established by Rossi as the approximate temperature range in training fires at 1 m (3.3 ft) off the ground [16]. Rossi's data were acquired approximately 1 m to 2 m (3.3 ft to 6.6 ft) from the fire set in order to approximate the firefighter's exposure. While this may provide a better approximation for the more intense conditions experienced by the firefighters compared to the wall mounted thermocouples at 1.2 m (4 ft), such an approach would be difficult to reliably utilize in a training environment where firefighters are moving. Further, the heat flux values reported by Rossi are significantly higher than the portable system's measurements reported here, likely due to the consistent and close proximity to the fire set in the former study. It is imperative that anyone using building temperatures to monitor a live-fire training environment (e.g. safety officer) understands the limitations of the data and uses it only in an advisory manner to maintain a safe training environment. The typical deployment of these sensors is not sufficiently dense within the buildings to describe the fire environment. However, a few thermocouples in the walls are the best-case scenario currently utilized in burn structures.

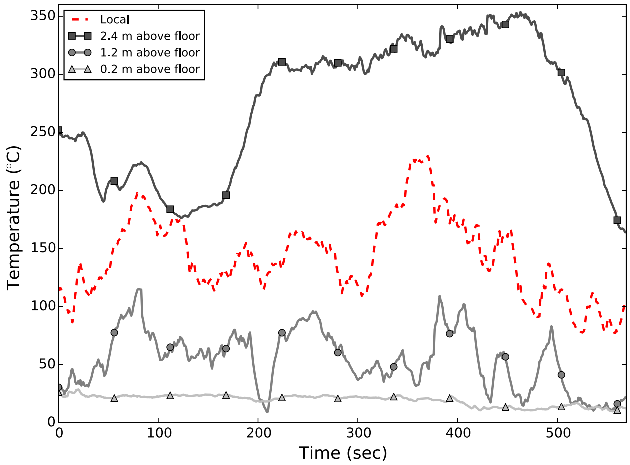


Figure 10. Local temperature of the firefighter's immediate environment and temperature data from the stationary thermocouple array in Structure A during Exercise 2.

These temperature comparisons also provide useful information for investigators designing research protocols for physiological testing of firefighters. Studies, such as those conducted in live-fire training buildings, have reported ambient temperatures at the 1.2 m (4 ft) level as approximately 71°C to 82°C [22], which is near the upper end of the average temperatures reported in Table 6 at 1.2 m (4 ft). However, these values are typically lower than the average temperatures of the firefighter's local environment during the same exposures. Laboratory-based physiological test scenarios (which are often necessitated due to sensitive equipment) are typically performed at temperatures around 35°C to 50°C. While these values match the lower end of the 1.2 m (4 ft) building temperature conditions, they do not approximate the firefighter's local exposure conditions. Furthermore, these physiology-focused studies typically employ temperatures that are relatively constant, which is different than the continuously varying temperatures typically encountered on the training ground (Figure 9). As Selkirk and McLellan [23] have shown, physiological responses to activities in PPE are affected by the temperature of the environment, so these differences should be considered in future iterations of firefighter physiological studies where possible. Finally, the effect of heat flux on firefighter physiological responses has not been studied to the same level of detail as exposure to high ambient air temperature environments.

4.2. Fire Behavior Demonstrations

4.2.1. Traditional Fire Behavior Demonstration The traditional fire behavior demonstration in Structure B resulted in firefighter exposure conditions shown in Figure 11. Table 7 summarizes the average and maximum heat fluxes and temperatures measured during the experiment along with the duration spent in each NIST Thermal Class based on both criteria.

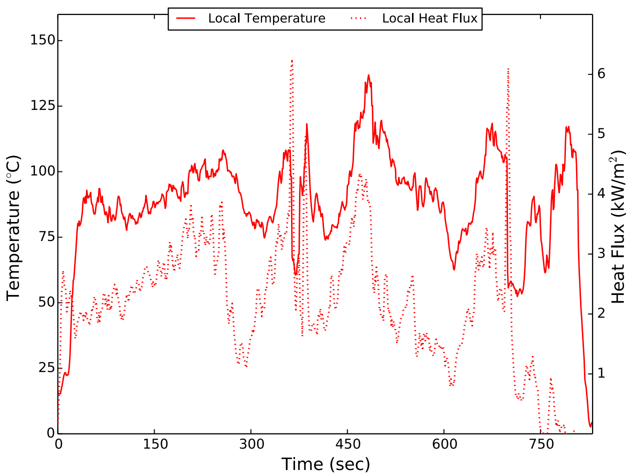


Figure 11. Local temperature and heat flux (moving average of 5 s) of the firefighter's immediate environment measured during the fire behavior demonstration in Structure B.

Table 7
Local Heat Flux and Temperature Results from fire Behavior Demonstration in Structure B

		NIST Thermal Class averages duration [mm:ss] (heat flux ± StdDev [kW/m^2])			
Average ± StdDev (kW/m^2)	Maximum (kW/m^2)	I	II	III	IV
Heat flux results					
2.1 ± 1.3	10.0	02:12 (0.0 ± 0.9)	03:48 (1.6 ± 0.3)	07:51 (2.9 ± 0.9)	00:00 (–)
		NIST Thermal Class average duration [mm:ss] (temperature ± StdDev [°C])			
Average ± StdDev (°C)	Maximum (°C)	I	II	III	IV
Temperature results					
87 ± 21	136	10:34 (80 ± 19)	03:17 (110 ± 8)	00:00 (–)	00:00 (–)

Compared to the live-fire training exercises, the thermal environment encountered during the traditional fire behavior demonstration in Structure B was defined by relatively moderate temperatures averaging 87°C (Class I) and reaching a maximum of 136°C (Class II) and moderate to severe incident heat fluxes averaging 2.1 kW/m^2 (Class III) and reaching a maximum of 10.0 kW/m^2 (Class III/IV). The average heat flux was typically higher than the coordinated fire attack scenarios, yet the average temperature was near the lowest levels encountered during the coordinated attack scenarios. In fact, based on the NIST Thermal Class heat flux criteria, the firefighters were exposed to Class III conditions for 7 min and 51 s, which exceeds the maximum suggested time of 5 min (as with the coordinated attack scenarios, the firefighter did not experience a continuous exposure to these levels). On the other hand, the conditions never entered the Class III region based on the temperature criteria. Figure 11 shows significant reductions in temperature at approximately 375 s and 675 s when water is applied to the fire. These breaks in the high temperature and heat flux conditions may have been enough to keep PPE damage from occurring. It is interesting to note that a sharp spike in local heat flux is experienced each time water is briefly applied to the fire. This phenomenon is attributed to convective heat transfer due to steam generation in the relatively small, enclosed room and close proximity to the fire set.

4.2.2. "Flashover Simulator" Fire Behavior Demonstrations Figure 12a, b contain plots of the ambient temperature and heat flux as a function of time for Exposures 1 (firefighter located closer to the fire set) and 2 (farther from the fire set), respectively, for the "flashover simulator" fire behavior demonstration in Structure C. Tables 8 and 9 list the average and maximum heat fluxes and ambient temperatures of the firefighter's immediate environment for each of the two exposures along with the total amount of time spent in each NIST Thermal Class.

Once again, using the ambient temperature data to define the thermal environment of each exposure produces drastically different results than using the incident heat flux data. Based on ambient temperature data, the environment of the "flashover simulator" training exercise was quite mild, with average ambient temperatures of 38°C and 51°C (Class I). Class II conditions were experienced for a total of 6 s during Exposure 1 and for a total of 4 s during Exposure 2, each instance occurring at the very end of the exposure when the firefighter stood up to exit the container. However, the incident heat flux data from the two exposures suggest the environment of the "flashover simulator" training exercise was severe, containing average heat fluxes of 3.0 kW/m^2 and 2.3 kW/m^2 (Class III in both cases) and maximum heat fluxes of 11.3 kW/m^2 and 8.3 kW/m^2 (Class IV and III, respectively) for each exposure. Additionally, the NIST Thermal Class durations generated using the heat flux data suggested that firefighters were in conditions that exceeded the Class III maximum recommendation (5 min) for each exposure.

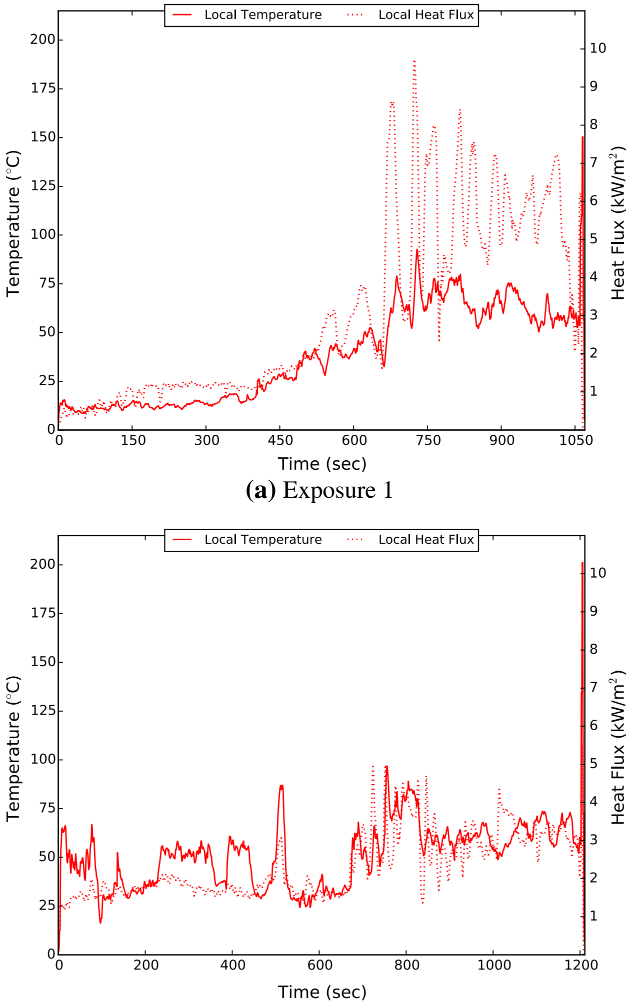
To further visualize the differences in NIST Thermal Classifications based on heat flux and temperature data, kernel density estimations (KDEs) were calculated to estimate the probability density functions of the heat flux and temperature data sets from each of the three fire behavior demonstration exposures (Figure 13).

Table 8
Local Heat Flux Results from ''Flashover Simulator'' Fire Behavior Demonstration Exposures in Structure C

			NIST Thermal Class average duration [mm:ss] (heat flux ± StdDev [kW/m^2])			
Exposure number	Average ± StdDev (kW/m^2)	Maximum (kW/m^2)	I	II	III	IV
1	3.0 ± 2.5	11.3	02:52 (0.6 ± 0.4)	06:10 (1.3 ± 0.3)	08:44 (4.9 ± 1.9)	00:04 (11.0 ± 0.3)
2	2.3 ± 0.9	8.3	00:11 (−0.3 ± 1.4)	10:08 (1.7 ± 0.2)	09:52 (3.1 ± 0.8)	00:00 (–)

Table 9
Local Temperature Results from ''Flashover Simulator'' Fire Behavior Demonstration Exposures In Structure C

			NIST Thermal Class average duration [mm:ss] (temperature ± StdDev [°C])			
Exposure number	Average ± StdDev (°C)	Maximum (°C)	I	II	III	IV
1	38 ± 24	150	17:44 (38 ± 23)	00:06 (122 ± 20)	00:00 (–)	00:00 (–)
2	51 ± 17	201	20:07 (51 ± 15)	00:02 (135 ± 0)	00:02 (201 ± 0)	00:00 (–)



(a) Exposure 1

(b) Exposure 2

Figure 12. Local temperature and heat flux (moving average of 5 s) of the firefighter's immediate environment during the two ''flashover simulator'' fire behavior demonstration exposures in Structure C.

The KDEs demonstrate the effect of the large radiant heat loading component of the fire behavior demonstrations, specifically on how these scenarios are classified by the NIST Thermal Classifications. The differences between the temperature and heat flux classifications are more extreme in the fire behavior demonstrations than the differences observed during Exercises 1–5. Compared to the coordinated attack scenarios, the fire behavior scenarios exposed firefighters to the highest heat flux conditions, yet also to the lowest ambient air temperature. Fire behavior scenarios typically involve larger radiant heat fluxes with less smoke (at least at the

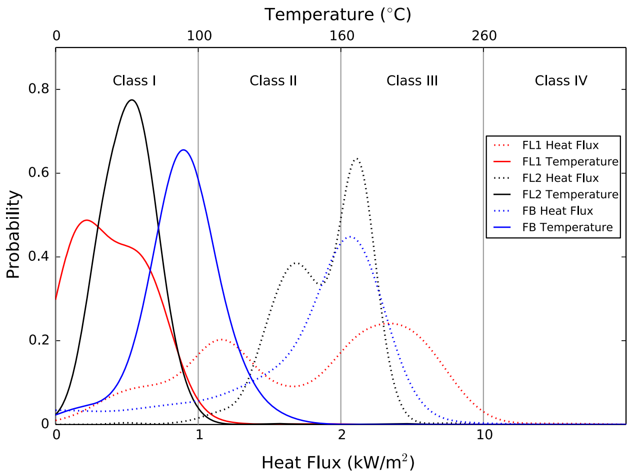


Figure 13. Estimated probability density functions for the National Institute of Standards and Technology Thermal Classes based on heat flux and temperature data from the Structure B traditional (FB) and Structure C ''flashover simulator'' (FL) fire behavior demonstrations.

trainee level) than the attack scenarios. While these demonstration scenarios provide great opportunities for firefighters to learn fire behavior in an immersive setting, it also exposes firefighters to conditions that can lead to PPE—particularly SCBA and helmet—damage and potential risk for increased thermal storage in bunker coats.

One important, yet unexpected, outcome from the ''flashover simulator'' scenario was that towards the end of Exposure 1, the SCBA facepiece of the firefighter equipped with the portable measurement and data acquisition system began to form bubbles (the firefighter immediately left the structure upon noticing this damage). A picture of the damaged facepiece is shown in Figure 14. Although the ambient temperature data indicate an extremely mild environment was present during the ''flashover simulator'' exercise and the firefighters participating in the exercise felt no physical discomfort, the thermal environment was quite severe.

According to Putorti et al, an SCBA facepiece can begin to bubble when exposed to a heat flux of 5 kW/m^2 for approximately 12 min or 7 kW/m^2 for 6 min [35]. During Exposure 1, bubbling of the facepiece began to occur after roughly 9 min of Class I and Class II heat flux exposures (average of 1.1 kW/m^2) followed by less than 9 min of Class III heat flux exposures containing an average of 5.0 kW/m^2. Preheating of the SCBA facepiece during the initial Class I and II conditions likely contributed to the earlier onset of damage at this heat flux level (i.e. 9 vs. 12 min). Thus, predicting risk for damage to PPE should account for the entirety of the exposure conditions, even those that may be considered subcritical based on the NIST Thermal Classes. Interestingly, during Exposure 2, no degradation occurred after more than 10 min of Class II exposure averaging 1.7 kW/m^2 and just under 10 min of Class III conditions averaging 3.1 kW/m^2.

Figure 14. Image of the facepiece damaged during Exposure 1 of the ''flashover simulator'' demonstration.

Compared to Exposure 1, the second exposure contained a longer duration at Class III, yet no visible damage occurred. This outcome could suggest that conditions in this range may need to be studied more carefully in terms of risk for PPE damage. For example, Foster and Roberts [12] propose slightly different exposure criteria where 'Hazardous Conditions' include heat fluxes from 1 kW/m^2 to 4 kW/m^2 while 4 kW/m^2 to 10 kW/m^2 would be considered 'Extreme Conditions'.

As shown repeatedly in these training scenarios and demonstrations, the measured heat flux suggests a more severe environment than the temperature measurements. In this case, the local temperature measurements indicate a very mild environment, yet fire fighting PPE was damaged. Only by measuring the local heat flux would we have any indication that these conditions reach the Class III level and present risk for such damage. While temperature measurements can be made in a simple and cheap manner, it appears more valuable to characterize the fire environment by the relatively expensive heat flux measurements.

5. Conclusions and Future Works

In order to effectively measure the heat flux and ambient temperature of a firefighter's local environment during live-fire training exercises, a portable measurement and data acquisition system was created and integrated into firefighter PPE.

Laboratory experiments were conducted at NIST to calibrate and characterize the variability associated with the HFM module of the portable measurement and data acquisition system compared to a NIST-traceable Schmidt–Boelter total heat flux gauge. The portable system was then used to measure the temperature and incident heat flux of a firefighter's immediate thermal environment in numerous live-fire training scenarios.

Of the environments encountered during the training exercises, the most severe thermal environments were typically defined by ambient temperatures generally between 150°C and 200°C and incident heat fluxes between 3 kW/m^2 and 6 kW/m^2, while the less severe environments consisted of ambient temperatures generally around 50°C and incident heat fluxes around 1 kW/m^2.

NIST Thermal Class definitions were used to better establish exposure severity of every live-fire training environment studied. For every exposure, heat flux data produced higher estimates for severity of exposure than those derived from temperature data. The difference in the exposure estimates was most extreme during the "flashover simulator" training exercise. Of particular interest, minor damage occurred to an SCBA facepiece in conditions in the Class I range based on temperature criteria, but Class III based on heat flux criteria.

Finally, the temperature data collected from the training structure's wall mounted, stationary thermocouple array represented only a rough approximate bound of the actual temperature of the immediate training environment. For the majority of the exposures studied, the actual local temperature of the crawling firefighter was between the temperatures measured at the 1.2 m (4 ft) and 2.4 m (8 ft) levels. Those using thermocouples to monitor the thermal conditions of a live-fire environment must understand the limitations of this measurement.

The portable measurement and data acquisition system that has been developed and proven effective during this project may play a significant role in future research such as studying other types of training scenarios (gas-fed burners, proximity or wildland fire fighting, etc.) or to study the impact of fire service tactics and strategies. Considering the lack of agreement between firefighter worn local and building installed temperature measurements, as well as the absence of congruence between temperature and local heat flux measurements, a useful future investigation could study improved methods of fixed environmental monitoring techniques, such as plate thermometers. Combining this thermal mapping capability with 3D firefighter tracking tools might also provide great additional insight into the locations where peak temperatures and heat flux exposures are encountered.

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