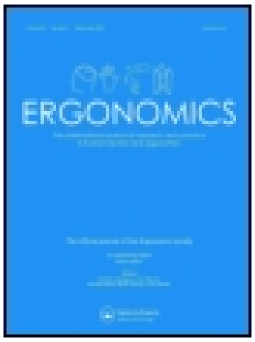

Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

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To cite this article: Gavin P. Horn, Richard M. Kesler, Steve Kerber, Kenneth W. Fent, Tad J. Schroeder, William S. Scott, Patricia C. Fehling, Bo Fernhall & Denise L. Smith (2017): Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic, Ergonomics, DOI: 10.1080/00140139.2017.1355072

To link to this article: http://dx.doi.org/10.1080/00140139.2017.1355072

ERGONOMICS, 2017
https://doi.org/10.1080/00140139.2017.1355072

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Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic

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ABSTRACT

Firefighters' thermal burden is generally attributed to high heat loads from the fire and metabolic heat generation, which may vary between job assignments and suppression tactic employed. Utilising a full-sized residential structure, firefighters were deployed in six job assignments utilising two attack tactics (1. Water applied from the *interior*, or 2. Exterior water application before *transitioning* to the interior). Environmental temperatures decreased after water application, but more rapidly with transitional attack. Local ambient temperatures for inside operation firefighters were higher than other positions (average ~10–30 °C). Rapid elevations in skin temperature were found for all job assignments other than outside command. Neck skin temperatures for inside attack firefighters were ~0.5 °C lower when the transitional tactic was employed. Significantly higher core temperatures were measured for the outside ventilation and overhaul positions than the inside positions (~0.6–0.9 °C). Firefighters working at all fireground positions must be monitored and relieved based on intensity and duration.

Practitioner Summary: Testing was done to characterise the thermal burden experienced by firefighters in different job assignments who responded to controlled residential fires (with typical furnishings) using two tactics. Ambient, skin and core temperatures varied based on job assignment and tactic employed, with rapid elevations in core temperature in many roles.

ARTICLE HISTORY
Received 11 January 2017
Accepted 7 July 2017

KEYWORDS
Firefighting; core temperature; heat stress; heat strain; body temperature

1. Introduction

Heat stress is one of the most common challenges that firefighters routinely encounter. Because firefighters perform strenuous work while wearing heavy, insulating personal protective equipment (PPE), a rise in body temperature almost always accompanies firefighting activity. High heat loads from the fire can also add to the heat stress experienced by firefighters. The physiological and thermal strain of firefighting activities have been documented based on simulated fireground work. The change in core temperature associated with firefighting activities has been reported by several research groups (Colburn et al. 2011; Horn et al. 2013; Hostler et al. 2010; Walker et al. 2015). Firefighting involves strenuous work that leads to maximal or near-maximal heart rates (HR) and, in some cases, rapid changes in core temperature (Tco) (Barr, Gregson, and Reilly 2010). Horn et al. (2011), reported average changes of 0.70 °C during short bouts of firefighting activity typical of residential 'room and contents' fires. The researchers noted that repeated bouts of firefighting or the use of multiple cylinders of air is associated with further increases in body temperature. It is important to note, however, the vast majority of work that has been done characterising the thermal stress of firefighting has occurred during training fires or in controlled laboratory conditions. Training fires differ considerably from residential fires in terms of the geometry of the structure, building materials and fuel loads. Because of these factors, firefighters may experience different thermal environments, as well as different chemical exposures, during actual fires in residential buildings than in a training burn. Recent measurement of ambient temperatures inside common structure fires have further detailed risks posed by firefighting activities in modern structure fires (Kerber 2013). However, these studies have not included human subjects. Portable thermal data acquisition systems carried by firefighters have

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been used to characterise risks faced by firefighters in live-fire training scenarios (Willi, Horn, and Madrzykowski 2016) and historically for firefighting activities that were largely exterior focused (Abeles, Delvecchio, and Himel 1973; Gempel and Burgess 1977). However, to date, these data acquisition systems have not been deployed in structure fire scenarios with typical residential fuel packages or linked to data from physiological status monitoring.

In order to investigate physiological responses to firefighting, many researchers (e.g. Havenith and Heus 2004; von Heimburg, Rasmussen, and Medbo 2006; Holmér and Gavhed 2007; Ilmarinen et al. 2008; O'Connell et al. 1986; Smith, Manning, and Petruzzello 2001) have each participant perform a set of 'typical' firefighting tasks, such as climbing stairs or ladders, advancing a hoseline, forcing a door, performing search and rescue, and completing overhaul tasks. These studies have been critical to advancing our understanding of the physiological strain associated with the various stressors that firefighters face. Unfortunately, such approaches that require performing 'typical' firefighting activities may obscure the fact that at actual fires, firefighters often perform distinct work and may operate in very different thermal environments depending on the jobs they are assigned to do. Smith and colleagues investigated cardiac strain during high-rise fireground operations and found that truck crews assigned to search and rescue operations and to material transport had different levels of cardiac strain than engine crews who were assigned fire suppression activities in a simulated fire scenario (Smith et al. 2015).

A primary goal of firefighting is to extinguish the fire to protect life and property. While this basic goal may seem obvious and straightforward to a civilian, the tactics used by the fire department to accomplish this goal may vary considerably. Based on an accumulating body of evidence, many fire departments are emphasising getting water on the fire as soon as possible to improve conditions inside the structure (Kerber 2013). Such an approach is often called a 'transitional' attack in which firefighters apply water through a window to initially suppress the fire before they enter the building to completely extinguish the fire and ensure there is no further fire growth. This approach contrasts with many departments that have been taught that it is best to enter the house through the front door with a charged hoseline. In theory, the goal of this 'interior' fire attack is to find the seat of the fire and extinguish it as soon as possible to protect potential victims. To date, there is no research that has considered the effect of different firefighting tactics on the firefighter's physiological responses to their work.

The increase in body temperature associated with firefighting is due to multiple factors, including, performance of heavy muscular work, the use of heavy insulative gear that adds to the metabolic work that is performed and that interferes with heat dissipation; and the high ambient temperatures (Smith, Manning, and Petruzzello 2001; Smith et al. 2016). Although some research has attempted to understand the effect of the ambient temperature (Smith et al. 1997) and the effect of PPE (Fehling et al. 2015) on body temperature, surprisingly little research has been done to investigate the effect of different thermal environments experienced by firefighters on body temperature responses.

The purposes of this study were to expand previous research on thermal responses of firefighters by (a) characterising the thermal environment in which firefighters operate in a modern residential fire with realistic fuel loads, (b) documenting the temperatures encountered by the firefighters in different job assignments, (c) evaluating core and skin temperature changes of firefighters assigned to different job assignments and (d) investigating the effect of firefighting tactic on the environmental conditions encountered and the temperature responses of firefighters.

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's (IFSI) Champaign campus (Horn et al. 2016). 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 Institutional Review Board. Forty ($n = 40$) firefighters (36 male, 4 female) from departments in Illinois, Georgia, Indiana, Ohio, South Dakota and Wisconsin participated in this study. The firefighters were 37.6 ± 8.9 years old, 1.80 ± 0.08 m tall, weighed 89.8 ± 14.5 kg and had an average BMI of 27.6 ± 3.4 kg/m^2 with an average of 14.9 ± 8.5 years of experience in the fire service.

All participants were required to have completed a medical evaluation consistent with National Fire Protection Association (NFPA) 1582 in the past 12 months. We recruited relatively experienced firefighters who had up to date training, could 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 (SCBA) prior to entering the structure. The research team supplied all PPE for the participants to enhance standardisation and to ensure that all protective equipment adhered to NFPA standards.

2.2. Study design

Teams of 12 firefighters were deployed to suppress fires in a realistic firefighting scenario that involved a multiple-room fire (two separate bedrooms) in a 111 m^2 residential structure. Each team of 12 firefighters worked in pairs to perform six different job assignments that included operations on the *inside* of the structure during active fire (fire attack and search & rescue), on the *outside* of the structure during active fire (command & pump operator and outside ventilation), and to conduct *overhaul* operations after the fire had been suppressed (firefighters searched for smouldering items and removed items from the structure). The job assignments are described in Table 1.

In all, 12 different trials were conducted (one per day) each with twelve firefighters as described above. The firefighters responded to two scenarios that differed only in the tactics used by the Inside Attack team: (a) traditional *interior* attack from the 'unburned side' (advancement through the front door to extinguish the fire) and (b) *transitional* attack (water applied into the bedroom fires through an exterior window – from the 'unburned side' – prior to advancing through the front door to extinguish the fire). The firefighters performed the same role using both tactics, then were reassigned to different job assignments and performed another two scenarios – again using the same two tactics on separate days. While most firefighters attended four sessions of the study ($n = 31$), a small group were only available for two sessions ($n = 9$) and one firefighter withdrew from the study and wasn't replaced until after the first two scenarios.

2.3. Study protocol

Following recruitment, participants completed all required paperwork and anthropomorphic measurements (height, weight) were collected. Firefighters received a core temperature pill that they ingested 6–12 h prior to data collection. Upon arrival on each day, firefighters were instrumented with skin temperature patches on the back of their neck and upper arm that they wore throughout the trial. Multiple pre- and post-firefighting cardiovascular measurements and chemical exposure samples (biological and PPE) were collected prior to the initiation of the live fire evaluation (these data will be reported elsewhere). The firefighter participants were then deployed to complete their firefighting work in a purpose-built live-fire research test structure.

In order to safely and reliably conduct this study, a structure was designed and built to have all of the interior finishes and features of a single family dwelling, yet contained specialised safety systems and hardened construction techniques that ensured participants' safety as described in Horn et al. (2016). The house was based on a design by a residential architectural company to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings. The home had an approximate floor area of 111 m^2, with 8 total rooms, including 4 bedrooms and 1 bathroom (closed off during experiments). Interior finishes in the burn rooms were protected by 15.9 mm Type X gypsum board on the ceiling and 12.7 mm gypsum board on the walls. To maximise the use of the structure and minimise time between experiments, the house was mirrored so that there were 2 bedrooms on each side where the fires were ignited. During each experiment a temporary wall was constructed at the end of the hallway to isolate 2 bedrooms so that they could be repaired and readied for the next experiment.

Furniture was acquired from a single source such that each room was furnished identically (same item, manufacture, make model and layout of all furnishings) for all 12 experiments. The bedrooms, where the fires were ignited, were furnished with a double bed (covered with a foam mattress topper, comforter and pillow), stuffed chair, side table, lamp, dresser and flat screen television. The floors were covered with polyurethane foam padding and

Table 1. Deployment protocol, job assignments and response times.

			Median time (min)	
Job assignment	Apparatus	Specific tasks	Outside structure	Inside structure
Outside command/pump	Engine 1	Incident command and operate the pump	20	0
Inside attack		Pull primary attack line (fire hose) from engine and suppress all active fire	3	8
Inside search	Truck 1	Forcible entry into the structure and then search for and rescue 2 victims (75 kg manikins)	2	8
Outside vent		Deploy ladders to the structure and create openings at windows and roof (horizontal and vertical ventilation)	19	0
Overhaul/backup	Engine 2	Pull a second attack line and support the first-in engine (from outside the structure) and then perform overhaul operations (remove drywall from walls/ceiling and furniture from room to locate any hidden fire) inside the structure after fire suppression	11	16
Overhaul/RIT		Set up as a rapid intervention team (RIT) and then perform overhaul operations inside the building after fire suppression	11	17

polyester carpet. All other rooms of the structure were also furnished to provide obstacles for the firefighter, but those furnishings were not involved in the fire. Figure 1 provides a rendering of the structure with the roof cut away to show the interior layout with furniture and floor coverings. The tan floor shows the carpet placement and the white floor shows the cement floor or simulated tile locations.

Fires were ignited in the stuffed chair in Bedrooms 1 & 2 (labeled Bedrooms 5 & 6 for the mirrored configuration) using a remote ignition device and a book of matches to create a small flaming ignition source. The flaming fire was allowed to grow until temperatures in the fire rooms reached levels determined to be near peak values based on pilot studies (i.e. room had 'flashed over'). When interior temperatures of both fire rooms exceeded 600 °C at the ceiling, the fire department dispatch was simulated and firefighters responded by walking approximately 40 metres from the data collection bay to the front of the structure. The time of dispatch was between 4 and 5 min after ignition for all 12 experiments.

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 Figure 1 and described in Horn et al. (2016). This report will focus on the thermal measurements.

Air temperature was measured with bare-bead, ChromelAlumel (type K) thermocouples with a 0.5 mm nominal diameter. Thermocouple arrays were located in every room. The thermocouple locations in the living room, dining room, hallway, Bedroom 4 and kitchen had an array of thermocouples with measurement locations of 0.3, 0.6, 0.9, 1.2, 1.5, 1.8 and 2.1 m above the floor. The thermocouple locations in Bedroom 1/5, Bedroom 2/6 and Bedroom 3 had an array of thermocouples with measurement locations of 0.3, 0.9, 1.5 and 2.1 m above the floor.

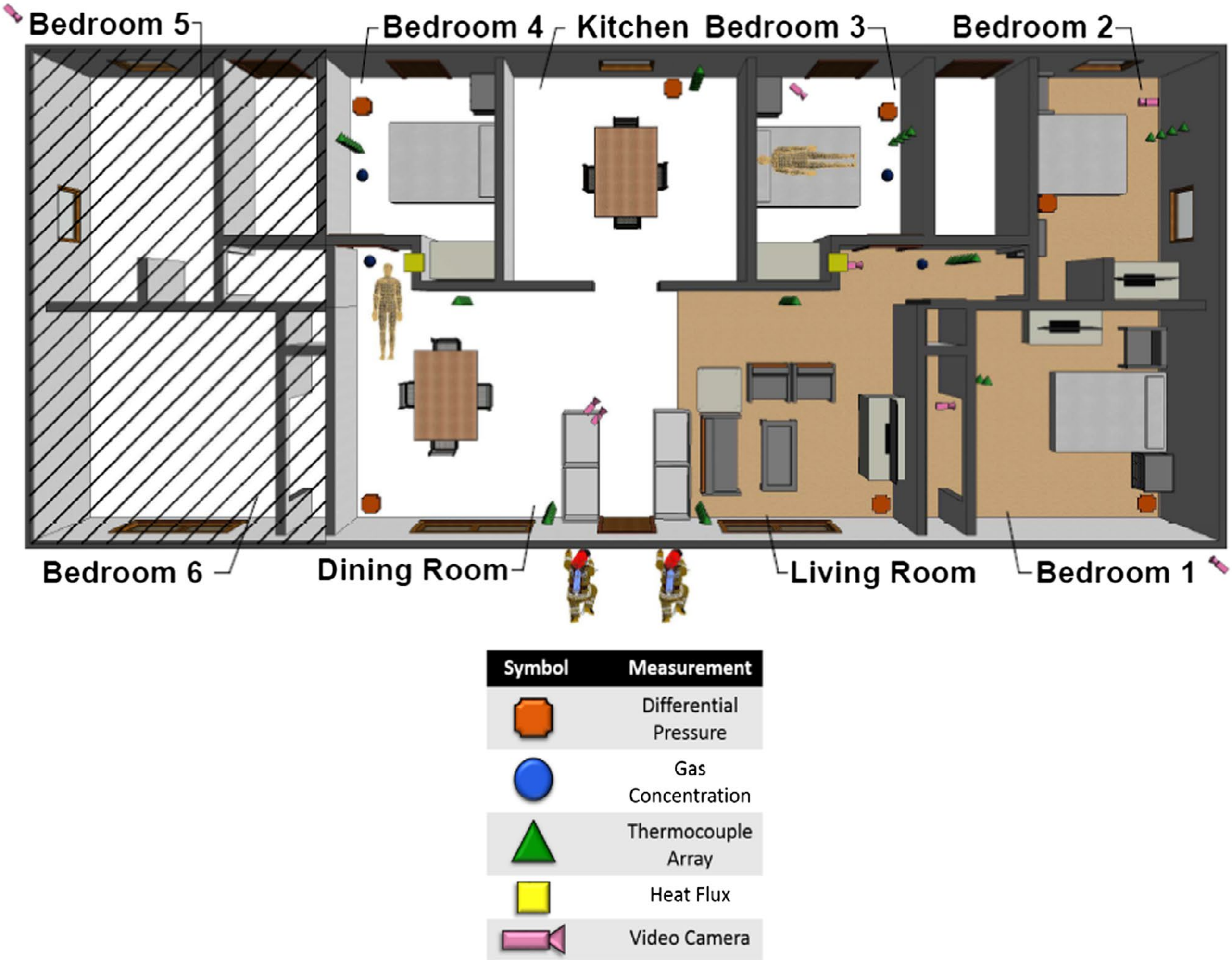

Figure 1. Schematic of data acquisition instrumentation location with the fire bedrooms (Bedroom 1 & 2) in the right side configuration.

Notes: The floor area with hash marks (Bedroom 5 & 6, part of hallway) was behind a movable false wall that could be moved to the same location on the opposite end of the structure to allow measurements on back-to-back days in a mirrored structure.

Heat flux (the speed of thermal energy transfer) measurements were made using a 25.4 mm nominal diameter water-cooled Schmidt-Boelter heat flux gauge. The gauges measured the combined radiative and convective heat flux. Heat flux was measured at 3 elevations: 0.3, 0.9 and 1.5 m above the floor in the hallway just outside Bedroom 3 and facing the fire in Bedroom 2. When the fire was on the opposite side of the structure, measurement locations were mirrored (outside bedroom 4, facing the fire in bedroom 5). These locations were chosen to characterise the heat flux a firefighter might face at a location where they can start to direct their water stream into both of the burning bedrooms from the interior.

2.4.2. Firefighter local temperatures

For each scenario, two of the firefighters operating at the front of their crews on the inside of the structure (nozzleman on the attack line and lead firefighter on the search team) wore a portable temperature sensor and data acquisition system affixed to the front of the helmet. Type K thermocouples with a 0.5 mm nominal diameter in conjunction with Omega Engineering UWTC wireless temperature sensors were used to monitor temperatures of firefighting crews. The wireless sensors incorporated internal cold junction compensation. Data was logged to an internal solid state memory and downloaded after each experiment. The sensors, programmed to a sampling rate of 0.5 Hz, synced to the main data acquisition system before each experiment. The resolution of the sensor was 1 °C, with an accuracy of 0.5% of the reading or 1 °C whichever is greater.

2.4.3. Assessment of firefighter core and skin temperature

Skin (neck and arm) and core body temperatures were continuously measured throughout all data collection sessions (Horn et al. 2016). A monitor (MiniMitter Vital Sense, Phillips Respironics, Bend, OR) was clipped to their belts before and after firefighting and carried in their bunker coat after donning their PPE. This unit communicated with and recorded data from the core temperature pill and local skin temperature patches. Participants swallowed a small disposable core temperature sensor capsule, which is designed to pass through the body and be eliminated in faeces within ~24 h. While the sensor was in the GI tract it transmitted temperature information to the remote recording device. If a firefighter retained a pill from a prior measurement day, the one ingested 6–12 h prior to activity was utilised for consistency.

2.5. Statistical analysis

Variables were checked for normal distribution using Shapiro-Wilk tests. A relatively small number of distributions were found not to be Gaussian, but differences between means and median values were typically less than 1%. Therefore, means and standard deviations are reported for results. Statistical comparisons were performed using parametric tests. Confirmatory analyses were conducted on log-transformed data for the few non-normal data-sets, which in all cases resulted in the same determination of statistical significance. Each of these analyses was performed in SPSS (v. 23 IBM, Armonk, NY) with significance set at an alpha of 0.05.

Data describing the environmental conditions within the structure at 0.9, 1.5 and 2.1 m above the floor are reported in various rooms of interest (Living Room, Dining Room, Hallway, Fire Bedrooms) for scenarios in which interior and transitional attack tactics were implemented. Maximum temperatures and hallway heat flux values recorded at each height and location throughout the structure are determined for the 'Interior attack' and 'Transitional attack' tactics and compared between these tactics using Student *t*-test to determine if conditions were similar prior to firefighter intervention. To characterise the impact of firefighting tactics on environmental temperatures, the values recorded from the same locations when firefighters arrived in the hallway were summarised and compared with a series of *t*-tests.

Local firefighter temperature exposures for the Inside job assignments were analysed using repeated measures 2 × 2 analysis of variance (ANOVA) to study the impact of specific Inside job assignment (Attack vs. Search) and tactic (Interior vs. Transitional). The average temperatures experienced by the Inside, Outside and Overhaul crews were compared using repeated measures ANOVA, followed by *post hoc t*-tests.

Finally, firefighters' skin and core temperatures exposures were analysed using repeated measures ANOVA to study the impact of four job assignments (Inside, Outside Command, Outside Vent and Overhaul) and tactic (Interior vs. Transitional), followed by *post hoc t*-tests where appropriate. Unfortunately, due to some 'lost' core temperatures pills near the beginning of the scenarios, loss of communications with sensors during data collection and skin temperature patches coming off due to heavy sweat, there was significant data loss. For these comparisons, we only report data from participants who had valid neck skin, arm skin and core temperature data for both Interior and Transitional attack scenarios ($n = 47$ of 72).

3. Results

3.1. Building temperature & heat flux profiles

Figure 2 provides example plots of the air temperatures at each of the 10 different measurement locations at

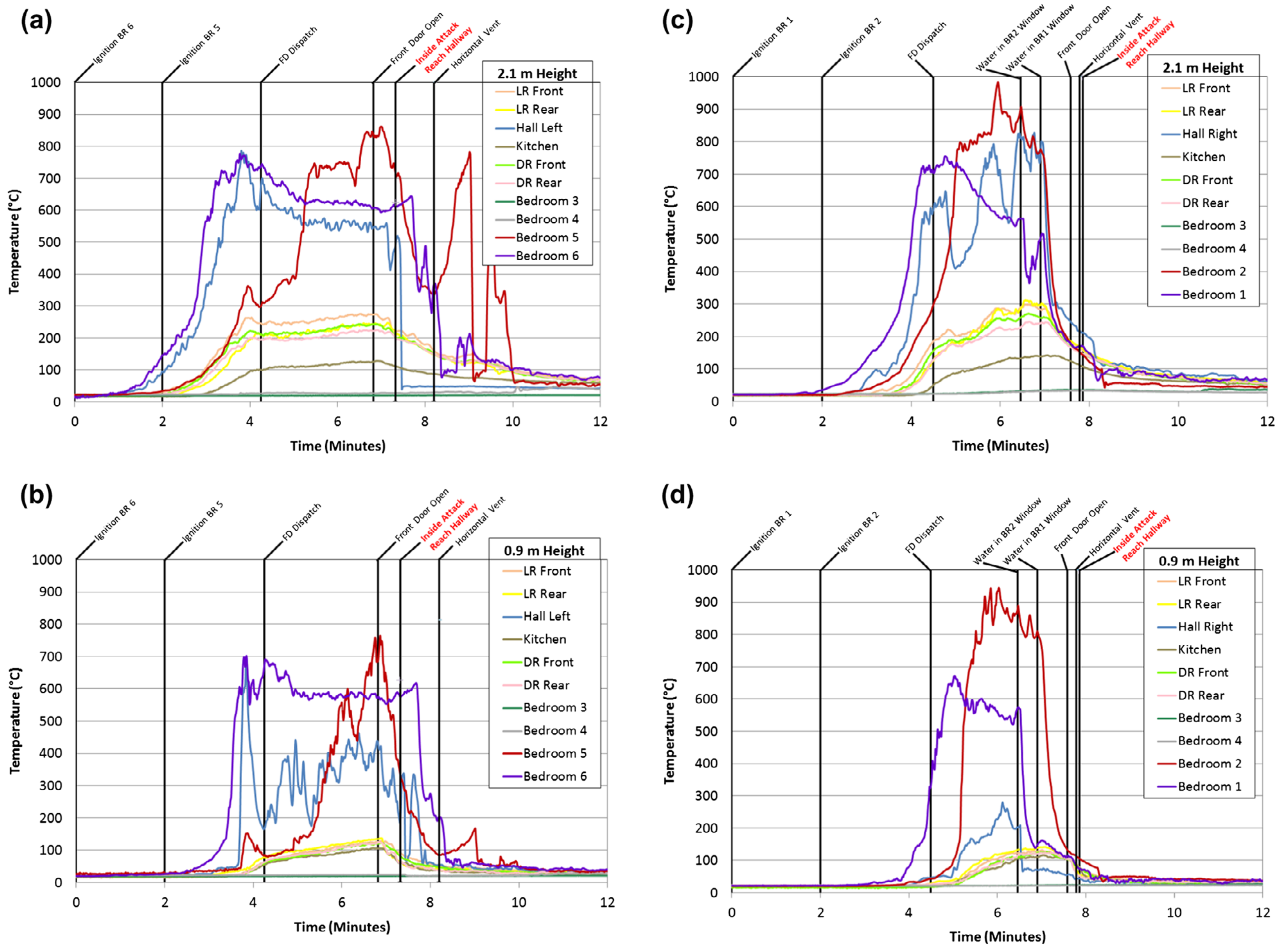

Figure 2. Building air temperatures at each of the measurement locations of the structure for an example and Interior attack scenario (a,b) and Transitional attack scenario (c,d) at measurement heights of 2.1 m (a,c) and 0.9 m (b,d).

Notes: Temperatures remain stable after minute 12, so the data is only shown to this time in order to better visualise the changes during Inside activities. LR = Living Room, DR = Dining Room, BR = Bedroom, FD = Fire Department.

the ceiling (2.1 m) and the crawling level of a firefighter (0.9 m) for a pair of scenarios completed by the same crew. Figure 2(a) and (b) are representative of the Interior attack scenarios and Figure 2(c) and (d) are representative of the Transitional attack scenarios. In each of the twelve fires, the two bedrooms where fires were ignited progressed to room flashover (full fire involvement with temperatures above 500 °C throughout the room) prior to firefighters entering the front door (Interior) or applying water through the window (Transitional). Table 2 provides a summary of maximum temperatures reached prior to firefighter intervention (averaged over the 6 Interior and 6 Transitional attack scenarios) at three heights (ceiling – 2.1 m, firefighter standing – 1.5 m, firefighter crawling – 0.9 m) at locations where firefighters would be operating. There were no statistically significant differences in these temperatures by tactic other than near the entrance to the structure (Living Room Rear at 0.9 m height). Firefighters conducting Transitional attack applied water to the fire significantly faster (on average 6:30 ± 0:26 (minutes:seconds) after the fires were ignited) than it took for firefighters conducting the Interior tactic to enter the front door (7:21 ± 0:26) ($p = 0.009$). Upon entry to the structure, firefighters began flowing water towards the hallway where the bedroom fires were located; however, it is not possible to compare the time to which the first water actually reached the burning materials and began suppressing the fire for the Interior attack scenarios.

Table 3 provides a summary of temperatures at the same locations and heights as reported in Table 2 (again averaged over the 6 Transitional and 6 Interior attack scenarios) at the time when the Inside Attack firefighters had made it to the hallway as identified by interior camera feeds. As Table 3 shows, there were statistically significant differences by tactic at nearly all locations other than near the front door (0.9, 1.5 and 2.1 m in the Living Room Rear location) and at 0.9 m in Bedrooms 2/5. Note the large standard deviation in the temperatures measured in Bedrooms 2/5. This large variability is the result of a single scenario where firefighters applied water into

Table 2. Mean (SD) of the maximum air temperatures and hallway heat flux (averaged over the 6 scenarios for each tactic) reached prior to firefighter intervention (water in window or front door open) at three heights at various locations.

		Maximum temperature pre-firefighter intervention (ºC)							Heat flux (kW/m^2)
Height (m)	Tactic	LR front	LR rear	DR front	DR rear	Hallway	BR2/5	BR 1/6	
2.1	Interior	309.6 (33.3)	308.5 (61.3)	280.1 (30.5)	240.4 (22.1)	809.4 (124.5)	978.2 (156.1)	774.8 (43.2)	
	Transitional	283.7 (20.3)	274.8 (27.9)	238.5 (47.3)	219.1 (16.4)	748.8 (104.0)	890.4 (75.4)	740.8 (35.7)	
1.5	Interior	278.4 (32.8)	209.8 (29.2)	250.6 (40.1)	233.4 (30.9)	739.7 (157.4)	952.1 (116.0)	810.9 (57.7)	28.22 (10.4)†
	Transitional	263.3(16.6)	167.4 (36.3)	211.9 (25.0)	202.3 (17.1)	648.0 (125.2)	910.3 (60.7)	756.0 (46.7)	22.35 (3.93)
0.9	Interior	114.1 (28.7)	165.8 (32.7)	130.5 (17.0)	160.8 (40.0)	435.7 (146.3)	954.3 (105.6)	709.3 (94.6)	13.39 (10.04)†
	Transitional	126.6 (15.4)	127.9 (12.3)*	120.0 (12.1)	132.1 (24.9)	393.0 (75.5)	875.8 (121.9)	662.6 (50.6)	9.00 (4.72)

Notes: LR = Living Room, DR = Dining Room, BR = Bedroom.
*Significantly different than Interior ($p < 0.05$); **Significantly different than Interior ($p < 0.001$); $^†n = 5$ due to data acquisition malfunction.

Table 3. Mean (SD) of the air temperatures and hallway heat flux measured at the instant when the Inside Attack firefighters had reached the hallway at each of these three heights at different locations (averaged over the 6 scenarios for each tactic).

		Temperature when 'inside attack reaches hallway' (ºC)							Heat Flux (kW/m^2)
Height (m)	Tactic	LR front	LR rear	DR front	DR rear	Hallway	BR2/5	BR 1/6	
2.1	Interior	286.2 (39.9)	244.7 (84.4)	254.5 (30.7)	228.0 (21.7)	581.5 (154.4)	744.0 (133.3)	642.0 (50.2)	
	Transitional	158.3 (69.6)*	163.0 (80.3)	142.5 (64.4)*	137.2 (57.3)*	210.7 (182.9)*	357.7 (352.6)*	340.7 (128.8)**	
1.5	Interior	240.5 (51.6)	161.7 (107.8)	209.7 (41.0)	201.5 (31.2)	520.0 (90.6)	726.7 (123.5)	641.7 (46.4)	19.34 (4.95)†
	Transitional	107.8 (53.7)*	107.8 (53.7)	124.2 (65.1)*	114.2 (57.8)*	135.5 (121.4)**	338.5 (366.4)*	176.5 (110.5)**	5.21 (5.00)*
0.9	Interior	114.7 (20.7)	90.7 (36.8)	95.2 (15.2)	99.2 (22.2)	311.3 (73.9)	650.3 (184.1)	583.3 (38.4)	7.94 (4.60)†
	Transitional	72.0 (28.9)*	61.5 (35.6)	63.7 (29.9)*	54.3 (21.0)*	65.5 (42.8)**	345.8 (373.5)	112.2 (51.1)**	2.98 (3.73)

LR = Living Room, DR = Dining Room, BR = Bedroom.
*Significantly different than Interior ($p < 0.05$); **Significantly different than Interior ($p < 0.001$); $^†n = 5$ due to data acquisition malfunction.

the fire rooms (Bedrooms 5 and 6) from the exterior for approximately 15 s each, then transitioned to the front of the structure where their entry was delayed while the front door was forced open. This water application successfully suppressed the bulk of the fire in Bedroom 6, but not in Bedroom 5. Prior to entering the structure, the fire in this second room regrew to nearly the same magnitude as it was prior to the exterior attack.

Firefighters conducting Transitional attack reached the hallway on average 8:56 ± 1:48 after the fires were ignited, which was not significantly different than the Interior firefighters who reached the hallway at 7:46 ± 0:26 after ignition ($p = 0.158$). The large variability in time for the Transitional Attack scenario is a result of one scenario where firefighters transitioned into the structure after exterior water application, but were disoriented in the smoke and were significantly delayed in making progress to the fire rooms (12:20). If this scenario were removed, the mean time to reach the hallway for Transitional Attack is 8:15 ± 0:46. While the difference in time to reach the hallway is not statistically significant when comparing the two tactics, this delay in progress to the hallway using the Transitional attack approach can impact time to locate a victim and may have important implications in a real situation.

Representative hallway heat flux data from the same two Interior attack and Transitional attack scenarios referenced in Figure 2 are shown in Figure 3. These figures show the heat flux that might be experienced while firefighters are standing (1.5 m), crawling (0.9 m), or very near the floor (0.3 m). Aforementioned Tables 2 and 3 also include maximum heat flux prior to firefighter intervention and heat flux that the firefighters might face when they reach the hallway when employing Transitional and Interior firefighting tactics. Heat flux at 1.5 m height when the firefighters had reached the hallway was significantly lower during Transitional attack than Interior attack (and nearly significant at 0.9 m height ($p = 0.080$)).

3.2. *Firefighter local temperature exposure data*

While Figures 2 and 3 provide a quantification of the thermal conditions firefighters may be exposed to if they remained in a stationary location, Figure 4 shows a representative measurement of local temperatures from firefighters as they move through the structure, from the helmet mounted temperature sensors on the attack (nozzleman) firefighter and the lead search team member from the same two scenarios as presented in Figure 2. Table 4 provides a summary of the maximum and average temperatures experienced by both Inside job assignments (Inside Attack, Inside Search). For comparison purposes, the average working temperatures measured inside the structure during Overhaul operations and exterior temperatures experienced by the Outside operations are also presented.

Based on helmet temperatures, firefighters operating on the hoseline (Inside Attack) were exposed to a significantly higher maximum and average temperatures than

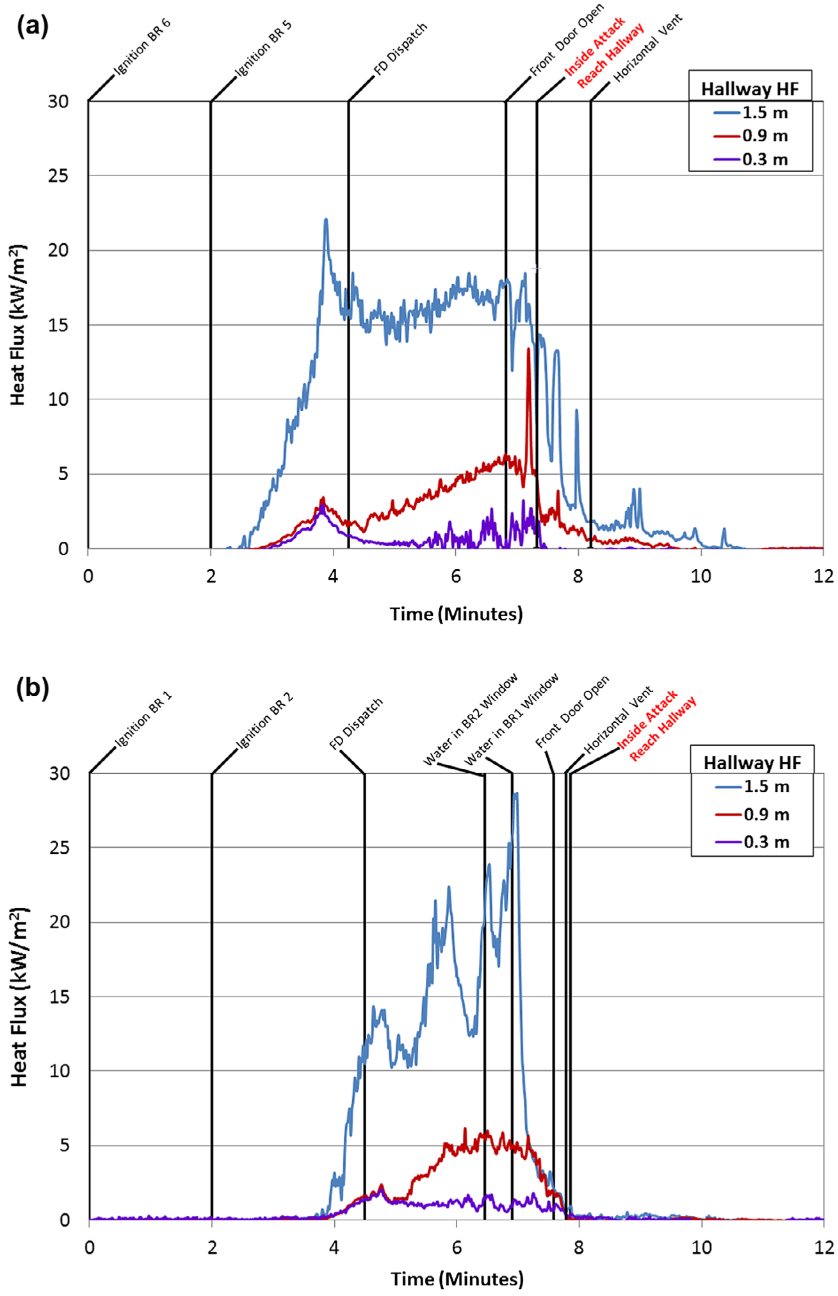

Figure 3. Heat flux measurements from the hallway immediately adjacent to the fire rooms with open doorways for an example (a) Interior attack and (b) Transitional attack scenario. LR = Living Room, DR = Dining Room, BR = Bedroom, FD = Fire Department.

the Inside Search team ($p < 0.001$ *each*). We also found significantly lower maximum and average temperatures for the Inside Attack crews when they used a Transitional attack compared to Interior attack ($p = 0.006$ *each*), with no significant impact of tactic on the Inside Search crew's thermal exposures (although the average temperature exposure difference was borderline significant, $p = 0.075$).

When comparing the average ambient temperatures among the Inside, Overhaul and Outside crews (Table 4), a significant main effect of job assignment was found (ANOVA $p < 0.001$). In *post hoc t*-tests, there was a significant difference in ambient temperatures experienced by each of the job assignments: Inside Attack > Inside Search > Overhaul > Outside ($p \leq 0.001$). Tactical choice did not significantly affect the ambient temperatures for the Overhaul or Outside assignments.

3.3. *Skin temperature*

Table 5 provides the mean values for arm and neck skin temperature by job assignment performed and firefighting tactic employed. We found a significant effect of job

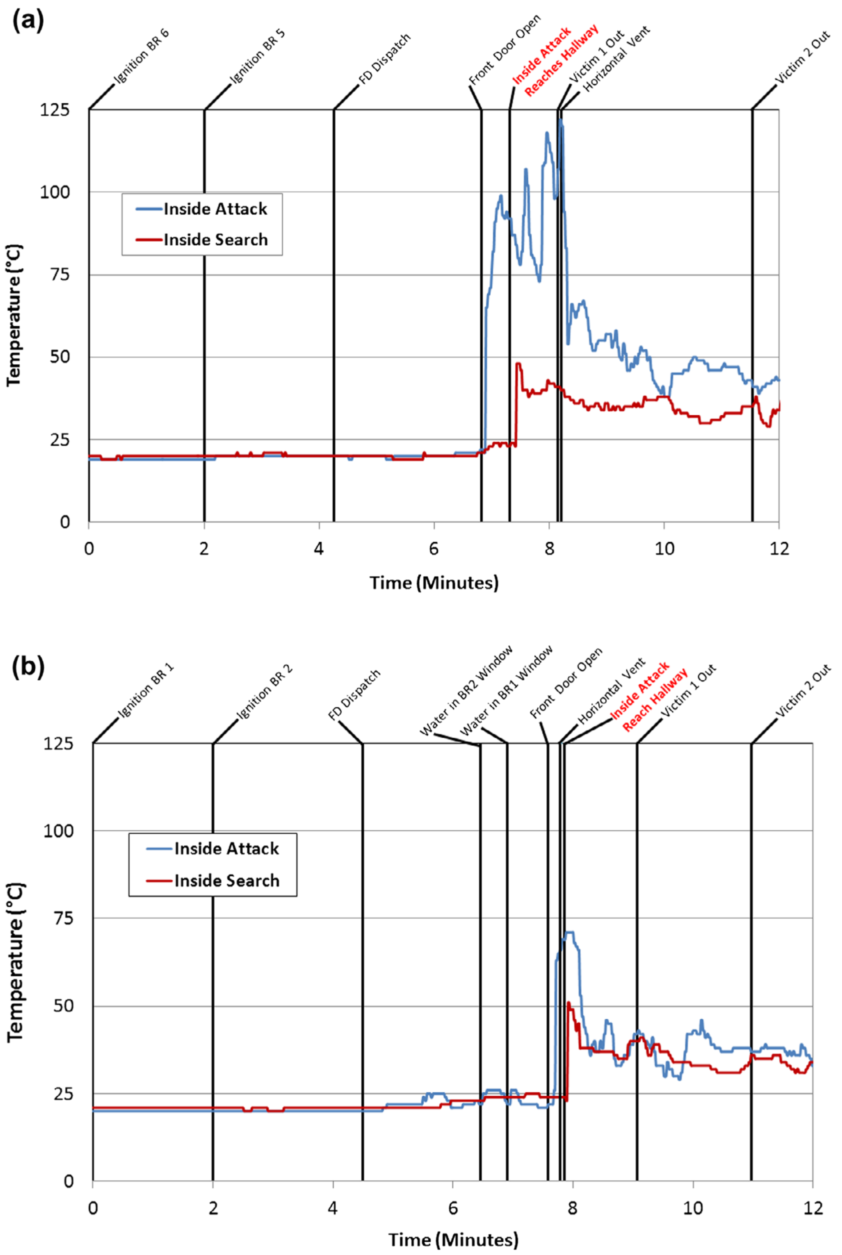

Figure 4. Helmet mounted temperature measurements collected from the nozzleman on the attack team and lead search team member for an example (a) Interior attack and (b) Transitional attack scenario. LR = Living Room, DR = Dining Room, BR = Bedroom, FD = Fire Department.

assignment on both skin temperature measurements (ANOVA $p < 0.001$). There was no difference between temperature measurements for the Inside crews (Inside Attack vs. Inside Search), so they were collapsed to a single 'Inside' group. Post hoc analysis revealed that when compared to the Outside Command operations (incident command and pump operator) as the referent, all other job assignments had higher arm and neck skin temperatures ($p < 0.001$). Additionally, neck skin temperatures for the Inside crews (averaged over both tactics) were significantly lower than Overhaul crews ($p = 0.048$). There were no detectable differences between the other job assignments despite significantly different ambient conditions reported in Table 4.

When analysing the full data-set, there were no significant main effects for tactic on skin temperatures. This finding is not surprising as the tactic only had a significant impact on environmental temperatures for the Inside crews. The effect of tactic on skin temperatures was also explored for inside crews (Inside Attack and Inside Search combined). Neck skin temperature was found to be significantly lower during Transitional attack than Interior attack

Table 4. Mean (SD) of maximum and average helmet mounted temperature measurements collected from nozzleman on the attack team and lead search team member.

Measure	Job assignment	Interior attack	Transitional attack	Significance
Helmet temperature (°C)				
Maximum	Inside attack	191.0 (48.6)	95.7 (54.9)	*p* = *0.006*
	Inside search	63.2 (13.0)	54.7 (101)	ns (0.245)
Average	Inside attack	57.6 (7.0)	42.2 (7.8)	*p* = *0.006*
	Inside search	39.7 (4.6)	34.9 (3.9)	ns (0.075)
Ambient temperature (°C)				
Average	Overhaul	25.0 (3.0)	26.6 (2.8)	ns (0.375)
	Outside	19.2 (1.2)	19.8 (1.4)	ns (0.505)

Note: For Overhaul and Outside job assignments, reported temperatures are the average hallway temperatures (1.5 m) during overhaul and exterior temperature throughout the scenario, respecitvely.

Table 5. Mean (SD) of the maximum skin temperature for firefighters operating in different job assignments and attack tactics.

Measure	Job assignment	Interior attack	Transitional attack	*N*
Maximum arm skin Temperature (°C)	Outside command/ pump	36.14 (1.32)	36.09 (1.36)	8
	Outside vent**	37.65 (0.71)	37.76 (0.62)	8
	Inside**	37.51 (1.07)	37.20 (0.82)	16
	Overhaul**	37.65 (0.76)	37.96 (0.43)	15
	Total	37.35 (1.09)	37.35 (1.02)	47
Maximum neck skin temperature (°C)	Outside command/ pump	36.40 (1.24)	36.20 (1.18)	8
	Outside vent**	37.72 (0.15)	37.67 (0.54)	8
	Inside**	37.67 (0.76)	37.21 (0.63)	16
	Overhaul**	37.81 (0.99)	38.06 (0.46)	15
	Total	37.50 (0.99)	37.39 (0.93)	47

*Significantly different than Outside Command/Pump ($p < 0.05$); **Significantly different than Outside Command/Pump ($p < 0.001$).

Table 6. Mean (SD) of the maximum core temperature and core temperature changes for firefighters operating in different job assignments and attack tactics.

Measure	Job assignment	Interior attack	Transitional attack	*N*
Maximum core temperature (°C)	Outside command/ pump	37.81 (0.40)	37.68 (0.26)	8
	Outside vent**	38.63 (0.37)	38.54 (0.42)	8
	Inside	37.91 (0.21)	37.99 (0.43)	16
	Overhaul**	38.88 (0.38)	38.81 (0.58)	15
	Total	38.32 (0.57)	38.29 (0.58)	47
Core temperature change (°C)	Outside command/ pump	0.85 (0.31)	0.64 (0.24)	8
	Outside vent**	1.84 (0.49)	1.64 (0.41)	8
	Inside*	0.93 (0.27)	1.15 (0.55)	16
	Overhaul**	1.74 (0.46)	1.77 (0.48)	15
	Total	1.33 (0.58)	1.34 (0.61)	47

*Significantly different than Outside Command/Pump ($p < 0.05$); **Significantly different than Outside Command/Pump ($p < 0.001$).

(ANOVA $p = 0.046$). There was no significant effect of tactic on Arm skin temperature for Inside firefighters.

3.4. Core temperature

The participants' core temperatures were monitored throughout the study and baseline and maximal values were recorded. Mean and standard deviation of the maximum core temperatures recorded and the change in core temperature from baseline are reported in Table 6. Figure 5 shows representative core temperature data from firefighters who completed four different job assignments (Inside Search, Outside Command/Pump, Outside Vent and Overhaul/RIT) from a single Transitional attack scenario. It is not possible to indicate the exact time of firefighting activities on this Figure as with earlier plots due to the limitations in linking between the different data acquisitions systems utilised. However, for this scenario, Inside operations were conducted for a little over 10 min after dispatch, while overhaul operations were conducted for 17 min after Inside operations ended. Similar trends in core temperature were found for the other scenarios, regardless of tactic employed. Prior to firefighting operations, the average core temperature of the group was 37.0 ± 0.4 °C. While there was some variation between groups (e.g. Outside Command/Pump group had slightly higher baseline core temperatures), there were no statistically significant differences among job assignments. During these scenarios, core temperatures for the firefighters operating on the Inside of the structure increased rapidly and prior to other assignments as they were the first deployed and began rigorous activity soon after dispatch. The Outside Command/Pump group also typically experienced increased core temperature early in the scenario, but the rise was less dramatic due to the lower physical exertion and lower ambient temperatures. Core temperature of Outside Vent crews increased later in the scenario as they were deployed later and typically began their rigorous activities after the initial advancement of the hoseline. Overhaul firefighters typically had the highest core temperatures, but the increase in core temperature was delayed while conducting low intensity activities outside of the structure (median time of 11 min) prior to entering for overhaul after the Inside firefighters completed their activities. Peak heart rates during firefighting activity were recorded for each crew. Using Outside Command/Pump as the referent group (152.9 ± 14.2 bpm), we found that peak heart rates were significantly higher for the Inside (178.4 ± 12.7 bpm), Outside Vent (187.9 ± 16.9 bpm) and Overhaul crews (180.0 ± 16.5 bpm).

Table 6 provides the mean values for the maximum core temperature and core temperature change by job assignment and firefighting tactic. While there was no main effect of Tactic on core temperature response, there was a main effect of job assignment for both maximum core temperature and rise in core temperature (ANOVA $p < 0.001$). Firefighters assigned to Overhaul had the highest core temperatures followed by Outside Vent. Using

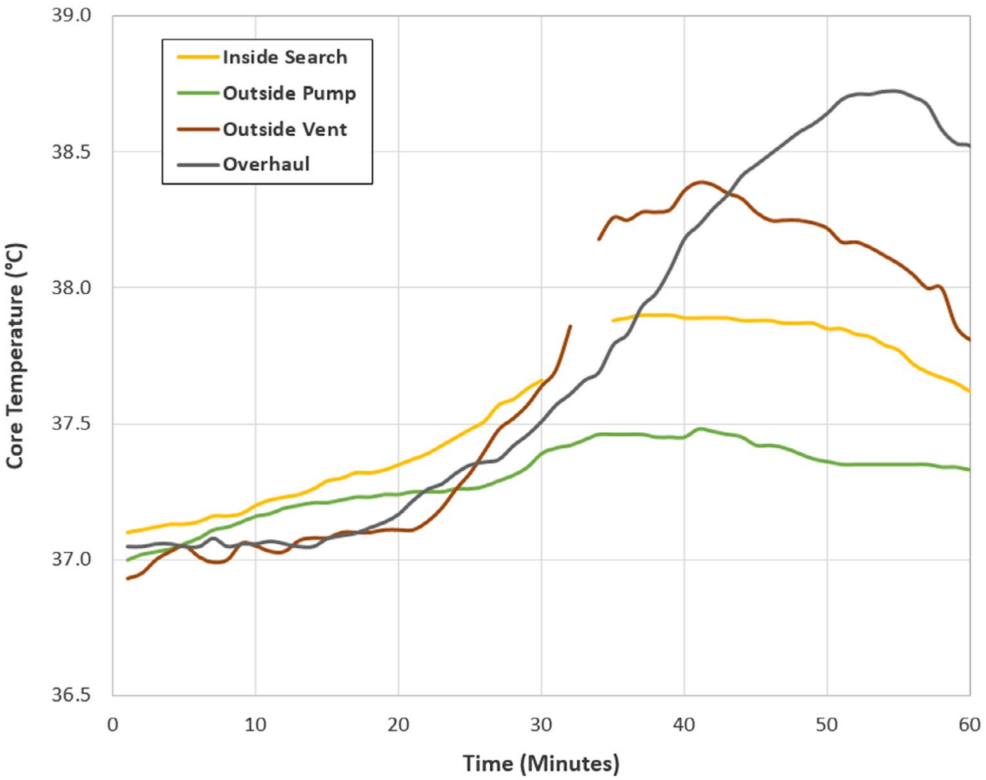

Figure 5. Typical core temperature plots from firefighters operating at 4 representative job assignments (Inside, Outside [Pump, Vent], and Overhaul) on the fireground.
Note: Discontinuities in the data occur when core temperature pill temporarily loses communication with the monitor.

Outside Command/Pump as the referent group, we found that maximum core temperature and core temperature changes were significantly higher for the Outside Vent and Overhaul crews (*p's* < 0.001). While Inside firefighters' maximum core temperatures were slightly higher in magnitude, they did not differ significantly from the Outside Command firefighters. However, their total change in core temperature was significantly larger ($p = 0.002$). This apparent discrepancy is attributed in part to a slightly (but not significantly) different baseline temperatures between these groups. Inside job assignments also had lower maximum core temperatures and core temperature changes than Outside Vent and Overhaul (*p's* < 0.001).

As with the skin temperature analysis, the tactic employed did not have a significant main effect on the core temperatures for the entire population. A follow-up repeated measures ANOVA was conducted for the Inside crews (Attack and Search) that are most likely to be affected by the differing environmental conditions, but there was no significant effect of tactic or job assignment on the core temperature response for this group of firefighters.

4. Discussion

This study provides the most complete characterisation of the thermal environment and temperature responses of firefighter working in a realistic residential fire common in the twenty-first century in the United States (and other countries with comparable building construction and employing similar tactics). For the first time, fireground operations were simulated with high fidelity using fires produced by a full scale room and contents structure fire using common furnishings and structure finishes. Furthermore, we provide the first description of firefighters' temperature responses based on fireground job assignment and firefighting tactic.

4.1. Building temperature & heat flux profiles

The environmental thermal data reported here complements the existing literature, with important additions. To date, the most detailed description of the modern fireground has been conducted by Kerber (2013) in a structure similar to that used here. The scenarios reported in Kerber (2013) were conducted inside a large laboratory where the ambient was carefully controlled, as were the firefighting actions. Furthermore, these scenarios were typically conducted with the structure closed during fire development, resulting in severly (ventilation limited fires) prior to firefighter intervention. Compared to Kerber (2013), the environmental temperatures in our study remained elevated in fire rooms until water was applied. In these cases, the rooms typically flashed over 2–4 min after ignition and the fire rooms remained above 500 °C until water was applied. While our scenarios were ventilation limited, we did have an open window in both rooms to provide some air exchange. Thus, we did not observe the drop in temperatures from lack of oxygen as was reported in Kerber (2013).

Temperatures measured near the ceiling level (i.e. 2.1 m from the floor in Figure 1) are similar to those commonly reported during fire tests as they represent the maximum temperatures of concern for structural stability. Temperatures that occupants might experience while crawling on the floor (e.g. 0.9 m) are also similar to those previously reported (Kerber 2013; Traina et al. 2016). Temperatures at these heights may also be representative of the exposure to firefighters in their operational roles as much of the work of firefighting during active fire, such as fire suppression and search and rescue, is performed while crawling or in the crouched position. In addition, we report temperatures at 1.5 m, which may be experienced by firefighters who are walking in the fire environment as opposed to crawling. While not a commonly recommended practice due to visibility concerns, there are occasions where firefighters will stand and move through the structure on foot. Prior to firefighter intervention (Table 2), the temperatures in the fire rooms were in excess of 600 °C and fairly consistent from floor to ceiling, which indicates that each room had reached the flashover stage. Even in full firefighting PPE, these conditions would rapidly overwhelm protection provided by the PPE resulting in compromise of the equipment (particularly SCBA facepieces (Willi, Horn, and Madrzykowski 2016)) and create risk for rapid and dangerous burn injuries. However, in the hallway just outside the burn rooms, the temperatures were more stratified. Hallway temperatures at the ceiling and 1.5 m level were still well above 600 °C, with heat flux values at 1.5 m at 22–28 kW/m^2, but firefighters operating in the crawling position would have significantly reduced ambient temperatures (~415 °C) and heat flux (~11 kW/m^2). Further from the fire room, in the living room and dining room, standing level (1.5 m) temperatures remained on average above 225 °C, while crawling temperatures averaged closer to 135 °C.

One way to interpret these data is through thermal classifications established by the National Institute of Standards and Technology (NIST). In 2006, researchers from NIST reviewed existing thermal environment classification data and proposed four thermal classes, shown in Table 7, to be used in defining standardised test criteria for electronic safety equipment used by firefighters (Donnelly et al. 2006). Operating in the hallway prior to water application would expose firefighters to NIST Thermal Class IV conditions. In fact, firefighters operating at the 1.5 m level in the living room and dining room could expect to be near the upper limit of Class III and possibly into the Class IV region. However, at the crawling level, nearly all of the temperatures in the Dining and Living rooms remained within the Class II region. NIST recommends that operations at Class IV are conducted for less than 1 min, while Class II conditions are recommended for less than 15 min. These criteria presume that the PPE has not already been preheated during earlier operations that were necessary to reach the hallway. While not a focus of this study, if a firefighter is searching ahead of the line as may be deemed necessary for rescuing a known trapped victim, he/she may experience these high-heat conditions, significantly increasing the risk of equipment failure and burn injury. Extended duration exposure to high heat flux, even in the absence of high ambient temperatures has been shown to be detrimental to firefighting PPE, particularly facepieces that may crack, bubble and deform even if the air temperature is relatively low (Putorti et al. 2013; Willi, Horn, and Madrzykowski 2016).

Table 7. National Institute of Standards and Technology (NIST) thermal classes (Donnelly et al. 2006)

Thermal class	Maximum time (min)	Maximum air 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 impact of firefighters flowing water into the fire rooms is apparent when comparing data from the same rooms and heights in Table 2 and Table 3. By the time the Inside Attack firefighters made their way to the hallway, water had either been applied through the exterior window during Transitional tactic or flowed towards the bedrooms while inside the structure during Interior attack. With the Interior tactic, slight reductions in ambient temperatures after water flow were seen throughout the structure, although fire room temperatures remained mostly above 600 °C. Hallway temperatures were over 500 °C with heat fluxes approximately 19 kW/m^2, still well beyond the Class III/IV condition limit. In comparison, using the Transitional tactic, temperatures in Bedroom 1/6 averaged less than 180 °C at walking height and 112 °C at crawling height by the time the firefighters had transitioned to the interior of the structure and made their way to the hallway. Note that average temperatures in the second fire bedroom were much higher as a result of the single scenario where entry was delayed and the fire regrew; the other five scenarios resulted in temperatures similar to Bedroom 1/6. When compared to the Interior tactic, the Transitional attack tactic resulted in lower hallway temperatures (135 °C vs. 520 °C [Class II vs. Class IV]) at standing height, with even more dramatic reductions at crawling height (65 °C vs. 310 °C [Class I vs. Class IV]). Likewise, heat fluxes were 5 kW/m^2 vs. 19 kW/m^2 (Class III vs. Class IV) at standing height and 3 kW/m^2 vs. 8 kW/m^2 (both Class III) at crawling height. Throughout the living room and dining room, temperatures were below 160 °C (Class II) at the standing level and well below 100 °C (Class I) at the crawling level when the Transitional attack was employed. Importantly, this study is the first to provide a direct comparison of attack tactics on environmental conditions inside a residential structure, quantifying the marked improvement in temperatures when water is applied early. In addition to the PPE that firefighters wear, choice of tactic can also provide a significant level of protection against thermal stress on the fireground.

4.2. Firefighter local temperatures

While ambient temperature measurements in stationary locations have value for describing fire dynamics and characterising risk for firefighters who may become trapped (or remain static for other reasons), it is also critical to better understand the thermal environment encountered by firefighters as they perform their typical work. This study provides the first measurement of thermal exposure to firefighters operating in (i.e. moving through) a structure with room and contents fires typical of the twenty-first century. Gempel and Burgess (1977) measured the thermal environment during structural firefighting in 1977, and found median maximum temperatures of 33 °C and that maximum temperatures in excess of 80 °C are only expected in about 1% of structure fires. Willi, Horn, and Madrzykowski (2016) provided measurements of firefighters moving throughout a training fire scenario with pallet and straw fuel loads. The structures and the fuels they contain have changed significantly over the past several decades and are very different than training environments, resulting in more rapid fire progression that subjects firefighters to significantly more intense thermal conditions (Kerber 2013).

While both Inside Attack and Inside Search are firefighting job assignments that may require operating inside a structure during active fire, there was significantly different environmental thermal exposures for these two groups of firefighters based on the tasks they performed. Regardless of tactic, the maximum and average temperatures (at helmet) of the Inside Attack firefighters were significantly higher than the Inside Search firefighters. Maximum temperatures recorded by the search team helmet never exceeded 80 °C, thus remaining NIST Class I throughout the scenarios, but Inside Attack firefighters often experienced temperatures that exceeded this threshold, most likely because they were operating much closer to the fire.

Importantly, firefighting tactic significantly impacted the local ambient temperatures of the Attack team. Both average and peak temperatures encountered by Attack crews inside the structure were higher when the Interior tactic was used. Of particular note, there was only one instance where the peak temperature experienced by the attack firefighter was higher when utilising the Transitional tactic than when conducting the Interior tactic. This instance corresponded to the scenario where the firefighters' transition to the inside of the structure was delayed and the bedroom fire regrew. This was the only Transitional attack scenario where firefighters were exposed to conditions beyond NIST Class I (in this case, NIST Class III). On the other hand, when the Inside Attack teams utilised the Interior tactic, they were exposed to maximal conditions that would be categorised as Class II on one scenario and Class III conditions on the other five scenarios, with the highest exposure (256 °C) just below the Class IV cut-off (>260 °C). The maximum time over which Class III conditions were experienced by the attack firefighter was 26 s, well below the maximum recommended exposure time of 5 min. Comparing the local temperature measurements to the static temperatures provided in Table 3, it is apparent that the firefighters spent most of their time during the initial suppression efforts crawling into the structure. Had firefighters chosen to walk in, these local measurements would have been even more severe.

Temperature variations during inside activities fluctuated significantly as firefighters conducted their Inside operations, reaching a peak just prior to suppression of the fire by the attack team. Once water was applied to the fire and rooms were ventilated, ambient temperatures began to decline rapidly as seen in Figure 4. The average local ambient temperatures during Inside Attack (~50 °C) and Inside Search (~37 °C) operations were significantly higher than average temperatures experienced during Overhaul (~26 °C) and Outside operations (~20 °C), which varied little throughout operations. On average, conditions that firefighters conducting each of these latter two job assignments faced would be classified as NIST Class I.

These data provide the first quantitative measurement of the thermal conditions that firefighters face during a coordinated attack scenario when the suppression line advances in front of the other operating crews who are crawling in the structure. It should be noted that these fires were confined to room and contents scenarios that were relatively rapidly extinguished. Had the fire spread in to the walls of the structure, longer exposures would be expected. These findings, combined with those reported by Willi, Horn, and Madrzykowski (2016) for training scenarios, should be considered when developing laboratory based assessment of repeated exposures of firefighting

PPE to 'typical' fireground conditions or for characterising the physiological impact of new PPE interventions.

4.3. Skin temperatures

While the environmental temperatures at which firefighters operated varied greatly between the different job assignments, these same patterns did not universally translate to skin temperature changes. While maximum skin temperatures measured from Outside Command crews were significantly lower than the others, there was no statistically significant difference in skin temperatures between the Inside, Overhaul or Outside Vent crews. There are likely several reasons for this result. First, firefighters completing Inside, Overhaul or Outside Vent worked at or near maximal effort during their activities based on measured heart rates, resulting in significant metabolic heat generation. Secondly, the firefighting PPE insulated the firefighters from their surroundings and provided protection from the elevated ambient conditions on the Inside of the structure. For example, while search and attack firefighters experienced significantly different maximum and average local temperatures (Table 4), their skin temperatures under the PPE were similar. The average neck temperatures tended to be higher for the Attack firefighters compared to Search, but this did not achieve significance ($p = 0.080$). It is reasonable to assume that had the firefighters operated in the high ambient temperatures for a longer period of time, the heat may have transferred through the gear to a greater extent.

While no difference was detected in arm skin temperature by tactic, neck skin temperature was significantly lower for the Inside firefighters conducting a Transitional Attack versus an Interior Attack. The neck is provided relatively less protection by a knit hood compared with other parts of the body that are covered in bunker gear with three layers (shell, thermal layer, moisture barrier). The measured difference in neck skin temperature is relatively small (0.5 °C), but the physiological impact must be further investigated as these differences may affect the body's ability to dissipate heat from the core and/or may alter the absorptivity of the skin for specific chemical exposures. For example, Fent et al. (2014) found that neck skin is an important site of dermal exposures during firefighting. Our findings suggest that Transitional attack may reduce exposure to radiant and convected heat and potentially fire smoke, especially in the neck area for the inside firefighters.

4.4. Core temperatures

Core temperature did not change uniformly among firefighters. In some job assignments, core temperature rose quite rapidly, while those in other job assignments had more modest increases over the relatively short timeframes experienced in this study. While core temperature was expected to increase during Inside firefighting operations due to elevated ambient temperatures, significant elevations were also seen for Outside Vent and Overhaul operations due to heavy muscular work.

This is the first study to quantify core temperature increase during realistic fireground operations with realistic fuel, common residential construction and typical firefighting tactics. While measurements of heart rate have been documented from real fire suppression emergencies for a number of years (e.g. Smith et al. 2010; Sothmann et al. 1992), measuring core temperature is more challenging due to the logistics of instrumentations. In 2013, Horn et al. summarised the literature that had reported core temperature rise during live fire activities. While the scenarios and environments varied significantly among the studies reviewed, core temperature changes ranged from 0.3 to 1.4 °C with rate of rise varying from 0.010 to 0.100 °C/min. For Inside firefighting crews in this study, the core temperature change and rate of change was near the upper end of the ranges (1.04 °C and 0.095 °C/min) reported by Horn et al.

In 1987, Romet and Frim collected similar data from fire-fighting crews performing different job assignments during a live-fire training simulation (Romet and Frim 1987). The 'Inside' crew here can most closely be compared to the 'Lead Hand' in that data-set. In the Romet and Frim study, a 24 min firefighting/search and rescue activity resulted in an average increase in rectal (~core) temperature of 1.3 °C and mean skin temperature of 37.4 °C, which is similar to that measured in the current study (1.0 and 37.4 °C, respectively), but duration of activity was shorter in our scenarios than in the Romet and Frim study (11 vs. 24 min). The tasks conducted by the 'Crew Captain' and 'Exterior Firefighting' groups in Romet and Frim (1987) are similar to the 'Outside Command/Pump' operations in the current study, but Romet and Firm reported significantly lower core temperature increases (0.3 and 0.4 vs. 0.7 °C) and lower maximum skin temperatures (33.9 and 34.9 vs. 36.3 °C) for a similar duration of activity. The higher temperatures reported in the current study are likely attributable to the lighter firefighting PPE worn in the mid-1980s compared to heavier, more encapsulating NFPA 1971 compliant PPE from 2015.

Interestingly, the Overhaul and Outside Vent crews had the highest maximum core temperatures (38.9 and 38.6 °C, respectively). On average, core temperatures increased 1.7–1.8 °C over baseline during both of these activities. To our knowledge, there have been no other studies that have focused on the thermal strain induced by these common fireground assignments. These job assignments are often considered to be lower risk for heat stress because they do not occur in a superheated fire environment. However, strenuous activities and physiological burden imposed by the firefighting PPE results in increased core temperature. It is important to note that the period of time over which Outside Vent (average of 22 min) and Overhaul (average of 11 min outside and 17 min inside structure) crews operated were significantly longer than the Inside Attack and Inside Search crews (11 min). The overall rate of rise in core temperature of the Outside Vent crew (0.092 °C/min) was remarkably similar to that from the Inside crews (0.095 °C/min). This rate of rise was more modest for the Overhaul firefighters (0.063 °C/min) if averaged over the entire 28 min of activity. However, if we assume that the core temperature increase over the first 11 min is similar to the Outside Command/Pump firefighters (0.037 °C/min) who had comparable physical demands outside of the structure, then the rate of rise during the strenuous overhaul activities inside the structure (17 min) would be closer to 0.08 °C/min.

While significant attention has been paid to the need for appropriate PPE protection from fireground contaminants during overhaul operations (Bolstad-Johnson et al. 2000; Fent et al. 2014), it is also important for firefighters and fire officers to understand the thermal burden induced from wearing this level of protection during heavy muscular work like overhaul operations. As shown in Table 6, we measured core temperatures for Overhaul firefighters that increased to over 38.8 °C after operating through a single '30 min' SCBA cylinder of air. This activity began with firefighters in a rested state (core temperatures of approximately 37.0 °C) and followed approximately 11 min of relatively low intensity work of setting up RIT or pulling a backup line. Had the firefighters begun their overhaul activities after completing another strenuous assignment, as is common on the fireground, they could have accumulated a significantly higher level of thermal strain. For instance, if firefighters had just completed Inside operations or Outside Vent, their average starting core temperatures could be closer to 37.9 or 38.6 °C, respectively (Table 6). Thus, final core temperatures during overhaul could approach 39.7–40.4 °C. According to the American Conference of Governmental Industrial Hygienists (ACGIH 2016), a healthy, acclimatised, experienced worker's core temperature should not exceed 38.5 °C. In addition, a core temperature of 40 °C is the upper range of clinical heat exhaustion, and above 40 °C, heat stroke can occur. Common rehabilitation recommendations and protocols often call for implementation of rehab after completing work with two 30-min SCBA (NFPA 1584). However, our data suggest that it may be prudent to bring in additional manpower as rapidly as possible to relieve the crews performing suppression and ventilation operations or other strenuous activities while wearing full turnout gear. Furthermore, if crews are working through extended overhaul operations and using larger SCBA, formal rehab protocols with rest, hydration and active cooling (where appropriate) must be enforced.

While this study provides the most complete characterisation of the thermal conditions experienced by firefighters operating on a typical modern fireground, important limitations are noted. Although this study used a realistic, purpose-built structure, and measured thermal conditions and stress experienced by firefighters, we did not collect data on the vast array of structure fires to which firefighters might respond. Fires were limited to 'room and contents' and did not spread into the walls of the structure, which may have resulted in longer term operations. Following good firefighter training practices, participants were provided with the opportunity to conduct a quick walk through of the structure prior to igniting the fires. Therefore, firefighters may have completed the tasks more rapidly than if they had not been familiar with the layout.

5. Conclusions

When firefighters respond to modern residential structure fires, the thermal impacts – from the environment to the firefighters' core temperature – can be effected by both their job assignment and suppression tactic in many different ways. Firefighters performing different job assignments experienced different ambient conditions and had different thermal responses. Firefighters who performed the most strenuous work, had the highest skin and core temperatures, regardless of ambient conditions in which they were operating. Firefighting tactic has a significant effect on environmental conditions encountered by firefighters operating inside the structure. When performing Transitional attack, thermal conditions for the Attack firefighters were significantly reduced with no apparent detrimental effect on the environment inside the structure. A further benefit of lower ambient temperatures during Transitional attack was lower neck skin temperatures for the Attack firefighters. However, the reduced ambient and neck skin temperature for firefighters operating inside the structure did not translate to reductions in core body temperature during Transitional attack. Thus, it is important that firefighters wearing fully encapsulating PPE and working on the fireground be provided rest, recovery and rehab based on intensity and duration of work, regardless of tactic utilised or the apparent risk from their ambient conditions alone.

Disclosure statement

There are no conflicts of interest regarding this work.

Funding

This work was supported by the Department of Homeland Security Fire Prevention and Safety Grant [#EMW-2013-FP-00766].

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