

Core Temperature, Recovery and Re-deployment during a Firefighting, Search and Rescue Scenario

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Executive Summary

Introduction

This document describes a study carried out by Optimal Performance Limited (OPL) in support of the Research and Statistics Division (RSD) in the Department for Communities and Local Government. The project describes the thermal and cardiovascular responses to an initial deployment, varied recovery periods, and a re-deployment, during a conventional firefighting, search and rescue scenario, under both ambient (Phase 1) and live fire conditions (Phase 2).

Objectives

The project aims were fourfold:

1. to describe the thermal and cardiovascular responses to an initial deployment, varied recovery periods, and a re-deployment.
2. to ascertain if performance and scenario outcome on the re-deployment were degraded, relative to the initial deployment.
3. to compare the thermal and cardiovascular responses to the varied recovery periods and to the re-deployment.
4. to recommend recovery conditions prior to re-deployment.

Approach

Twenty one firefighters undertook a search and rescue scenario, comprising an initial deployment, a recovery period and a re-deployment under both thermo-neutral conditions (Phase 1 – Ambient) and conditions of live fire (Phase 2 – Live Fire). Firefighting was also undertaken during Phase 2. The two work bouts were separated by three different recovery periods, comprising a 30 minute cold recovery outdoors (averaging 13°C), and 30 minute (25°C) and 120 minute (22°C) warm recoveries indoors, reflecting typical recovery temperatures and durations encountered by firefighters when on duty. During the recoveries firefighters had access to water ad libitum. No active cooling methods were included in the recovery period so as to evaluate simple strategies of removal of outer PPE at the earliest opportunity and the consumption of reasonable volumes of cool fluids.

Measurements were made of the total load carried, the fitness of the firefighters and the temperature of the buildings. Firefighters were monitored for core body temperature, skin

temperature, heart rate, body mass changes and fluid intake to estimate sweat loss, air use and physical activity levels.

The thermal and cardiovascular responses to the scenarios, including both work bouts and the recovery periods are described and compared using analysis of variance (ANOVA). Generally, there were few effects of either the bout (initial deployment vs re-deployment) or the scenarios with different recovery conditions (30 minute cold vs 30 minute warm vs 120 minute warm). However, a number of 'interactive' effects were noted, where one of the bouts combined, or interacted, with one or two of the scenarios with different recovery periods, to produce a different response.

Phase 1 conclusions

The following conclusions were drawn from the Phase 1 search and rescue scenarios performed in thermo-neutral ambient conditions:

1. The thermal and cardiovascular responses were unremarkable. The cardiovascular response was significant and similar to that described previously (Rayson *et al.*, 2004). The thermal response was moderate and its extent was partially limited by the use of Standard Duration Breathing Apparatus (SDBA) – air supply being the only reason for early termination of the scenarios and failure to achieve the objectives on some occasions.
2. Performance on the re-deployment was not substantially degraded compared with the initial deployment, with the same proportion of successful outcomes resulting from the re-deployments as the initial deployments. No differences in heart rate, ventilation, physical activity or body mass changes were reported between experimental conditions in the re-deployment work bout.
3. Although differences in core and skin temperature responses were noted between experimental conditions during both the recovery periods and the re-deployments, there were no differences in the final core or skin temperatures at the end of the re-deployment. While the 120 minute warm recovery produced the lowest core temperature (due primarily to the additional recovery duration and more complete removal of PPE during this period), and the 30 minute cold recovery produced the lowest skin temperatures (primarily due to the colder ambient temperature), at the end of the re-deployment these differences had disappeared.
4. No differences were noted in the rates of decline of core temperature during the first 30 minutes of recovery in the three recovery conditions. This probably reflects the firefighters not fully removing their outer PPE during the shorter recovery periods (especially during the 30 minute cold recovery), which may have resulted in the higher baseline core temperatures being maintained during the shorter recovery periods.

5. In 4% of cases firefighters exceeded Graveling's proposed upper core temperature limit for trainers of 39°C; only one of these was during a re-deployment and that was in the 30 minute warm condition.
6. The outcomes were most favourable on the re-deployment after the 30 minute cold recovery, but the total number of outcomes was small, so caution should be exercised in generalising this finding.

Phase 2 conclusions

The following conclusions were drawn from the Phase 2 firefighting, search and rescue scenarios performed under live fire conditions:

1. Compared with the Phase 1 scenarios performed under ambient conditions, the live fire scenarios were shorter (possibly due to the smaller building used) and the thermal response was greater during both the initial deployment and re-deployment. Thermal recovery was similar between scenarios. Lack of success in achieving the scenario objectives through the firefighters failing to locate all the casualties was the only source of failure, which occurred in 29% of deployments.
2. The outcomes and physiological performance on the re-deployments were not substantially degraded relative to the initial deployments, with more successful outcomes occurring during the re-deployments than the initial deployments. However, the redeployments were shorter than the initial deployments and the firefighters undertook less total physical activity.
3. A few differences were noted between experimental conditions:
 - relatively little further decline in core temperature was achieved beyond the first 45 minutes in the 120 minute recovery period
 - the final core temperature at the end of the re-deployment was higher in the 30 minute recovery conditions compared to the 120 minute recovery condition.
4. No differences were noted in the rates of decline of core temperature during the first 30 minutes of recovery in the three recovery conditions. This probably reflects the firefighters not fully removing their outer PPE during the shorter recovery periods (especially in 30 minute cold), which may have resulted in the higher baseline core temperatures being maintained during the shorter recovery periods.
5. No differences were noted in ventilation, rate of rise of core or mean skin temperature, activity rate or body mass loss between experimental conditions in the re-deployment work bout.

6. In 9% (seven occasions) of cases firefighters exceeded Graveling's proposed upper core temperature limit for trainers of 39°C. Four cases occurred during an initial deployment and three cases occurred during a re-deployment; one was in the 30 minute cold condition and two were in the 30 minute warm condition.
7. Taken as a whole, all recovery conditions appeared adequate to allow firefighters to recover sufficiently between work bouts. However, 30 minutes of cold recovery was the only condition to result in a 100% re-deployment success rate.

Recommendations

Based on the findings from this study, the following recommendations are made to optimise recovery between deployment bouts, to prolong work duration, and to maximise performance and health and safety.

1. For search and rescue activities conducted under thermo-neutral ambient conditions and continued to the operation of the low cylinder pressure warning whistle, the average firefighter should have at least 23 minutes of recovery, ideally, but not necessarily in a cool environment, with their PPE removed, and to consume a minimum of 500 ml cold water. This recovery duration should be extended to at least 28 min to prevent 95% of firefighters from reaching a core temperature of 39°C on more typical 20 min deployments and redeployments, thereby protecting the majority of firefighters during most deployments.
2. For firefighting, search and rescue activities conducted under conditions of live fire and continued to the operation of the low cylinder pressure warning whistle, the average firefighter should have at least 50 minutes of recovery, ideally, but not necessarily in a cool environment, with their PPE removed, and to consume a minimum of 1000 ml cold water. This recovery duration should be extended to at least 65 min to protect 95% of firefighters engaged in more typical 20 min deployments and redeployments.
3. Given that some firefighters exceeded a core temperature of 39.0°C during a single wear of an SDBA under both ambient and live fire conditions, the wearing of personal core temperature monitors is recommended to allow their withdrawal before critical core temperatures are reached.
4. Simple cooling strategies should be reinforced in firefighters to optimise the cooling process during recovery. These include the complete removal of outer PPE at the earliest opportunity, relocation to a cool, shaded place ideally with air movement, the consumption of reasonable volumes of cool fluid, and potentially the use of other active cooling strategies such as forearm cooling.

Chapter 1

Introduction

1.1 Study background

Work commissioned to Optimal Performance Limited (OPL) previously by the Buildings Disaster Assessment Group (BDAG) established that heat strain was the greatest single source of performance limitation and physiological threat to firefighters' wellbeing when undertaking firefighting and search and rescue activities in a built environment (Rayson *et al.*, 2004). In the absence of being able to make direct measurement of core body temperature in firefighters (which would potentially alleviate the need to set conservative normative-based limits to protect most firefighters on most occasions), revised, lower, maximum distances for horizontal penetration into buildings were proposed by OPL of approximately 30 metres, or less if stair climbing was involved.

However, this work was constrained to investigating single exposures, and these single exposures were somewhat artificially extended by the use of Extended Duration Breathing Apparatus (EDBA). In reality firefighter teams may be recommitted to deal with the same incident or another unrelated incident very quickly – and the response of firefighters to recommitment has not yet been investigated. Further, EDBA is not in widespread use, and it is Standard Duration Breathing Apparatus (SDBA) that would be used in the overwhelming majority of incidents. Again, other than knowing that the use of SDBA limits wear time to approximately 30 minutes (and sometimes much shorter periods depending on the demands of the scenario) therefore restricting the core temperature response, it is not known how repeated bouts of firefighting activities, interspersed with recovery periods, affect core temperature response, and hence the health, safety and operational effectiveness of firefighters.

This project attempted to build upon the evidence base quantifying the stress and strain to which firefighters are subjected. As with the previous work carried out for BDAG (Rayson *et al.*, 2004), the current project consisted of two phases: conventional search and rescue and firefighting activities in both ambient conditions (Phase 1) and live fire conditions (Phase 2). It pursued the major limiting factor to firefighter well-being and operational effectiveness (core body temperature) and examined firefighters' response to an initial deployment, a variable recovery period, and a subsequent re-deployment. The outcomes of this project will support and assist those in command by assisting in Risk Management Planning and dynamic risk assessment. In the absence of a direct measure of core body temperature, it provides evidence as to the adequacy or otherwise of different recovery conditions (durations and ambient temperatures) and the likelihood of firefighter safety and effectiveness during a re-deployment.

1.2 Review of literature

Numerous studies have been carried out to investigate intermittent exercise (work-rest-work etc), with wide ranging variations in the intensity of the exercise, the mode of exercise, duration of the work-rest periods and the ambient conditions. However, the majority of these studies were not interested in the effect of the rest period *per se* or in the decrement in performance between successive work bouts, but rather they were using the intermittent exercise as a particular exercise model ie to replicate team sports' activities such as soccer or as a model of endurance performance. Despite the different emphasis of these studies, insight can be gleaned from them with respect to the following questions:

- Is there a difference in physiological responses between successive work/exercise bouts separated by a rest period?
- What is the extent of the physiological recovery (ie reduction in core temperature) during rest periods of varying durations (30 to 120 minutes)?

Much of the early work on intermittent exercise concentrated on short duration (< 1 minute), supramaximal intensity (>100% VO₂max) exercise. The consensus from these studies was that the amount of work performed was, in part, dependant upon the length of the rest period. For example, Margaria and colleagues (1969) demonstrated that the number of successive bouts of 10 second high intensity running (18 km.h⁻¹) was significantly increased when they were separated by 30 second rest periods compared to 0, 10 and 20 second rest periods. In contrast, during more moderate intensity work (75% VO₂max), it has been reported that when the rest periods are short in comparison to the work periods (eg 27 minutes work – 3 minutes rest – 27 minutes work), the frequency and duration of the rests do little to improve performance (Gleser and Vogel, 1971). At the opposite end of the spectrum, McLellan et al. (2002) has recently shown that physical work performed on the previous day has no negative effect on the thermoregulatory response of soldiers carrying out work the next day.

In studies investigating low to moderate intensity exercise with longer rest periods (> 5 minutes) than those reported in the earlier studies of Margaria et al. (1969) and Gleser and Vogel (1971), conflicting findings are reported. Edwards and colleagues (1978) exercised subjects at a low intensity (75-100 Watts) for successive bouts of 10 minutes separated by 10 minutes rest at an ambient temperature of 24°C. Core temperature (oesophageal) increased by approximately 0.2°C and 0.3°C in the two exercise periods (significance not reported), and decreased by approximately 0.5°C in the intervening rest period. In contrast, House *et al.* (2003) investigated intermittent bench stepping exercise (10 minutes work, 5 minutes rest, repeated) in a climatic chamber maintained at 36°C and 55% relative humidity (RH). In this study core temperature (rectal) continued to rise during the rest periods, a finding which has been reported by previous, similar studies (Epstein *et al.*, 1990; Ohnaka *et al.*, 1993).

The reason for the discrepancy in findings can most likely be attributed to differences in the experimental protocols. In the Edwards study (1978) the ambient temperature was 24°C compared to 33-36°C in the other studies (Epstein *et al.*, 1990; House *et al.*, 2003; Ohnaka *et al.*, 1993). The higher ambient temperature in the latter studies will have compromised the potential for heat loss during the recovery period. Also, subjects wore standard physical training clothing (shorts and vest) in the Edwards study (1978), whereas they wore either cotton fatigues (Epstein *et al.*, 1990) or impermeable protective clothing (House *et al.*, 2003, Ohnaka *et al.*, 1993) in the latter studies, compromising the potential for heat loss. Finally, the site used for the measurement of core temperature also differed between studies, with Edwards (1978) using oesophageal and the remainder using rectal. Rectal temperature is known to respond slowly to thermal transients, unlike oesophageal temperature which has a quicker response time (Aikas *et al.*, 1962; Moran and Mendal, 2002). Interestingly, Edwards *et al.* (1978) also reported some rectal temperature data in the same study and these continued to rise during the rest periods, albeit at a slower rate than during exercise, demonstrating the lag of rectal relative to oesophageal temperature.

Kaciuba-Uscilko *et al.* (1992) had subjects perform alternating bouts of 30 minutes of exercise (cycling at 50% VO_2max) and 30 minutes of rest in an environment maintained at 22°C and 60% RH. Subjects were given 250 ml of fluid during the rest periods and it is assumed that they wore standard physical training clothing. Starting core temperature (rectal) was significantly higher in the second (approximately (~) 36.75°C) compared to the first exercise bout (~ 36.65°C). In addition, final core temperature was significantly higher in the second (~ 37.40°C) compared to the first exercise bout (~ 37.30°C). However, the rate of rise of core temperature was similar between exercise bouts (~ 0.022°C.min⁻¹). Heart rate was also significantly higher in the second compared to the first exercise bout despite returning to baseline values at the end of the rest period. Core temperature declined by ~ 0.55°C during the first 30 minute rest period. It was concluded that the progressive elevation of plasma concentrations of heat-liberating hormones was responsible for the increased core temperature and heart rate response over time (Kaciuba-Uscilko *et al.*, 1992).

In a similar study, Bennett and colleagues (1995) investigated alternating bouts of 30 minutes of exercise (walking at 1.12 m.s⁻¹) and 30 minutes of rest in an environment maintained at 34°C. Subjects were allowed to drink ad libitum during the protocol and wore standard Navy-issue damage-control gear at all times (Nomex firefighting ensemble, flashhood, helmet, boots and gloves). During the intervening rest period, unlike the findings of the previous study (Kaciuba-Uscilko *et al.*, 1992), core temperature (rectal) continued to rise, albeit at a lower rate (~ 0.017°C.min⁻¹) than during the exercise. The rate of rise of core temperature appeared (significance not reported) to be greater in the second compared to the first exercise bout (~ 0.037°C.min⁻¹ and ~ 0.030°C.min⁻¹ respectively).

Once again, the discrepancies between the findings of the two studies can most likely be explained by protocol differences. In the former study the ambient conditions for both

the exercise and rest periods were lower than the latter's (22°C vs. 34°C respectively). Furthermore, although fluid was available in both studies during the rest break, subjects wore heavy, partially impermeable firefighting clothing in the Bennett study (1995) which they were not permitted to doff during the rest phase. This clothing would have markedly reduced the cooling potential of the rest phase.

In a later study, Brenner and colleagues (1997) had subjects exercise (cycling at 50% VO_2max) on two occasions separated by 45 minutes of rest, either in an environment maintained at 23°C or 40°C. Subjects were 'lightly clothed' and water was freely available at all times. During the trial at 23°C the rise in core temperature (rectal) was significantly greater during the second bout of exercise compared to the first ($0.033 \pm 0.010^\circ\text{C} \cdot \text{min}^{-1}$ and $0.023 \pm 0.007^\circ\text{C} \cdot \text{min}^{-1}$ respectively). This was also the case during the trial at 40°C ($0.050 \pm 0.013^\circ\text{C} \cdot \text{min}^{-1}$ and $0.033 \pm 0.013^\circ\text{C} \cdot \text{min}^{-1}$ for the second and first bouts respectively). The rates of rise in the 40° trial were significantly greater compared to the respective values in the 23°C trial. Unfortunately, due to the limited display of the data, it is not possible to describe precisely the core temperature response in either trial during the rest period. However, it appears that core temperature in both trials decreased by ~0.2-0.3°C during the 45 minute period (Brenner *et al.*, 1997).

Recently a study investigated 120 minutes of rest separating two bouts of exercise (cycling at 60% W_{max}) performed either in thermo neutral (21°C) or hot (35°C) conditions (Armada Da Silva and Jones, unpublished observations). In both trials the 120 minutes of rest was carried out in thermo-neutral conditions, subjects wore standard exercise clothes and fluid losses were replaced during the rest period. Contrary to the authors' expectations, there was no difference in core temperature response between the first and second bouts of exercise in either ambient condition. This was a result of the substantial rest period and fluid replacement, which together resulted in core temperatures returning to baseline values by the start of the second exercise bout. This equated to a reduction in core temperature of 1.0-1.5°C in 120 minutes in both ambient trials.

Recently, OPL carried out work into cooling techniques with the UK Fire and Rescue Service (Carter *et al.*, 2005). A group of 10 firefighters performed simulated search and rescue, together with other simulated firefighting tasks, for a period of up to 50 minutes. Following this work period they were removed from the fire training building, doffed their PPE, consumed 1000 ml of cool water and sat in a cool (~15°C), ventilated room for 20 minutes. During this period core temperature (gastro-intestinal tract) declined by $0.65 \pm 0.40^\circ\text{C}$.

In summary, it appears that significant reductions in core temperature may occur during a rest period between successive bouts of exercise or work, depending on the ambient conditions surrounding the subject, the duration of the rest period, the clothing worn and the amount of fluid consumed. Under ambient conditions most akin to those proposed during the indoor recovery periods proposed in the present study, during 30 minutes of rest in thermo-neutral conditions (22°C) following 30 minutes of moderate exercise, a 0.55°C reduction in core temperature in lightly clothed subjects has been reported.

With 120 minutes of rest in similar ambient conditions, reductions in core temperature of 1.0-1.5°C have been reported in lightly clothed subjects. These reductions in core temperature are likely to be accentuated in the cooler ambient temperatures expected during the outdoor rest period in the present study.

Regarding the physiological burden associated with repeated exercise bouts, some studies report an increased core temperature response in the second bout relative to the first, while others report no difference. From the earlier studies it seems that the efficacy of the rest period may be crucial. In those studies reporting no difference in core temperature rate of rise between exercise bouts the rest period resulted in a relatively large reduction in core temperature ($>0.5^{\circ}\text{C}$). However, in those studies reporting an increased rate of core temperature rise in the second bout, the rest period resulted in little or no reduction in core temperature ($\leq 0.3^{\circ}\text{C}$). The progressive elevation of plasma concentrations of heat-liberating hormones may be responsible for the increased core temperature and heart rate response during exercise over time, despite regular rest periods. These hormones are likely to be released as a consequence of increasing fatigue symptoms, such as dehydration and carbohydrate depletion. As a result, euhydrated (normally hydrated) subjects with a high level of aerobic fitness, and who can increase their fuel stores during the rest periods by eating and drinking, are likely to perform better, with less physiological burden, than less fit, dehydrated subjects who do not re-fuel between exercise bouts.

Chapter 2

Study objectives

The objectives of this project were fourfold:

1. to describe the thermal and cardiovascular responses to an initial deployment, varied recovery periods, and a re-deployment.
2. to ascertain if performance and scenario outcome on the re-deployment were degraded relative to the initial deployment.
3. to compare thermal and cardiovascular response to the varied recovery periods and to the re-deployment¹.
4. to recommend recovery conditions prior to re-deployment.

¹ While we can compare these responses we may not be able to attribute causality, as we will have relatively poor control over other external confounding factors such as firefighters' work rates, their learning the routes, the environmental conditions in the building etc.

Chapter 3

Approach

3.1 Participants

With the assistance of London Fire Brigade, and West Yorkshire and Somerset Fire and Rescue Services (FRS) a group of 21 firefighters were secured as volunteers for participation in the Recovery and Re-deployment study. All participants were given a written and verbal brief and informed written consent was voluntarily provided. The occupational Physician from their FRS had recently medically screened all participants. All participants carried out the multistage fitness test during the study to enable values for maximum heart rate and maximal aerobic power (VO_2max) to be collected. Seventeen of the 21 were selected as the primary participant pool for the ambient trials (Phase 1) and, due to availability, a slightly different cohort of 16 were selected for the later live fire trials (Phase 2). During the Phase 1 trials only data from participants who carried out all three experimental conditions were analysed and reported in the results section ($n=13$ – refer to Section 3.7 for explanation). All 16 participants in the Phase 2 trials completed all conditions; therefore all data were presented in this case. The demographic and physiological profile of these two groups of participants is shown at Appendix A in Tables A1 and A2. A risk assessment was performed and risk management strategies were adopted. Ethics approval for the procedures was secured from the University of Birmingham School of Sport and Exercise Sciences Ethics Sub-Committee.

3.2 Experimental conditions and procedures

Throughout this report, several definitions are used to describe and differentiate the various elements in both Phases 1 and 2. These definitions are as follows:

- Scenario – a generic term used to describe the work carried out by the firefighters from a firefighting perspective.
- Serial – one serial was performed by a team of four firefighters and consisted of two work bouts ('initial deployment' (a) and 're-deployment' (b)), separated by a 'recovery' period (r).
- Work Bout – two work bouts, consisting of an initial deployment and a re-deployment were performed.

Condition – refers to the content of the serial and specifically the duration and location/ambient temperature of the recovery periods: 30 minutes outdoors (A1); 30 minutes indoors (A2) or 120 minutes indoors (A3).

Participants attended the Fire Service College (FSC) at Moreton-in-Marsh to undergo the Phase 1 ambient scenario three times, under each of the experimental conditions as defined by the client. All deployments were performed in the heated BA Complex building by four teams of four firefighters. The teams were formed in a randomised fashion and varied from day to day, and the order in which the conditions were performed was also randomised to minimise learning effects and bias. The three conditions, referred to as A1-A3, are depicted in Table 3.1 and four serials were performed per experimental condition.

Firefighters worked in teams of four (with 2 fulfilling the firefighting (FF) role and 2 the search and rescue (SR) role). In the initial deployment the task was to locate and rescue one casualty. The firefighters then retired to one of three recovery sites: a ‘cool’ area with temperatures approximately 13°C (Outdoors – A1 r), the drying room in the BA Complex maintained at around 25°C (Indoors – A2 r), or a classroom also within the BA Complex maintained at 22°C (Indoors – A3 r). During the 30 minute recovery periods participants partially removed their PPE (over trousers rolled down and firefighting tunic removed) for body cooling. During the 2 hour recovery period the firefighters doffed their PPE and spent the period in their regular work-wear. During all recovery periods participants were permitted to drink water *ad libitum*; the consumption of any other food or fluid was prohibited. The re-deployment involved a repeat of the scenario but on a different floor of the BA Complex to ensure that they were not familiar with the route.

Table 3.1. Phase 1: ambient experimental conditions			
Condition	Length of Recovery Period (min)	Location of Recovery Period	Number of Serials
A1	Initial deployment – 30 min rest – Re-deployment	Outdoor	4
A2	Initial deployment – 30 min rest – Re-deployment	Indoor	4
A3	Initial deployment – 120 min rest – Re-deployment	Indoor	4

Standard operating Procedures (SOP) were followed at all times. Under all conditions 51 mm hose was used between the appliance and the door to the building on the fire floor. Assistance was provided with all of the support tasks (eg charging the hose, pulling the hose up the stairs to the door, feeding the hose in through the door), enabling the four firefighters who were being monitored to focus on their designated roles. Safety officers were in attendance at all times. The trials were performed self-paced. All conditions during Phase 1 were performed with total visual obscuration to simulate worst case conditions of a smoke-logged building. Participants were instructed to ‘stay low’ according to their SOP, again to mimic worst case scenario under conditions of live fire. New search routes were devised for every scenario to ensure that on each deployment the route was unfamiliar to the firefighters. This ensured that the firefighters did not retain a mental picture of the

route, therefore preventing them proceeding faster on subsequent trials. The maximum horizontal distance of penetration was ~40-45 m.

Two weeks after the Phase 1 trials 16 firefighters again attended the FSC to undergo Phase 2 of the trials. The operational details had evolved from Phase 1, and live fires were included. Three live fire serials were performed each test day. All serials were carried out in the Domestic building at the FSC (Figure 3.1). Participants were randomly allocated in pairs to the FF and SR roles. Both FF and SR wore SDBA, and 70 mm hose was used to supply water from the hydrant to the appliance. In all instances the firefighting attack was undertaken using 51 mm hose from the fire appliance.

In the initial deployment the task was to locate and rescue up to six casualties. The firefighters then retired to one of three recovery sites: a 'cool' area with temperatures around 15°C (Outdoors – L1 r), the drying room in the BA Complex maintained at approximately 24°C (Indoors – L2 r) or a classroom also within the BA Complex maintained at approximately 22°C (Indoors – L3 r). During the 30 minute recovery periods participants partially removed their PPE (over trousers rolled down and firefighting tunic removed) for body cooling. During the two hour recovery period the firefighters doffed their PPE and spent the period in their regular work-wear. During all recovery periods participants were permitted to drink water *ad libitum*, but other food and drinks were prohibited. The re-deployment task involved a repeat of the scenario whilst locating and rescuing one or more casualties. The maximum horizontal distance of penetration was ~30-35 m, the maximum available within the small building. Both floors of the building were used, necessitating the climbing and descending of a single flight of stairs.

Figure 3.1. The Domestic building at the FSC used in Phase 2



Overall, 12 live fire serials were conducted over three different conditions, detailed in Table 3.2.

Table 3.2. Phase 1: live fire experimental conditions

Table 3.2. Phase 1: live fire experimental conditions			
Condition	Length of Recovery Period (min)	Location of Recovery Period	Number of Serials
L1	Initial deployment – 30 min rest – Re-deployment	Outdoor	4
L2	Initial deployment – 30 min rest – Re-deployment	Indoor	4
L3	Initial deployment – 120 min rest – Re-deployment	Indoor	4

3.3 Fire and firefighting environment instrumentation

Each serial in Phase 2 was carried out using both floors of the Domestic Building at the FSC. A number of standard single FSC wooden cribs were used as the target fires consisting of five pallets (Figure 3.2). In addition straw bales were ignited to create smoke.

Figure 3.2. An example of a standard FSC crib burning in the Domestic building



3.3.1 Instrumentation to measure the firefighting environment

The Domestic Building was instrumented with two thermocouple trees to measure fire gas temperatures and the data logged at 3 second intervals during all serials.

Thermocouples

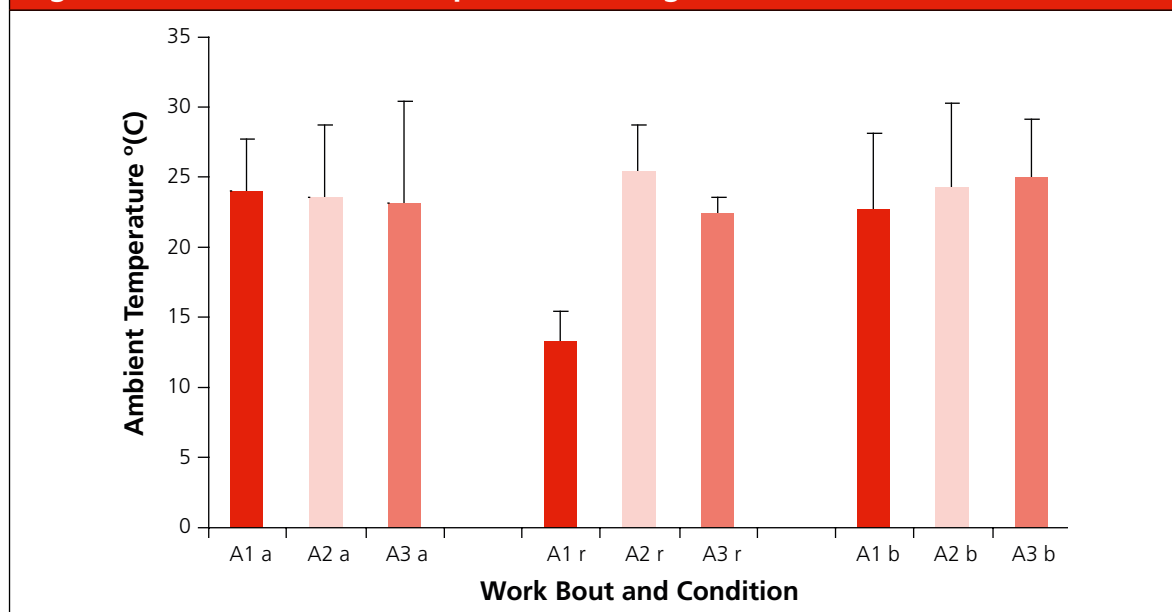
The thermocouple trees were positioned approximately three metres away from each of the cribs on the ground and first floors. Each tree contained six thermocouples positioned at heights of one, two, three, four, five and six feet off the floor.

3.4 Environmental conditions

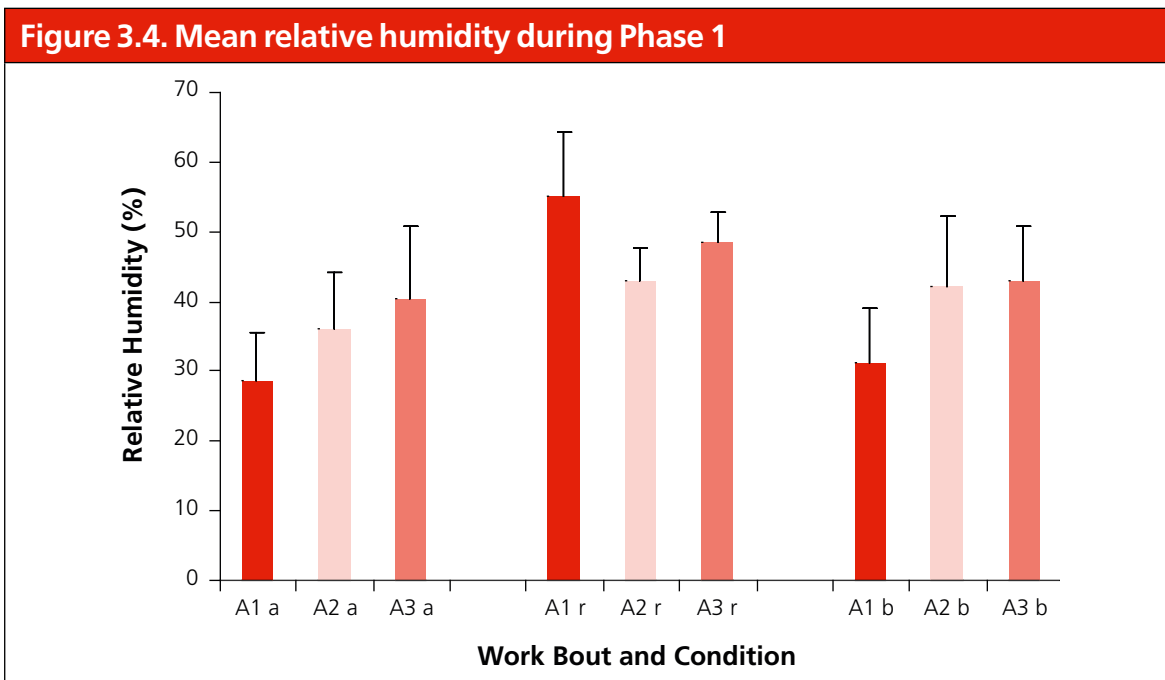
3.4.1 Ambient conditions during Phase 1

An external probe that one of the pair of firefighters carried, attached to, but not in contact with the BA set, recorded ambient temperature during the ambient serials. Summary data for both the temperature and humidity inside the building during the initial deployment (a), and the re-deployment (b), as well as the recovery period (r), are displayed for all conditions in Figures 3.3 and 3.4 and Table B1 in Appendix B. There were no differences in ambient temperature during the work bouts between conditions, with the overall mean temperature inside the BA complex for all trials being $23.8 \pm 5.1^\circ\text{C}$. During the 30 minute cold recovery period (condition A1) average ambient temperatures ($13.3 \pm 2.2^\circ\text{C}$) were significantly lower than temperatures during the warm recovery periods (A2: $25.5 \pm 3.2^\circ\text{C}$ and A3; $22.4 \pm 1.1^\circ\text{C}$, $p < 0.001$).

Figure 3.3. Mean ambient temperature during Phase 1



Where a refers to the initial deployment, r refers to the recovery period and b refers to the re-deployment



3.4.2 Ambient conditions during Phase 2

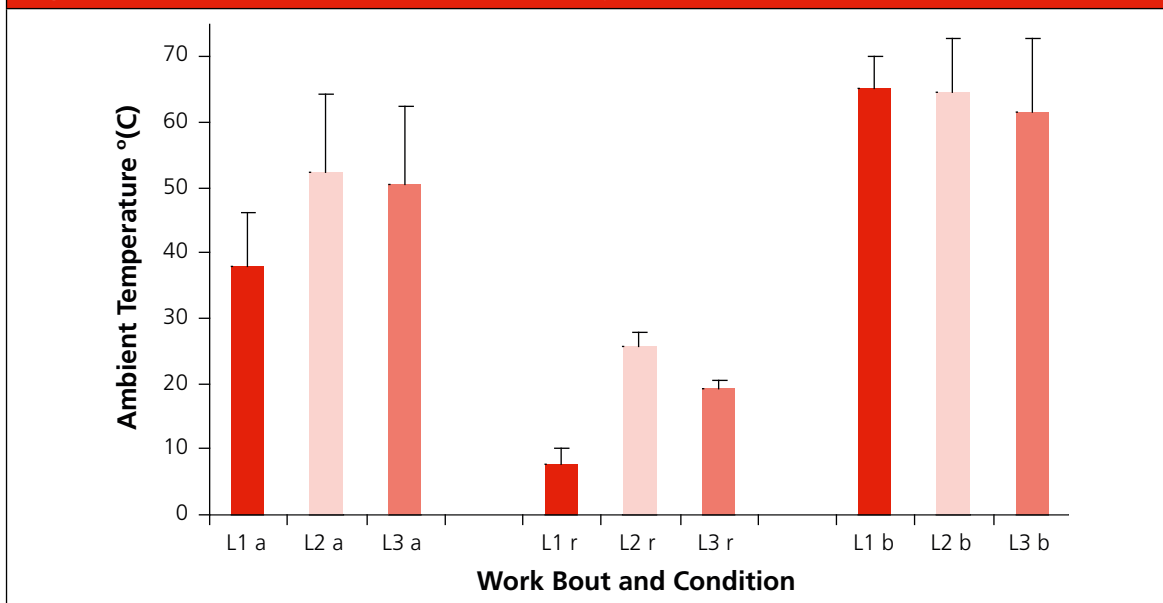
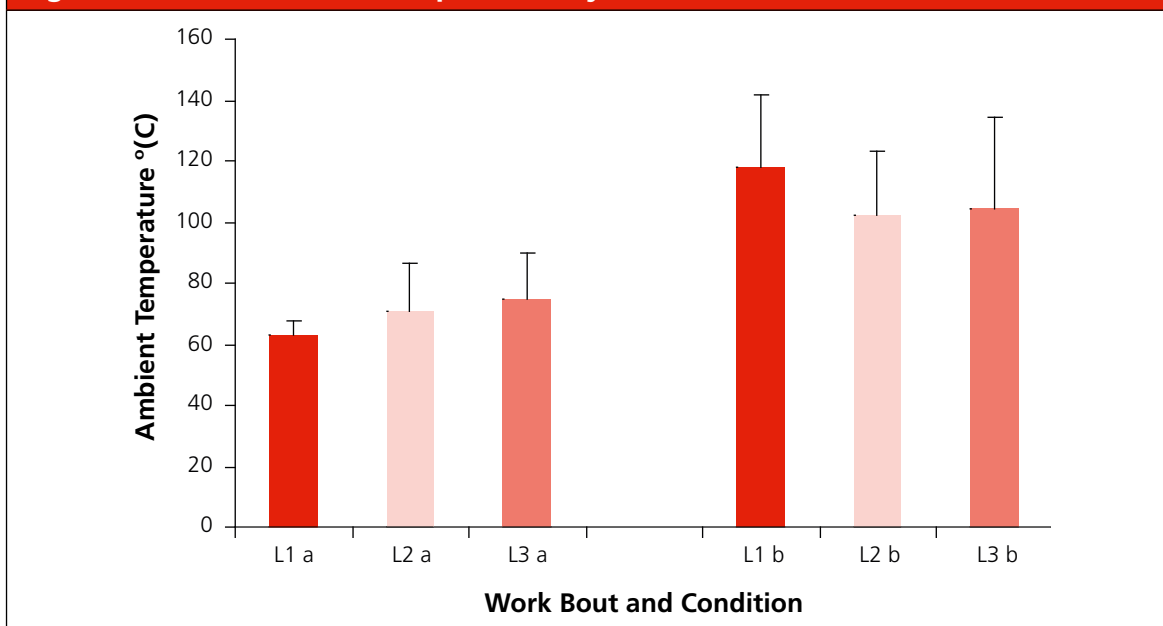
All members of each team carried an external temperature probe that recorded ambient dry bulb² temperature during the live fire serials. The mean ambient dry bulb temperatures experienced by the firefighters from the start of the serial to when they came 'off air'³ are shown in Figure 3.5 and Table C 1 in Appendix C and the peak temperatures recorded are shown in Figure 3.6.

There was a difference in ambient temperatures between work bouts (a: $48.4 \pm 12.2^{\circ}\text{C}$, b: $63.4 \pm 9.0^{\circ}\text{C}$, $p < 0.01$) but not between experimental conditions (L1: $51.6 \pm 15.8^{\circ}\text{C}$, L2: $58.5 \pm 11.7^{\circ}\text{C}$, L3: $56.0 \pm 12.6^{\circ}\text{C}$, $p > 0.05$) and there was no interaction ($p > 0.05$). Therefore, ambient temperatures were greater in the re-deployment irrespective of condition. As expected mean ambient temperature was significantly different during the recovery conditions, with L1 ($7.6 \pm 2.5^{\circ}\text{C}$) colder than L3 ($19.4 \pm 1.1^{\circ}\text{C}$) which was colder than L2 (L2: $25.7 \pm 2.3^{\circ}\text{C}$, $p < 0.01$).

As with ambient temperature, there was a difference in peak ambient temperatures between work bouts (a: $70.7 \pm 14.2^{\circ}\text{C}$, b: $106.4 \pm 26.0^{\circ}\text{C}$, $p < 0.01$) but not between experimental conditions (L1: $90.4 \pm 33.2^{\circ}\text{C}$, L2: $86.3 \pm 24.5^{\circ}\text{C}$, L3: $89.3 \pm 28.0^{\circ}\text{C}$, $p > 0.05$) and there was no interaction ($p > 0.05$).

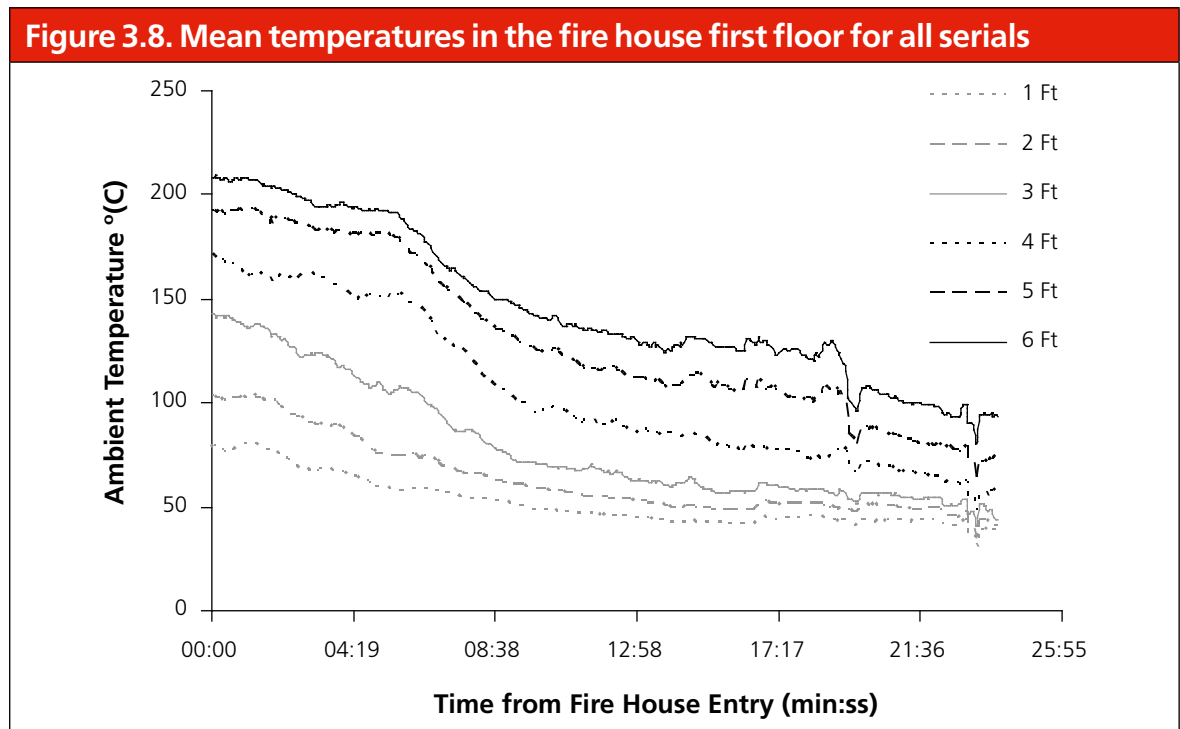
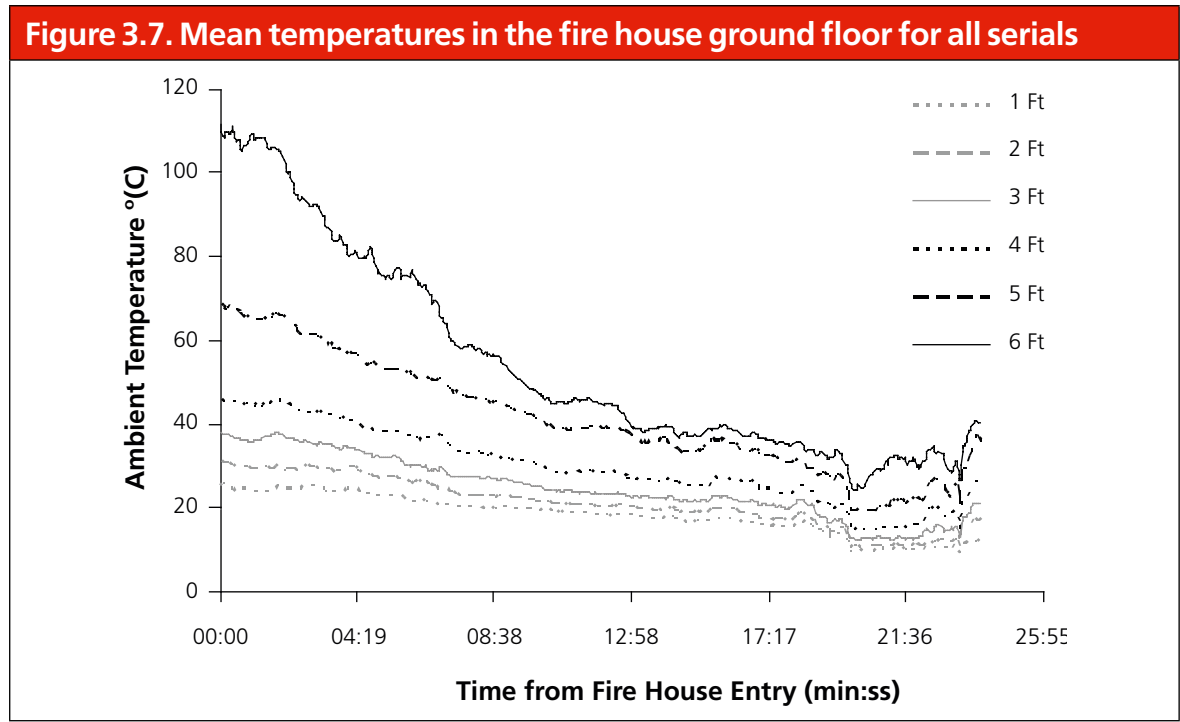
² No measure of radiative heat was made by the body-borne probes, which would have been significant in these live fire situations.

³ 'Off air' refers to the moment at which the firefighter stops breathing air from the breathing apparatus. 'On air' refers to the moment at which the firefighter starts breathing from the breathing apparatus. 'Under air' refers to the period between 'on air' and 'off air'.

Figure 3.5. Mean ambient temperature by condition and team

Figure 3.6. Peak ambient temperature by condition and team


Figures 3.7 and 3.8 show the mean temperatures recorded by the thermocouples mounted at different heights (1, 2, 3, 4, 5 and 6 feet from the floor) in the ground floor and first floor of the fire house. Progressively increased temperatures were recorded with increasing height within the house on both floors, with significantly greater temperatures recorded on the first compared to the ground floor. For example, peak temperatures of approximately 38°C were recorded at 3 ft on the ground floor compared to 143°C at the same height on the first floor. Similarly, peak temperatures of 111°C and 209°C were recorded at a height of 6 ft on the ground and first floors, respectively. On the ground floor (Figure 3.7) the temperatures declined sharply during the first 10 minutes as the firefighters attacked the fires, before levelling off for the remainder of the exercise once the fires had

been extinguished. A similar pattern was seen on the first floor (Figure 3.8), although the rate of temperature decline is less steep reflecting the floor’s higher temperature due to the often greater number of fires on this floor, the longer burn time compared to fires on the ground floor, and the heat rising from the ground floor up the stairwell.



3.5 Physiological measurements

The firefighters arrived in their teams at least one hour before performing each serial for pre-testing and instrumentation having swallowed an indigestible core temperature thermometer pill (HQ Inc, Cortemp, USA) the previous evening⁴. They had been asked to abstain from eating for two hours prior to their test and to ensure that they were in a state of good hydration. Following nude weighing, firefighters were instrumented for skin temperature (four sites: neck, shoulder, hand and shin) using skin thermistors (Grant, UK) and heart rate (Polar Team System, Polar, Finland). The data loggers (Squirrel Loggers, Grant, UK; and HQ Inc, Cortemp, USA) were connected and secured to the firefighters and recording was started. In addition, firefighters wore a triaxial activity monitor (3dNX™, BioTel Ltd, UK) in the small of the back, attached using an elasticated belt worn around the waist, to provide a measure of activity rate during the scenario. Data were logged every 5 seconds (heart rate), 20 seconds (core and skin temperature) and 60 seconds (activity) throughout each scenario. Finally the firefighters dressed in their standard firefighting PPE, donned their SDBA sets, were re-weighed and then either walked approximately 50 m to the BA complex building (Phase 1) or boarded the transport to take them 500 m to the domestic building (Phase 2).

Immediately prior to the start of the serial, baseline measures of SDBA pressure and core temperature were recorded. Thereafter, at 5-minute intervals, readings of core temperature were taken by telemetry, both as a backup to the 20-second logged data and for safety reasons. If a core temperature of 39.0°C was reached, readings were taken every 2.5 minutes. In addition to the ambient temperature being recorded by the temperature probe carried by the firefighter, humidity during each serial was measured by a humidity probe carried by a physiologist accompanying the firefighters at all times during Phase 1 and during the recovery period in Phase 2. Air use was recorded both as pre- and post-pressure gauge readings, and also by the DrägerMan BodyGuard (Draeger Safety UK Limited) computerised system, though these BodyGuard data are not reported here. The BodyGuard system recorded the pressure drop in the SDBA every 20 seconds and the data were uploaded at the end of the serials.

The serials began on the instruction of the Incident Commander once the fires had established themselves (in the case of Phase 2) and the physiologists and firefighters were ready. The FF and SR teams were briefed by the Incident Commander before proceeding to the entry control point where they went under air and subsequently entered the fire compartment. Support teams fed hose as far as the compartment entrance. The teams were instructed to perform a right- or left-hand search, following the walls in the nominated direction. The primary role of the lead FF team was to suppress the fires, while that of the SR team was to search the compartment for casualties and remove them from the fire compartment, handing them to support firefighters at the compartment entrance.

⁴ Throughout the study two different radio frequency pills were used in an attempt to ensure all firefighters contained a temperature pill at a sufficient depth in their GI tract as to be unaffected by drinking cold fluid. As a consequence, all firefighters were checked they contained a pill the night before each test, with a new pill swallowed if they had excreted their previous pill. On the infrequent occasions (~5%) that a firefighter arrived for instrumentation without a pill in their GI tract, they were immediately given a new pill and instructed not to consume any fluid during the ensuing serial.

At the termination of the initial deployment, final readings were taken of SDBA pressure and core temperature before the firefighters were escorted back to the recovery area either on foot (Phase 1) or by transport (Phase 2) where they doffed their SDBA, partially/fully removed their PPE and were handed a 2 litre bottle of cool water. During the recovery period the firefighters rested quietly, whilst drinking as much water as they wished. In the case of a firefighter requiring the toilet during this period they were weighed before and after, with this loss accounted for in determination of overall body mass changes. Total water intake was measured during the recovery period and final body mass was corrected for this intake to calculate estimated sweat loss. Following the recovery, the firefighters donned their PPE and a new charged SDBA cylinder and were escorted back to the Incident Commander. Once the firefighters had received a verbal brief on the re-deployment, it was carried out using the same protocols as in the initial deployment. During the re-deployment, FF and SR roles were reversed. To avoid learning effects different routes to the casualty and alternating floors were used between deployment bouts in Phase 1, whilst in Phase 2 the location of the casualties differed between deployments.

At the termination of the re-deployment, final readings were taken of SDBA pressure and core temperature before the firefighters were escorted back to the instrumentation area either on foot (Phase 1) or by transport (Phase 2) where they were de-instrumented and re-weighed nude. All measurements of firefighters' activity, water usage and changes in environmental conditions as a result of firefighting activities were recorded on a common time line for subsequent analysis.

3.6 Termination and safety criteria

The overall exercise was under the control of an officer with extensive experience of fire ground exercises at the FSC, retained to the project for this purpose. Full paramedic cover was available throughout the trial to deal with any medical emergency which may have occurred. Each pair of firefighters undertaking the trials was monitored by one safety officer who was familiarised with the escape points from every floor of the firehouses. If one firefighter was withdrawn, then the whole team was also withdrawn to allow the recovery period to start at the same time.

The test termination criteria were four-fold:

- The air pressure in the BA sets, as judged by the firefighters, became low and the firefighters withdrew.
- Core temperature of 39.5°C was reached⁵, the firefighter team was withdrawn and the individual actively cooled.

⁵ To mitigate the risks of heat exhaustion and heat stroke, the World Health Organisation proposes an upper core temperature limit of 38.5°C for industrial populations. The Guidance on the Management of the Risk of Heat Stress during Training (Fire Research Report Number 1/2001) proposes 39°C as a safe upper limit for live fire training in firefighters. In this series of research studies conducted by OPL, an upper working limit of 39.5°C was imposed, coupled with individual monitoring of core temperature and the presence of a paramedic.

- Safety officers judged the firefighter to be unsafe at any time, or the firefighter requested to stop for any reason, the firefighter was withdrawn, and where appropriate, actively cooled.
- The firefighter team succeeded in completing the task (ie extinguishing the fires, rescuing the casualties using standard operating procedures and returning safely to the entry control point).

Members of the safety staff were also dynamically monitored for core temperature and withdrawn from the compartment if their core temperature reached 39.5°C, though these data were not recorded or reported here.

3.7 Statistical analysis

The results in this report are expressed as mean \pm one standard deviation (SD). Comparative analyses were performed using standard parametric statistics (ANOVA) run on Statistical Package for the Social Sciences (SPSS) version 12 for Windows. A two-way (work bout and condition) repeated measures ANOVA was used to analyse the data. Although this means that only those subjects who had complete data sets for all three trials could be included in the final analyses, this type of design reduces potential variation by controlling for individual variability, thereby providing a more powerful statistical analyses of the data than using a between subjects design. Post-hoc pair wise comparisons were made using t-tests (for condition) or Tukey's honestly significant differences test (for interaction effects). Statistical significance was set a-priori at $p < 0.05$; where $p < 0.05$ indicates the probability that the difference documented occurred by chance is 0.05, or 5%. P values of 0.01 and 0.001 indicate significance at the 1% and 0.1%, respectively, indicating progressively increasing degrees of confidence in the differences reported. The terms 'approaching statistical significance' or 'tended' are used to denote a probability of less than 0.1 or 10%. Heart rate data were expressed as a percentage of Heart Rate Reserve (%HRR) as this index of cardiovascular strain is recommended by the American College of Sports Medicine, and it takes into account individually measured sleeping and maximal heart rates measured during the study.

The data for Phase 1 and Phase 2 has been reported in three separate sections for each condition. The first section describes the physiological responses to the initial deployment in any one condition (coded **a** in figures and tables). This describes the period between the firefighters going on air and entering the building for the first time to exiting the building and coming off air for the first time. The second section describes the physiological responses to the recovery period between work bouts (coded **r** in figures and tables). This describes the period between the firefighters coming off air for the first time to going on air for the second time. The third section describes the physiological responses to the re-deployment in any one condition (coded **b** in figures and tables). This describes the period between the firefighters going on air and entering the building for the second time

to exiting the building and coming off air for the second time. Typically, there was a 1-2 minute time interval between the firefighters going on air and entering the building during Phases 1 and 2.

3.8 Participants' fitness

In the Phase 1 cohort, of the 13 that participated in all experimental conditions eight were male and five female. All completed the multistage fitness test. An individual breakdown of participants' physiological characteristics is provided in Appendix A, Table A1. In summary, age averaged 32 years and ranged from 24 to 40 years. Mean height was 175 cm and mean mass was 81 kg. Mass ranged from 61 to 106 kg providing a good range of body sizes. From the multistage fitness test, mean maximal aerobic power ($\text{VO}_{2\text{max}}$) was $42 \text{ ml.kg}^{-1}\text{min}^{-1}$ and 3.4 l.min^{-1} with values ranging from 30 to $50 \text{ ml.kg}^{-1}\text{min}^{-1}$ and from 2.0 to 4.5 l.min^{-1} .

In the Phase 2 cohort, 10 of the 16 were male, six were female, and all firefighters completed the multistage fitness test. An individual breakdown of participants' fitness is provided in Appendix A, Table A2. In summary, age averaged 33 years, ranging from 24 to 42 years. Mean height was 176 cm and mean mass was 81 kg. Mean maximal aerobic power ($\text{VO}_{2\text{max}}$) was $44 \text{ ml.kg}^{-1}\text{min}^{-1}$ and 3.6 l.min^{-1} with values ranging from 30 to $55 \text{ ml.kg}^{-1}\text{min}^{-1}$ and from 2.6 to 4.5 l.min^{-1} .

It appears that a majority of participants in both cohorts fell in the middle range of the fitness distribution of serving firefighters, based on our best estimate that the mean $\text{VO}_{2\text{max}}$ of serving firefighters is around $43 \text{ ml.kg}^{-1}\text{min}^{-1}$ (Rayson et al., 2003). Eight of the 18 fitness-assessed participants from the Phase 1 and 2 cohorts were below this value. Three were male and five were female. Mean aerobic fitness data on the UK general population⁶ have been reported as being approximately $50 \text{ ml.kg}^{-1}\text{min}^{-1}$ for men aged 25-34 and approximately $46 \text{ ml.kg}^{-1}\text{min}^{-1}$ for men aged 35-44, though these figures are thought to be unrepresentatively high. Comparative values for women are 38 and $35 \text{ ml.kg}^{-1}\text{min}^{-1}$, respectively. The mean values of around $43 \text{ ml.kg}^{-1}\text{min}^{-1}$ in these cohorts is beneath the $45 \text{ ml.kg}^{-1}\text{min}^{-1}$ until recently recommended for entry to the Service.

⁶ The Allied Dunbar National Fitness Survey, 1992, p88.

Chapter 4

Phase 1 Results: Ambient Conditions

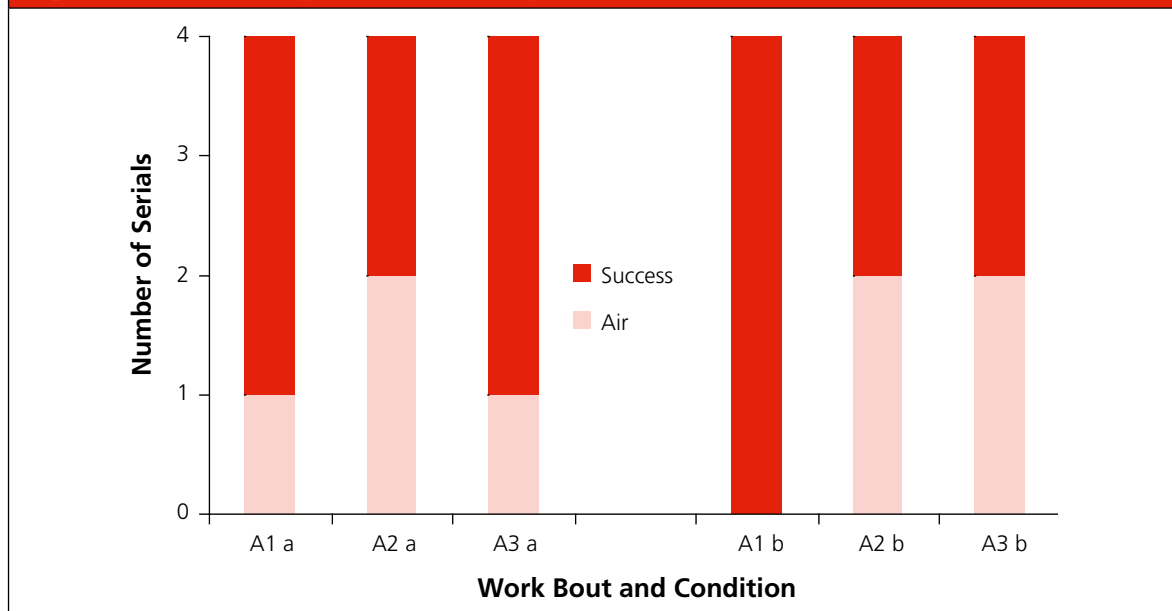
4.1 Summary of outcomes by condition

The outcomes of the three experimental conditions each performed by four teams are shown in Figure 4.1 and provided numerically in Table B2 in Appendix B. Over all (initial deployment and re-deployment work bouts combined to give 24 tests) the ambient serials:

- 16 (67%) were successful in completing the scenario, rescuing the casualty
- 8 (33%) were terminated prematurely due to a shortage of air.

Condition A1 (30 minutes rest outdoors) had the highest success rate in the re-deployment work bout (100%), with both A2 and A3 conditions having a 50% success rate. In these two conditions shortage of air was the sole reason for early termination.

Figure 4.1. Summary of outcomes by condition and work bout

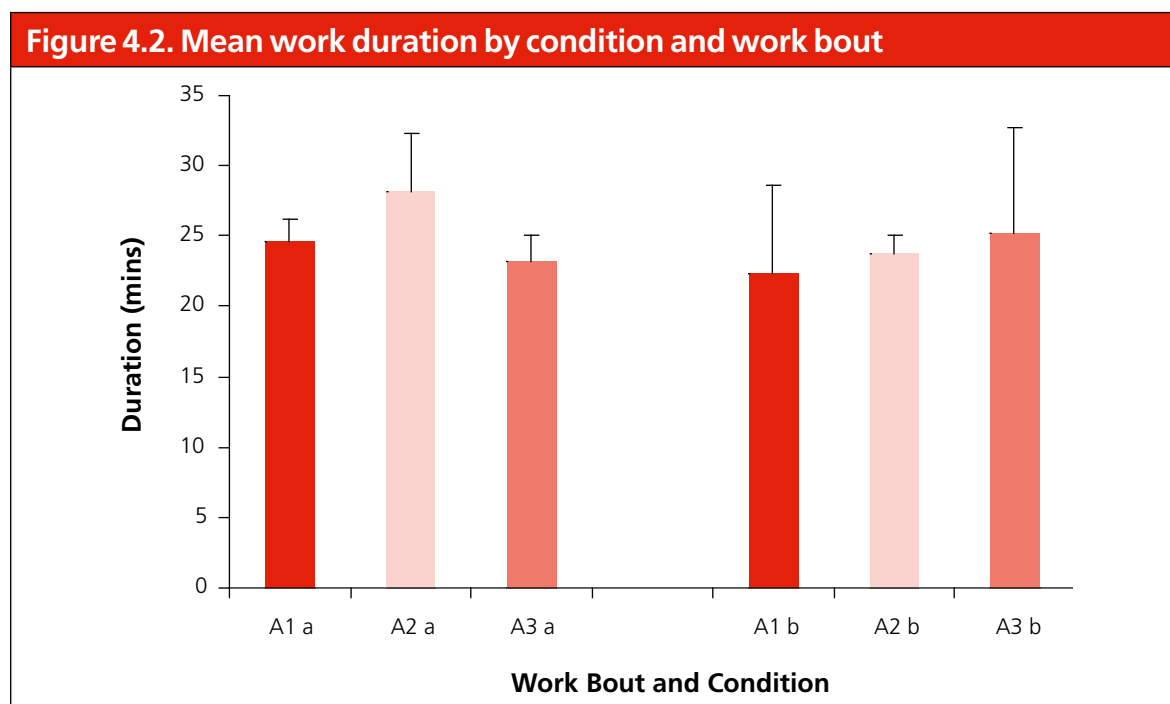


4.2 Work duration and external load

Figure 4.2 shows the total work duration for the two work bouts in all three experimental conditions. The mean work duration for each work bout was calculated as the time the first firefighter entered the building to the time the first firefighter came off air, having exited the building.

There were no differences in work duration between work bouts (a: 25.3 ± 3.3 min, b: 23.7 ± 5.7 min, $p=0.13$) or conditions (A1: 23.5 ± 4.6 min, A2: 25.9 ± 3.8 min and A3: 24.2 ± 5.4 min, $p=0.17$). However, there was an interaction effect between work bout and condition ($p=0.01$), where A2a was greater than A3a ($p<0.05$), A1b ($p<0.01$) and A2b ($p<0.05$). Therefore, apart from the long initial deployment work duration in A2a (28.1 ± 4.2 min), all other work durations were similar (23.8 ± 4.5 min).

As planned, recovery duration (from the end of the initial deployment to the start of the re-deployment) was significantly longer in A3 (129.9 ± 3.7 min, $p<0.01$) compared to A1 (41.2 ± 2.3 min) and A2 (41.9 ± 3.7 min).

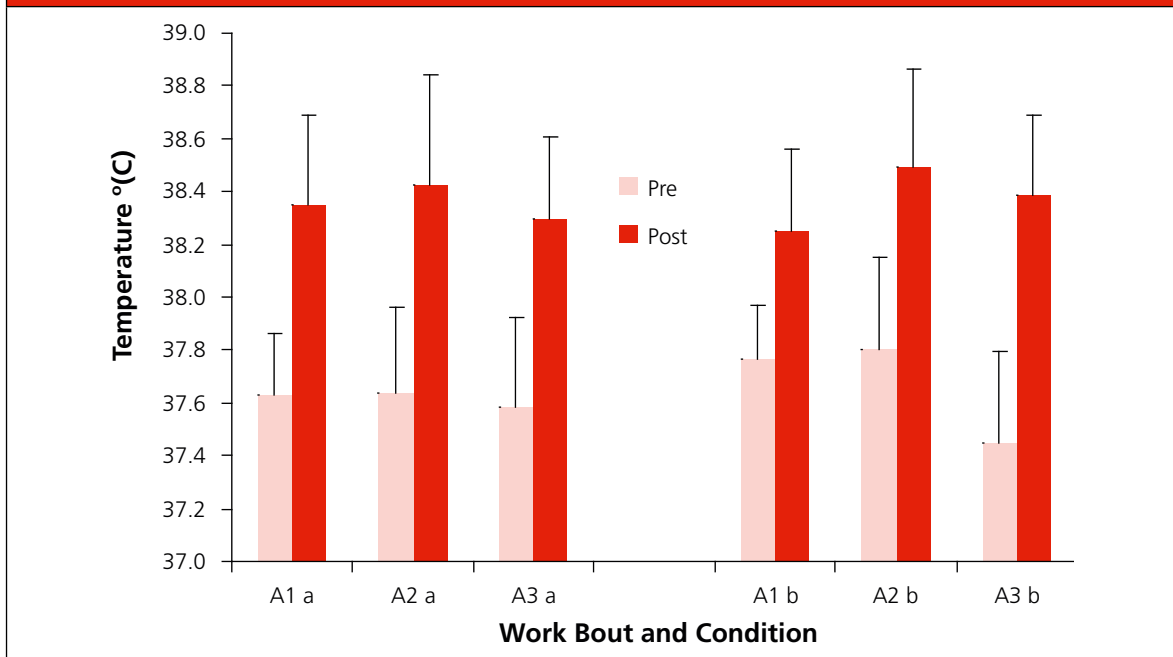


Where $n = 13$ for all work bouts and conditions.

Firefighters carried $22.9 (\pm 0.8)$ kg of external load during Phase 1, which equated to 29 (± 4) % of their group mean body mass. Some firefighters carried less relative load than others. For example, external loads represented only 21 % of body mass for the heaviest firefighter, compared to 37% for the lightest.

4.3 Core temperature response

Figure 4.3 and Table B3 in Appendix B show the core temperature response, as measured by the GI tract telemetry pills, by experimental conditions and work bouts. The columns in Table B3 show the number of firefighters in each condition, the mean duration of the test in minutes, the core temperatures at the beginning and end of the test, the rise in core temperature over the duration of the test, and the rate of rise of temperature.

Figure 4.3. Mean core temperature response by condition and work bout

There were no differences in baseline core temperatures between work bouts (a: $37.6 \pm 0.3^\circ\text{C}$, b: $37.7 \pm 0.3^\circ\text{C}$), but there were between conditions ($p=0.03$), where baseline core temperature was lower in condition A3 ($37.5 \pm 0.3^\circ\text{C}$) than in A1 ($37.7 \pm 0.2^\circ\text{C}$, $p=0.07$) and A2 ($37.7 \pm 0.3^\circ\text{C}$, $p<0.01$). An interaction effect ($p<0.01$) revealed that the lower baseline core temperature in A3 was due to A3b ($37.4 \pm 0.3^\circ\text{C}$) being lower than A1a ($p<0.05$), A1b ($p<0.01$) and A2b ($p<0.01$). Therefore, prior to the initial deployment, there were no differences in baseline core temperature. Prior to the re-deployment, the baseline core temperature was lower following 120 min of recovery than following either of the 30 min recovery conditions.

There were no differences in the final core temperatures reached at the end of each work bout either between bouts or conditions, with the average final core temperature over the six bouts being $38.4 \pm 0.3^\circ\text{C}$. No firefighters reached the cut-off core temperature of 39.5°C but three of the 66 firefighters (4%) reached core temperatures in excess of 39°C . only one occurred during the re-deployment and that was during the 30 minute warm condition. In previous SDBA search and rescue work, two firefighters (6%) attained the cut-off core temperature and six of the 32 firefighters (19%) exceeded 39°C (Rayson *et al.*, 2004).

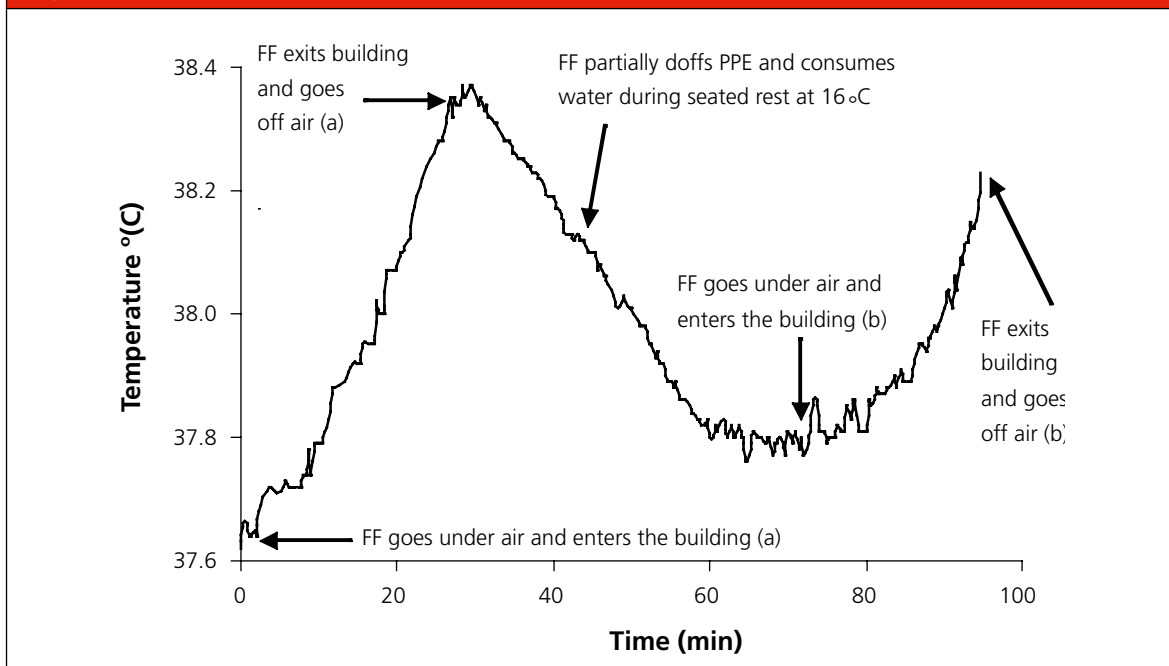
There were no differences in the rises in core temperature between work bouts (a: $0.74 \pm 0.28^\circ\text{C}$, b: $0.71 \pm 0.38^\circ\text{C}$, $p=0.62$), or between conditions (A1: $0.60 \pm 0.32^\circ\text{C}$, A2: $0.74 \pm 0.28^\circ\text{C}$, A3: $0.82 \pm 0.36^\circ\text{C}$, $p=0.11$). However, an interaction effect ($p<0.01$) revealed that the rise in temperature during A1a ($0.72 \pm 0.30^\circ\text{C}$) and A2a ($0.79 \pm 0.30^\circ\text{C}$) were both greater than A1b ($0.48 \pm 0.31^\circ\text{C}$, $p<0.05$), and that A1b and A2b ($0.70 \pm 0.27^\circ\text{C}$) were both less than A3b ($0.94 \pm 0.41^\circ\text{C}$, $p<0.05$). Therefore, although the rise in core temperature was similar between the three conditions during the initial deployment, during the re-deployment the rise in core temperature was greater following 120 min of warm recovery.

Once the rise in core temperature had been corrected for bout duration there were no differences in the rate of rise of core temperature between bouts ($p=0.92$) or conditions ($p=0.09$). However, an interaction effect ($p<0.01$) revealed that the rate of rise of core temperature in A1b ($0.021 \pm 0.014^\circ\text{C}\cdot\text{min}^{-1}$) was lower than in A2b ($0.030 \pm 0.012^\circ\text{C}\cdot\text{min}^{-1}$, $p<0.05$) and A3b ($0.036 \pm 0.011^\circ\text{C}\cdot\text{min}^{-1}$, $p<0.01$).

There were no differences ($p=0.98$) in the rates of decline of core temperature in the recovery periods, when each condition was compared after 30 min of recovery, with a mean decline of $-0.017 \pm 0.013^\circ\text{C}\cdot\text{min}^{-1}$ over this period (see Table B3).

Therefore, during the initial deployment, the rates of rise of core temperature were similar between the three conditions. However, following 30 minutes of cold recovery, the rate of rise during the re-deployment was less than that attained following the 30 and 120 minutes of warm recovery. The rate of decline in core temperature was similar in the three recovery periods.

An individual plot of core temperature response is shown in Figure 4.4 as an example. This particular firefighter spent approximately 95 minutes engaged in this condition (A1), with 25 minutes spent in the first work bout, 40 minutes between deployments and 30 minutes spent in the second work bout. The core temperature response shows a markedly sharp increase during the first work bout before reaching a peak as the firefighter exited the building and came off air for the first time. Throughout the rest interval the core temperature declined steadily and fairly linearly until 60 minutes, after which it began to plateau. As with the first work bout, core temperature increased throughout the second work bout reaching a peak of 38.2°C after 95 minutes.

Figure 4.4. An example core temperature response to A1

Where FF refers to the firefighter, (a) refers to the initial deployment and (b) refers to the re-deployment.

4.4 Skin temperature response

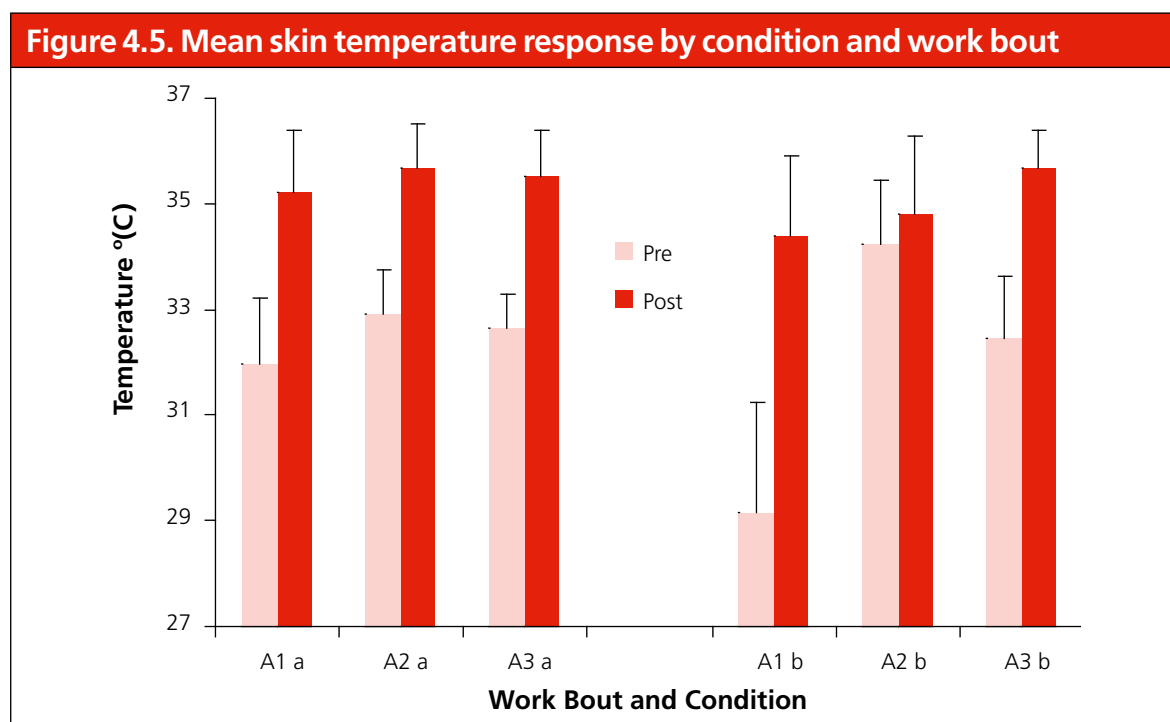
A summary of the mean skin temperature response is shown in Figure 4.5 and the data are shown in Table B4 in Appendix B.

There were differences in baseline skin temperatures between work bouts (a: $32.5 \pm 1.0^\circ\text{C}$, b: $32.0 \pm 2.6^\circ\text{C}$, $p=0.01$) and conditions (A1: $30.6 \pm 2.2^\circ\text{C}$, A2: $33.6 \pm 1.2^\circ\text{C}$, A3: $32.6 \pm 0.9^\circ\text{C}$, $p<0.01$). An interaction effect ($p<0.01$) revealed that despite similar baseline skin temperatures before the initial deployment ($32.5 \pm 1.0^\circ\text{C}$), prior to the start of the re-deployment, skin temperature was lower following 30 minutes of cold recovery ($29.2 \pm 2.1^\circ\text{C}$, $p<0.01$), higher following 30 minutes of warm recovery ($34.2 \pm 1.2^\circ\text{C}$, $p<0.05$), and similar following 120 minutes of warm recovery ($32.5 \pm 1.2^\circ\text{C}$).

There were no differences in final skin temperatures following either the initial deployment or re-deployment between work bouts ($p=0.14$) or conditions ($p=0.341$), with a combined final skin temperature across all bouts of $35.2 \pm 1.2^\circ\text{C}$.

Due to the different baseline skin temperatures prior to the re-deployment an interaction effect ($p<0.01$) showed the rise in skin temperature was similar during the initial deployment between conditions ($3.0 \pm 0.9^\circ\text{C}$), but was higher during the re-deployment following 30 minutes of cold recovery ($5.2 \pm 1.3^\circ\text{C}$, $p=0.05$), lower following 30 minutes of warm recovery ($0.6 \pm 2.1^\circ\text{C}$, $p<0.05$), and similar following 120 minutes of warm recovery ($3.2 \pm 1.0^\circ\text{C}$).

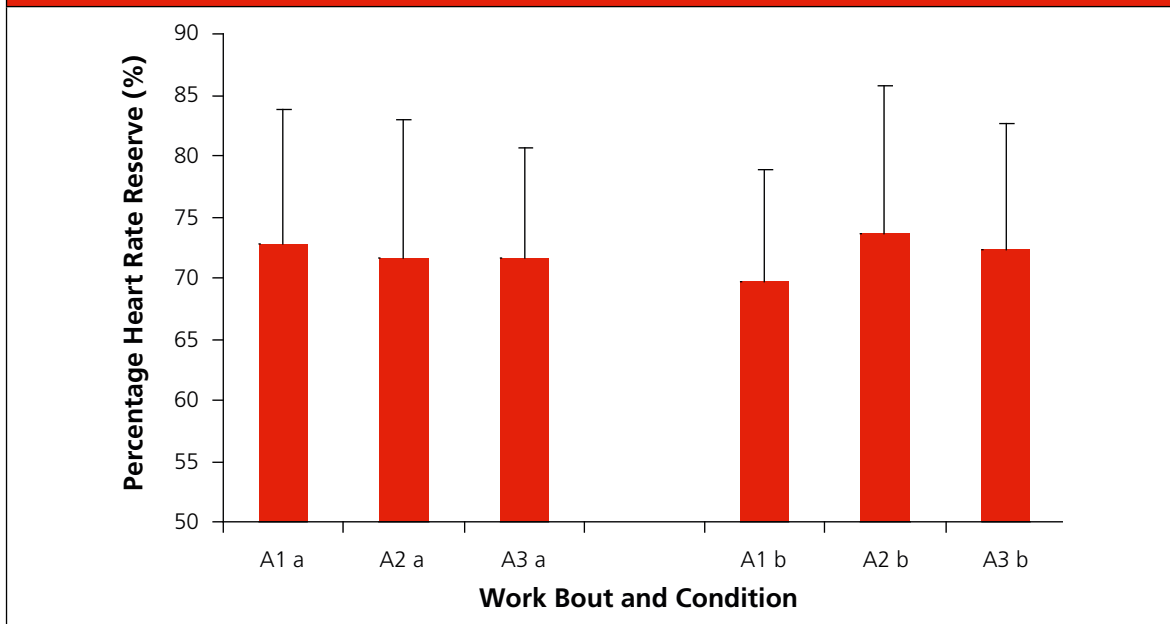
Once the change in skin temperature has been corrected for work bout duration, an interaction effect ($p < 0.01$) showed that the rate of rise was similar during the initial deployment between conditions ($0.119 \pm 0.044^\circ\text{C}$). However, the rate of rise of skin temperature during the second work bout was higher following 30 minutes of cold recovery ($0.232 \pm 0.064^\circ\text{C}$, $p < 0.05$) and lower following 30 minutes of warm recovery ($0.028 \pm 0.087^\circ\text{C}$, $p < 0.05$), compared to 120 minutes of warm recovery ($0.137 \pm 0.062^\circ\text{C}$).



4.5 Heart rate response

Figure 4.6 and Table B5 in Appendix B summarise the mean and standard deviation %HRR for each of the four conditions. There were no differences in %HRR between work bouts ($p = 0.89$) or conditions ($p = 0.77$). The average %HRR sustained over the six work bouts was 72 ± 10 %HRR. This corresponds to Howley's 'hard' classification of intensity (60-84 %HRR), though 18% of firefighters completed some conditions with a mean %HRR of between 50 and 59 % HRR, which corresponds to 'moderate' intensity for activities lasting 1 hour.

The % HRR during recovery was different between conditions ($p < 0.01$). The %HRR was lowest during 120 min warm recovery (30 ± 7 %HRR). The %HRR was higher during 30 min cold recovery (38 ± 8 %HRR, $p < 0.01$), and greatest during 30 min warm recovery (44 ± 8 %HRR, $p < 0.01$).

Figure 4.6. Mean Heart rate response by condition and work bout

4.6 Body mass changes and fluid intake

Body mass changes during the trials, which primarily reflect fluid loss via sweating, are shown in Table 4.1. There were no differences between conditions for total sweat loss ($p=0.33$), despite the -0.4 l greater sweat loss in 120 min warm recovery (Table 4.1). When sweat loss was corrected for the duration of the conditions, there were no differences in sweat rate, which averaged 0.009 ± 0.006 l.min⁻¹ or 0.56 ± 0.35 l.h⁻¹. There was a non-significant trend for total fluid intake during the recovery periods to be different ($p=0.10$), and further analysis revealed that there was a greater fluid intake during the 30 min warm recovery compared to 30 min cold recovery (Table 4.1, $p=0.05$).

Table 4.1. Mean sweat loss, sweat rate and fluid intake by condition

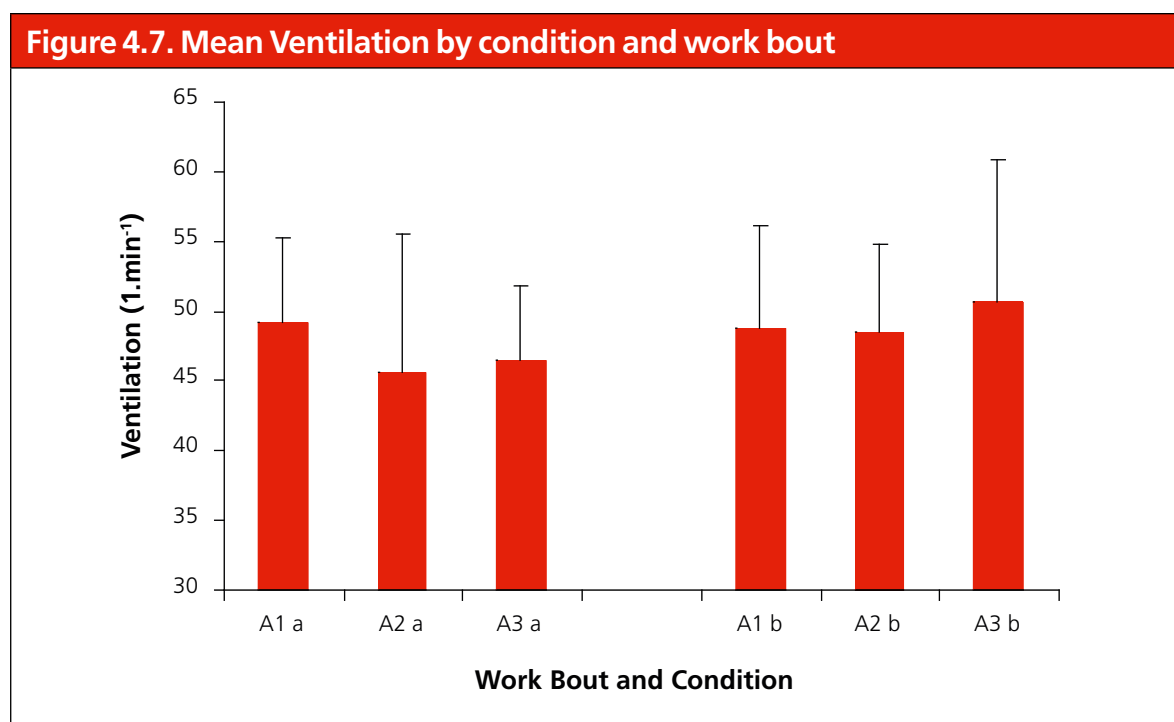
Condition	Duration (min)	Sweat Loss (l)	Sweat Rate (l.min ⁻¹)	Fluid (l)
A1	88.1 ± 9.3 (10)	0.96 ± 0.45	0.011 ± 0.005	0.59 ± 0.29
A2	93.4 ± 5.6 (10)	0.93 ± 0.70	0.010 ± 0.008	1.06 ± 0.45
A3	179.8 ± 14.0 (10)	1.35 ± 0.84	0.007 ± 0.005	0.84 ± 0.56
T	120.4 ± 43.9 (30)	1.08 ± 0.69	0.009 ± 0.006	0.83 ± 0.47

Where duration refers to the total work duration of the trial, including duration of the first and second work bouts together with the rest period, T refers to the pooled response across all three conditions (A1, A2 and A3) combined, and the number in parenthesis after each SD refers to the sample size.

4.7 Air use

Estimated air use, derived from pressure gauge readings at the beginning and end of each trial indicated mean air use in SDBA to be $48 \pm 8 \text{ l.min}^{-1}$ and is displayed in Figure 4.7 and Table B6 in Appendix B. This assumes conversion factors of ‘bar used’ x 8.37 (9 litres x 1 cylinder x 0.93 correction factor⁷) for SDBA. There were no differences between work bouts ($p=0.20$) or conditions ($p=0.56$) for the rate of ventilation during the six work bouts.

The BA Entry Tables assume a mean ventilation of 40 l.min^{-1} . During these ambient trials, SDBA use therefore averaged 120% of the ventilation assumed in the BA Entry Tables.



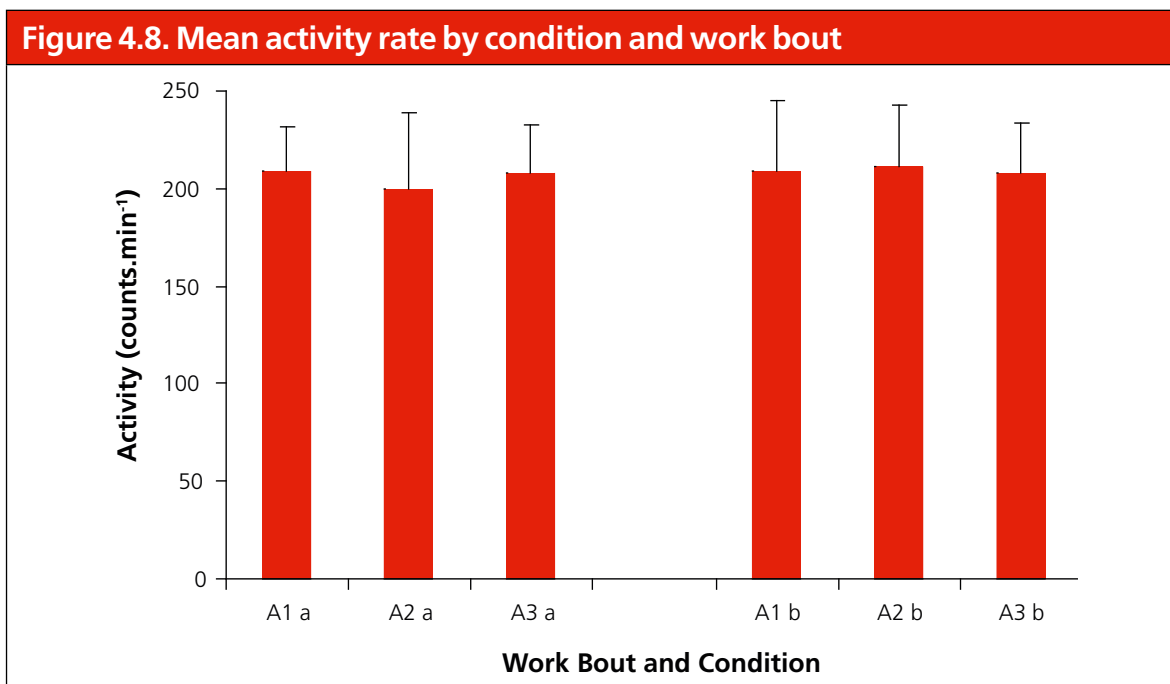
The mean ventilation rate reported in the current work (48 l.min^{-1}) is somewhat lower (17%) than that reported in previous work incorporating a similar methodology (58 l.min^{-1} – Rayson *et al.*, 2004). According to heart rate data, subjects were working at a similar intensity between studies (approximately 70 %HRR) and therefore, work rate appears not to account for the discrepancy. However, several additional reasons remain that may be responsible for the difference. Firstly, subjects’ body mass was approximately 3.5 kg lighter in the current study compared to the previous study. When body mass is accounted for (ventilation expressed as litres per kg body mass per minute) SDBA use in the current trials was only 9% lower than that of the previous work and marginally significant ($0.61 \pm 0.08 \text{ l.kg}^{-1} \text{ .min}^{-1}$ vs. $0.67 \pm 0.09 \text{ l.kg}^{-1} \text{ .min}^{-1}$, $p=0.055$). Secondly, subjects in the current study had a much lower core temperature response ($0.029 \pm 0.012^\circ\text{C.min}^{-1}$) compared to subjects in the previous study ($0.048 \pm 0.014^\circ\text{C.min}^{-1}$, $p<0.001$). As hyperthermia is known to increase the ventilatory response to exercise due to a stimulating effect of temperature on

⁷ Telecons Kerry Donovan (OPL) with Dave Mannings & Malcolm Stanton (LFB) & Mark Rayson (OPL) with Tom Ore (Dräger).

the neurons of the respiratory centre (Whipp and Wasserman, 1970; Jentjens *et al.*, 2002), the different thermal loads experienced may well account for the differences observed.

4.8 Activity

There were no differences in total activity counts or activity rates (derived from the activity monitors) between work bouts ($p=0.27$ and $p=0.49$) or conditions ($p=0.55$ and $p=0.85$), suggesting that firefighters were performing the same volume and rate of movement on all occasions. The activity data are shown in Figure 4.8 and Table B7 in Appendix B.



4.9 Summary of Phase 1 findings

The following summary points are made:

1. The success rate of the Firefighting, Search and Rescue Scenario performed under ambient conditions, was moderate (A2a 50%) to high (A1a, A3a 75%) during the initial deployment. Following the recovery period, 30 minutes cold was the only condition to record a 100% success rate in the re-deployment (A1b), with both warm conditions recording a 50% success rate (A2b and A3b).
2. All failures (8 of 24 tests – 33%) were a result of teams withdrawing early due to shortage of air. Air use averaged 48 litres per minute (5.7 bar.min⁻¹), which equates to 120% of the use assumed in the BA Entry Tables. There was no difference in air use between work bouts or between experimental conditions. Assuming a starting cylinder pressure of 200 bar (1674 l) and the low cylinder

pressure warning whistle sounding at 50 bar (419 l), and with this ventilation rate, firefighters had approximately 26 minutes of wear time. Actual work durations were 25.3 ± 3.4 min and 23.7 ± 5.7 min for the initial deployment (a) and re-deployment bouts (b), respectively.

3. The rate of rise of core temperature was similar between initial deployment (a: 0.029 ± 0.011 °C.min⁻¹) and re-deployment work bouts (b: 0.029 ± 0.012 °C.min⁻¹) and did not differ between experimental conditions during the initial deployment. No teams had to withdraw early due to core temperatures exceeding 39.5 °C and/or suspected exertional heat stress during either work bouts. Assuming a baseline core temperature of 37.6 °C (actual mean baseline core temperature in initial deployment), it would have taken firefighters 48 minutes on average to reach Graveling's proposed upper limit for trainers of 39 °C⁸. Using the more valid curvilinear rates of rise calculated in section 6, this time would be reduced to 41 minutes before reaching 39°C.
4. The rates of decline of core temperature were similar over the 3 recovery periods, when compared after 30 min of recovery (-0.017 ± 0.013 °C.min⁻¹). The 120 minute warm recovery resulted in a significantly lower baseline re-deployment core temperature (A3r: 37.4 ± 0.3) compared to both 30 minute recovery conditions (A1r, A2r: 37.8 ± 0.3), potentially reducing the wear time after the 30 minute recoveries by 14 minutes.
5. During the re-deployment rate of rise of core temperature was significantly less following the 30 minute cold recovery (A1b: 0.021 ± 0.014 °C.min⁻¹) than the other two conditions (A2b: 0.033 ± 0.012 °C.min⁻¹, A3b: 0.033 ± 0.012 °C.min⁻¹). Assuming the baseline core temperatures recorded in the re-deployment bouts of 37.8 °C (A1b and A2b) and 37.4 °C (A3b), these rates of rise would have allowed approximately 57 (A1b), 40 (A2b) and 44 minutes (A3b) of operational time before 39 °C was reached.
6. The lower rate of rise of core temperature during the re-deployment after the 30 minute cold recovery (A1b) appears to be unrelated to the core temperature cooling in the recovery period, which did not differ between the two 30 minute recovery periods. The explanation may lie in the different skin temperature responses between conditions (see points 7 and 8).

⁸ Graveling et al (2001). *Firefighter Training: Physiological and Environmental Factors*. Fire Research Report Number 1/2001. Institute of Occupational Medicine, Edinburgh, Scotland.

7. There was no difference between conditions in the mean skin temperature response during the initial deployment. A greater rate of mean skin temperature decline (A1r: -0.146 ± 0.046 °C.min⁻¹) in the 30 minute cold recovery period resulted in a significantly lower baseline mean skin temperature in the 30 minute cold re-deployment bout (A1b: 29.2 ± 2.2 °C) compared to both warm recovery conditions (A2b: 34.2 ± 1.2 °C, A3b: 32.5 ± 1.1 °C). This established a greater temperature gradient between body core and periphery in the cold recovery condition.
8. The rate of rise of mean skin temperature during the re-deployment was highest following 30 minute cold recovery (A1b: 0.232 ± 0.064 °C.min⁻¹) and lowest following 30 minute warm recovery (A2b: 0.028 ± 0.087 °C.min⁻¹). It would appear that the substantial cooling of the skin in the cold recovery condition (A1r) mitigated the rise in core temperature during re-deployment, the skin and periphery acting as a heat sink to absorb some of the heat generated.
9. The heart rate data, providing an index of cardiovascular strain, indicated that firefighters were working 'hard', averaging 72% of their Heart Rate Reserve across all conditions. A minority worked 'moderately'. There was no difference in heart rate response between initial deployment (a) and re-deployment (b) work bouts or between experimental conditions, indicating that the total level of cardiovascular strain, reflecting work rate and thermal load, was similar. The activity data (measured by accelerometry), which was similar between work bouts and conditions, averaging 5081 ± 1120 total counts and 208 ± 29 counts per minute, supports the contention that the rate of work did not differ between bouts or conditions.
10. Fluid loss through sweating averaged 1.1 litres and the rate of sweat loss averaged 0.6 litres per hour, being similar between work bouts and conditions. Fluid intake was highest in the 30 minute warm recovery period (A2r: 1.1 ± 0.4 litres) and lowest in the 30 minute cold recovery period (A1r: 0.6 ± 0.3 litres), which may explain the similar rates of core temperature decline in the 30 minute cold and warm recovery periods (see point 4).

4.10 Conclusions

The following conclusions are drawn:

1. The thermal and cardiovascular responses to these search and rescue scenarios performed in thermo-neutral ambient conditions were unremarkable. The cardiovascular response was significant and similar to that described previously (Rayson *et al.*, 2004). The thermal response was moderate and its extent was partially limited by the use of SDBA – air supply being the only reason for early termination of the scenarios and failure to achieve the objectives on some occasions.
2. Performance on the re-deployment was not substantially degraded, with the same proportion of successful outcomes resulting from the re-deployments as the initial deployments. No differences in heart rate, ventilation, activity or body mass changes were reported between experimental conditions in the re-deployment work bout.
3. Although differences in core and skin temperature responses were noted between recovery conditions, there were no differences in the final core or skin temperatures at the end of the re-deployment between conditions. While the 120 minute warm recovery (A3r) produced the lowest core temperature (due primarily to the additional recovery duration), and the 30 minute cold recovery (A1r) produced the lowest skin temperatures (primarily due to the colder ambient temperature), at the end of the re-deployment these differences had disappeared.
4. In 4% of cases firefighters exceeded Graveling's proposed upper limit for core temperature in trainers of 39 °C; only one of these occurred during a re-deployment and it was in the 30 minute warm condition (A2b).
5. The outcomes were most favourable on the re-deployment after the 30 minute cold recovery, but the total number of outcomes was small, so caution should be exercised in generalising this finding.

Chapter 5

Phase 2 Results: Live Fire Conditions

5.1 Summary of outcomes by condition

The outcomes of the three experimental conditions each performed by four teams are shown in Figure 5.1 and provided numerically in Table C2 in Appendix C. Over all (initial deployment and re-deployment work bouts combined to give 24 tests) the live fire serials:

17 (71%) were successful in completing the scenario, rescuing all casualties, 7 (29%) were terminated prematurely due to the firefighters failing to locate all the casualties.

Condition L1 (30 minutes rest outdoors) had the highest success rate in the re-deployment work bout (100%), with L2 and L3 conditions having a 50% and 75% success rate, respectively.

Figure 5.1. Summary of outcomes by condition and work bout

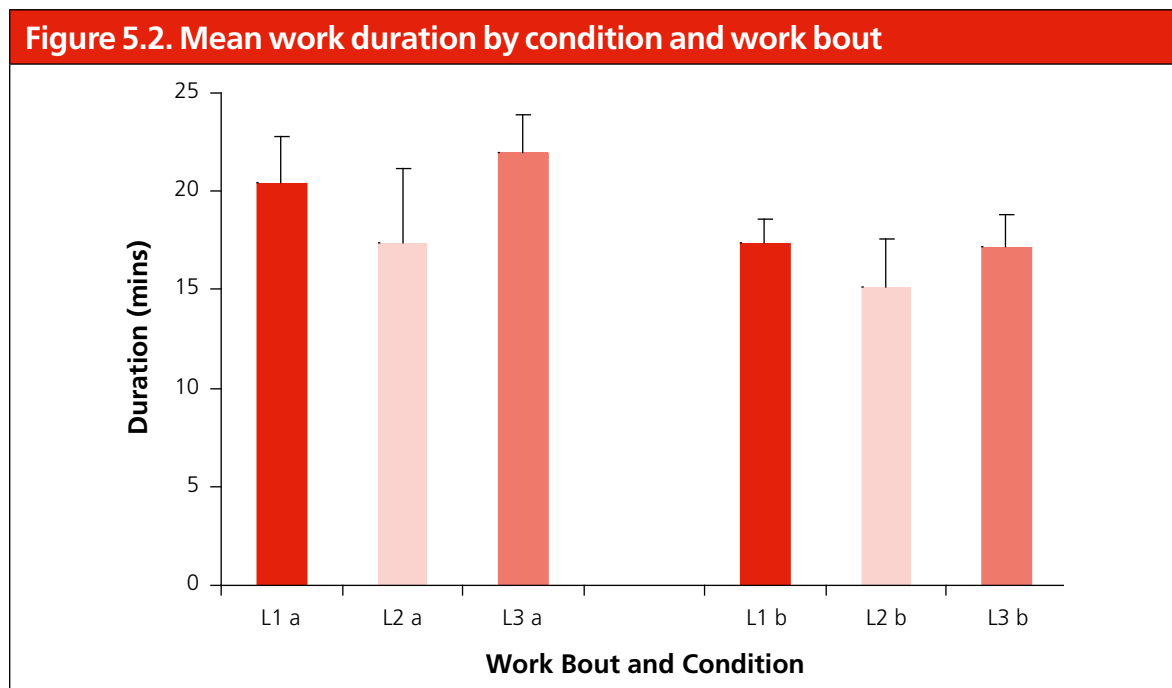


5.2 Work duration and external load

Figure 5.2 shows the total work duration for the initial deployment and re-deployment work bouts in all three experimental conditions. The mean work duration for each work bout was calculated as the time from when the first firefighter entered the building to exiting the building and coming off air.

There were differences in work duration between work bouts (a: 19.9 ± 3.3 min, b: 16.6 ± 2.0 min, $p < 0.01$) and conditions (L1: 18.9 ± 2.4 min, L2: 16.3 ± 3.3 min, L3: 19.6 ± 3.0 min, $p < 0.01$), but there was no interaction effect ($p = 0.19$). Condition L1 was shorter than condition L3 ($p < 0.01$), and both were longer than Condition L2 ($p < 0.05$ and $p < 0.01$ respectively). These findings show that work duration was reduced for the re-deployment following a recovery period, and that this duration was the shortest following 30 min warm recovery and longer following 120 min warm recovery and 30 min cold recovery (Figure 5.2).

As expected, recovery duration (from the end of the initial deployment to the start of the re-deployment) was significantly longer in L3 (134.0 ± 1.5 min, $p < 0.01$) compared to L1 (40.3 ± 7.6 min) and L2 (47.3 ± 4.9 min).



Where $n = 16$ for all work bouts and conditions (four serials carried out by teams of four firefighters for each work bout and condition).

Firefighters carried $23.8 (+ 0.5)$ kg of external load during Phase 2, which equated to $30 (\pm 5)$ % of their group mean body mass. Some firefighters carried less relative load than others. For example, external loads represented only 22% of body mass for the heaviest firefighter, compared to 41% for the lightest.

5.3 Core temperature response

Figure 5.3 and Table C3 in Appendix C show the core temperature response, as measured by the GI tract telemetry pills, by experimental conditions and work bouts. The columns in Table C3 show the number of firefighters in each condition, the mean duration of the test in minutes, the core temperatures at the beginning and end of the test, the rise in core temperature over the duration of the test, and the rate of rise of temperature.

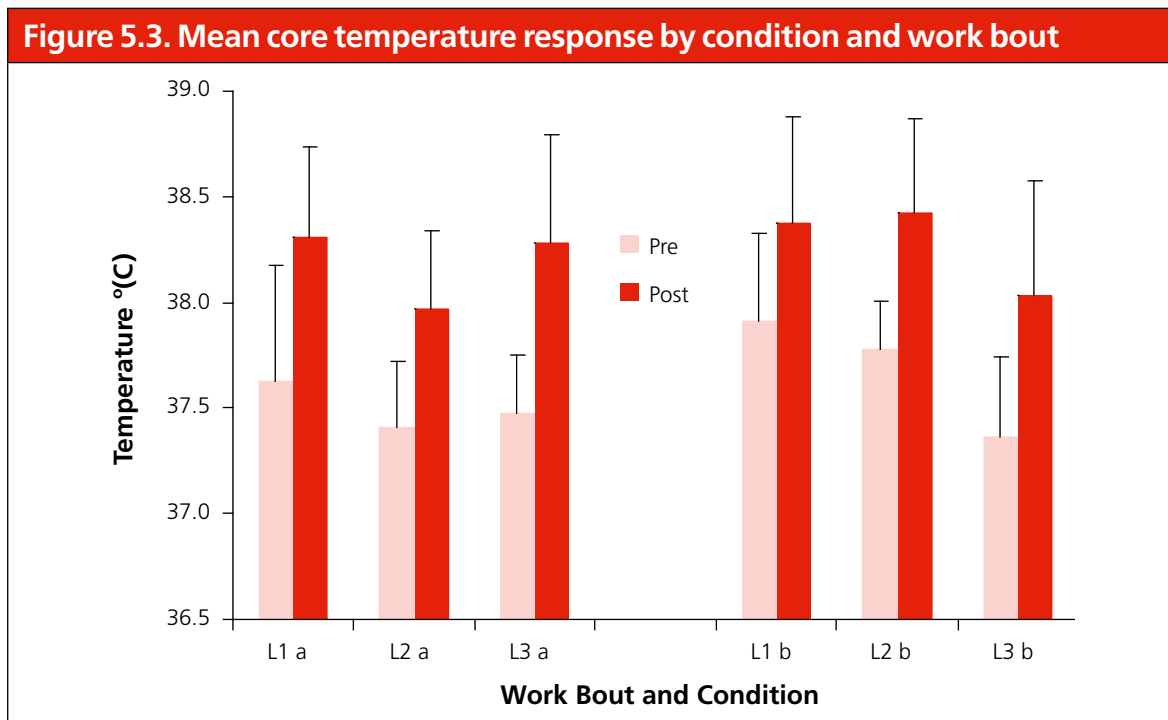
There were differences in the baseline core temperature between initial deployment and re-deployment work bouts (a: $37.5 \pm 0.4^\circ\text{C}$, b: $37.7 \pm 0.4^\circ\text{C}$, $p < 0.01$) and conditions ($p = 0.02$). The baseline core temperature was lower in L3 ($37.4 \pm 0.3^\circ\text{C}$) than in L1 ($37.8 \pm 0.5^\circ\text{C}$, $p = 0.01$) and L2 ($37.6 \pm 0.3^\circ\text{C}$, $p = 0.02$). An interaction effect ($p < 0.01$) revealed that following both 30 min recovery periods, baseline core temperature before the start of the re-deployment was higher ($p < 0.05$) than it was prior to the start of the initial deployment, but there was no difference in baseline core temperature following 120 min warm recovery (Figure 5.3).

There were no differences in the final core temperatures reached at the end of each work bout ($p = 0.34$) or between conditions ($p = 0.41$). An interaction effect ($p < 0.01$) revealed that the final core temperatures at the end of both work bouts were similar with 30 min cold ($38.3 \pm 0.4^\circ\text{C}$ and $38.4 \pm 0.5^\circ\text{C}$) and 120 min warm recovery ($38.3 \pm 0.5^\circ\text{C}$ and $38.0 \pm 0.5^\circ\text{C}$), but were higher at the end of the re-deployment following 30 min warm recovery ($38.0 \pm 0.4^\circ\text{C}$ to $38.4 \pm 0.4^\circ\text{C}$, $p < 0.05$). No firefighters reached the cut-off core temperature of 39.5°C and in the six work bouts seven of the 78 firefighters (9%) reached core temperatures in excess of 39°C . Of the three during the re-deployments, one was in the 30 minute cold condition while the other two were in the 30 minute warm condition.

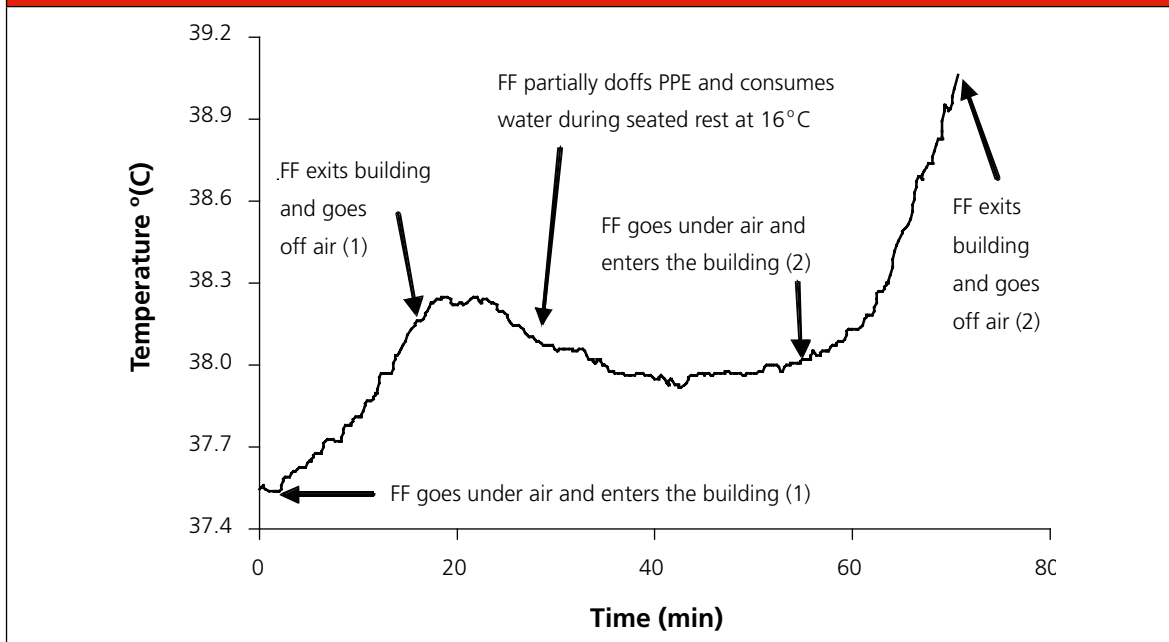
There were no differences in the rise in core temperature between work bouts (a: $0.68 \pm 0.32^\circ\text{C}$, b: $0.59 \pm 0.31^\circ\text{C}$, $p = 0.27$), or between conditions (L1: $0.57 \pm 0.30^\circ\text{C}$, L2: $0.60 \pm 0.27^\circ\text{C}$, L3: $0.74 \pm 0.36^\circ\text{C}$, $p = 0.11$) and there was no interaction.

Once the rise in core temperature had been corrected for bout duration, there were no differences in the rate of rise of core temperature between bouts ($p = 0.83$) or conditions ($p = 0.14$). The average rate of rise in core temperature across all six work bouts was $0.035 \pm 0.017^\circ\text{C} \cdot \text{min}^{-1}$ (Figure 5.3).

There were no differences ($p = 0.23$) in the rates of decline of core temperature in the recovery periods, when each condition was compared after 30 min of recovery, with a mean decline of $-0.017 \pm 0.011^\circ\text{C} \cdot \text{min}^{-1}$ over this period (see Table C3). However, this non-significant finding may well be due to the large individual variation in the response to the 120 min warm condition (see Figure 6.2 for mean core temperature recovery profiles during the three recovery conditions).



An individual plot of core temperature response is shown in Figure 5.4 as an example. This particular firefighter spent approximately 75 minutes engaged in this condition (L2), with 15 minutes spent in the first work bout, 40 minutes between deployments and 20 minutes in the second work bout. The core temperature response shows a markedly sharp increase during the first work bout before reaching a peak as the firefighter exited the building and came off air for the first time. Throughout the rest interval the core temperature declined slowly and with diminishing rate until 40 minutes, after which it began to rise again slightly. As with the first work bout, core temperature increased throughout the second work bout reaching a peak of 39.1 °C after 75 minutes.

Figure 5.4. An example core temperature response to L2

Where FF refers to the firefighter, (1) refers to the initial deployment and (2) refers to the re-deployment.

5.4 Skin temperature response

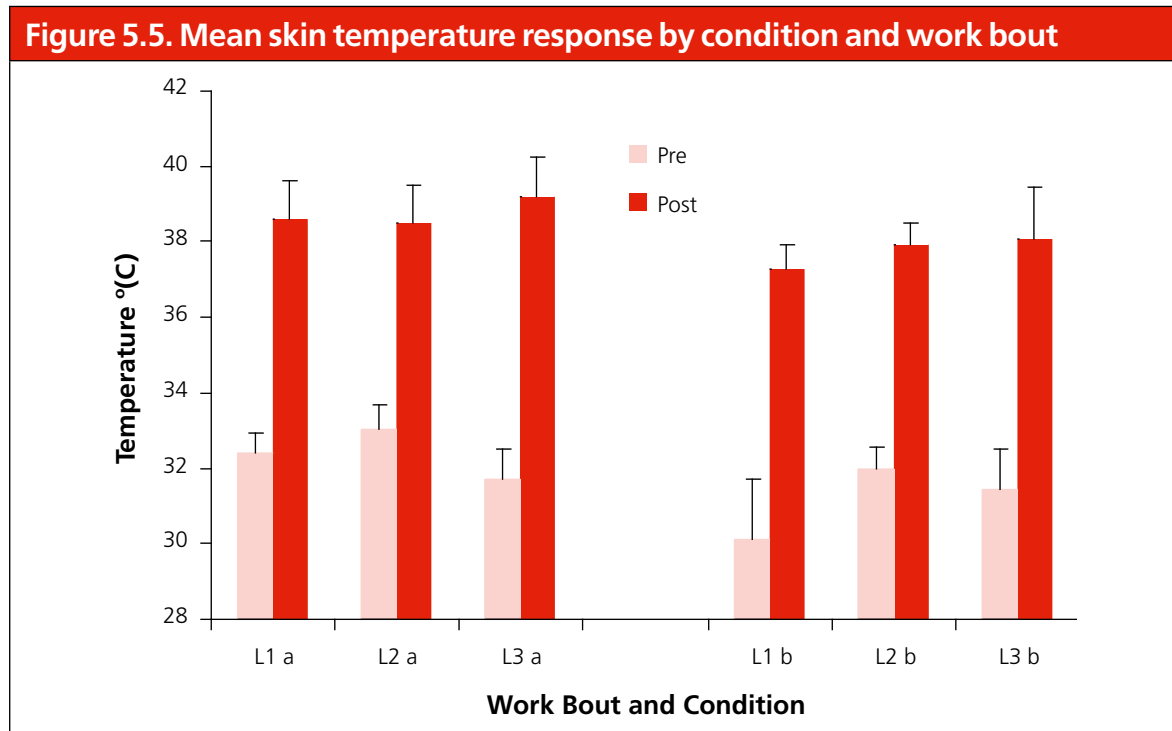
A summary of the mean skin temperature response is shown in Figure 5.5 and the data are shown in Table C4 in Appendix C.

There were differences in baseline skin temperatures between work bouts (a: $32.4 \pm 0.8^\circ\text{C}$, b: $31.2 \pm 1.4^\circ\text{C}$, $p < 0.01$) and conditions (L1: $31.3 \pm 1.6^\circ\text{C}$, L2: $32.5 \pm 0.8^\circ\text{C}$, L3: $31.6 \pm 0.9^\circ\text{C}$, $p = 0.03$). Baseline skin temperature in L2 was warmer than L1 and L3 ($p < 0.05$). An interaction effect ($p = 0.04$) revealed that despite similar baseline skin temperatures before the initial deployment (a: $32.4 \pm 0.8^\circ\text{C}$), prior to the start of the re-deployment, skin temperature was lower following 30 min cold recovery ($30.1 \pm 1.6^\circ\text{C}$, $p < 0.01$), but similar following both 30 min warm recovery ($32.0 \pm 0.6^\circ\text{C}$) and 120 min warm recovery ($31.4 \pm 1.1^\circ\text{C}$).

There was a difference in post-bout skin temperature between work bouts (a: $38.8 \pm 1.0^\circ\text{C}$, b: $37.8 \pm 0.9^\circ\text{C}$, $p < 0.01$), but not between conditions ($p = 0.23$).

There were no differences in the rise in skin temperature between work bouts ($p = 0.67$) or between conditions ($p = 0.11$), with an average rise of $6.5 \pm 1.5^\circ\text{C}$ during all six work bouts, and no interaction.

Once the change in skin temperature has been corrected for bout duration, there was a difference in the rate of rise of skin temperature between work bouts (a: $0.326 \pm 0.062^{\circ}\text{C} \cdot \text{min}^{-1}$, b: $0.405 \pm 0.084^{\circ}\text{C} \cdot \text{min}^{-1}$, $p=0.02$), but not between conditions ($p=0.78$) and there was no interaction. Therefore, skin temperature heated up quicker during the second work bout, irrespective of the experimental condition (Figure 5.5).



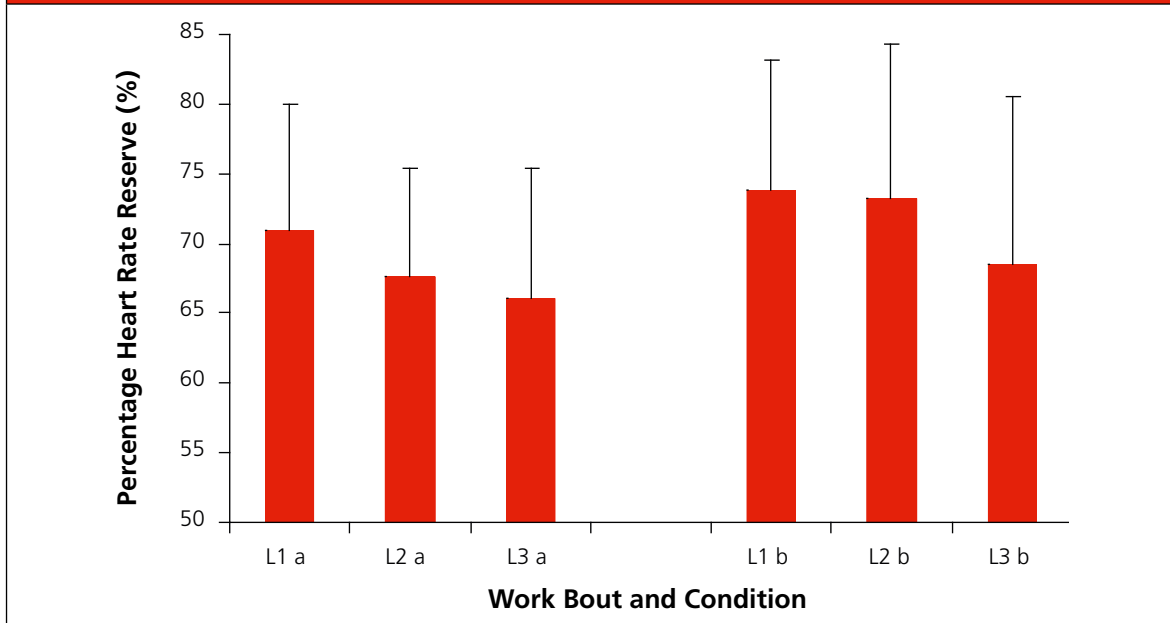
5.5 Heart rate response

Figure 5.6 and Table C5 in Appendix C summarise the mean and standard deviation %HRR for each of the four conditions.

There was a trend ($p=0.08$) for the %HRR to be higher during the re-deployment (a: 68 ± 9 %HRR, b: 72 ± 11 %HRR). The %HRR was also different between conditions ($p<0.01$), with the %HRR during the bouts with 120 min warm recovery (67 ± 11 %HRR) being lower than both 30 min cold and 30 min warm recovery (72 ± 9 %HRR and 70 ± 10 %HRR respectively, $p<0.05$) but there was no interaction. These intensities correspond to Howley's 'hard' classification of intensity (60-84 %HRR), though 19% of firefighters completed some conditions with a mean %HRR of between 40 and 59 % HRR, corresponding to 'moderate' intensity for activities lasting one hour. Hence, firefighters sustained a lower %HRR during 120 min warm recovery condition than during both 30 min recovery conditions, but in all conditions, the %HRR during the re-deployment was somewhat greater than that sustained during the initial deployment (Figure 5.6).

The % HRR during rest was different between conditions ($p < 0.01$). The %HRR was lowest during 120 min warm recovery (25 ± 6 %HRR). The %HRR was higher during 30 min cold recovery (43 ± 7 %HRR, $p < 0.01$), and during 30 min warm recovery (40 ± 7 %HRR, $p < 0.01$).

Figure 5.6. Mean heart rate response by condition and work bout



5.6 Body mass changes and fluid intake

Body mass changes during the trials, which primarily reflect fluid loss via sweating, are shown in Table 5.1.

There were no differences between conditions for total sweat loss ($p = 0.59$) (Table 5.1). When sweat loss was corrected for the duration of the conditions, sweat rate during 120 min warm recovery condition ($-0.36 \text{ l}\cdot\text{h}^{-1}$) was lower than both 30 min recovery conditions ($-0.75 \text{ l}\cdot\text{h}^{-1}$, $p < 0.05$).

Total fluid intake during the recovery periods was not different ($p = 0.08$), although there was a trend ($p = 0.06$) for a greater fluid during 120 min warm recovery compared to 30 min cold recovery (Table 5.1).

Table 5.1. Mean sweat loss, sweat rate and fluid intake by condition

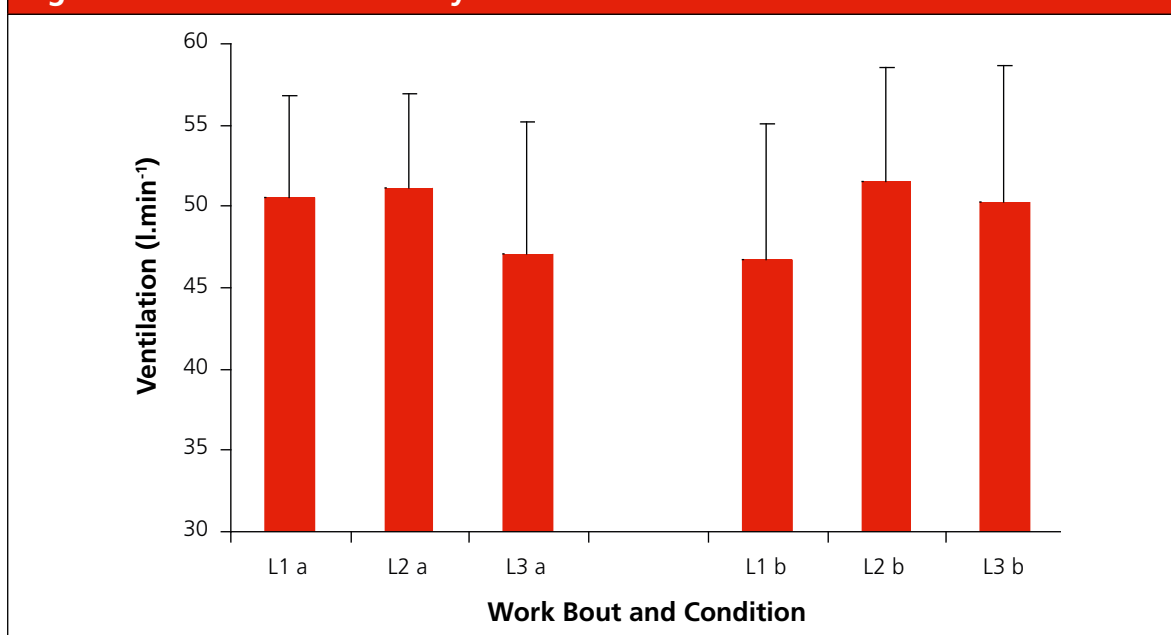
Condition	Duration (min)	Sweat Loss (l)	Sweat Rate (l.min ⁻¹)	Fluid (l)
L1	78.6 ± 7.5 (15)	0.88 ± 0.48	0.011 ± 0.006	0.55 ± 0.12
L2	80.4 ± 9.4 (15)	1.08 ± 0.46	0.014 ± 0.006	0.73 ± 0.45
L3	173.1 ± 3.3 (15)	1.03 ± 0.67	0.006 ± 0.004	1.03 ± 0.50
T	110.7 ± 45.2 (45)	1.00 ± 0.54	0.010 ± 0.006	0.77 ± 0.42

Where duration refers to the total work duration of the trial, including duration of the first and second work bouts together with the rest period, T refers to the average firefighter response across all three conditions (L1, L2 and L3) combined and where the number in parenthesis after each SD refers to the sample size.

5.7 Air use

Estimated air use, derived from pressure gauge readings at the beginning and end of each trial, indicated mean air use in SDBA to be 50 ± 7 l.min⁻¹, is displayed in Figure 4.7 and Table B6 in Appendix B. This assumes conversion factors of 'bar used' x 8.37 (9 litres x 1 cylinder x 0.93 correction factor⁹) for SDBA. There were no differences between work bouts ($p=0.98$) or conditions ($p=0.17$) for the rate of ventilation during the six work bouts.

The BA Entry Tables assume a mean ventilation of 40 l.min⁻¹. During these live fire trials, SDBA use was 125% of the ventilation assumed in the BA Entry Tables.

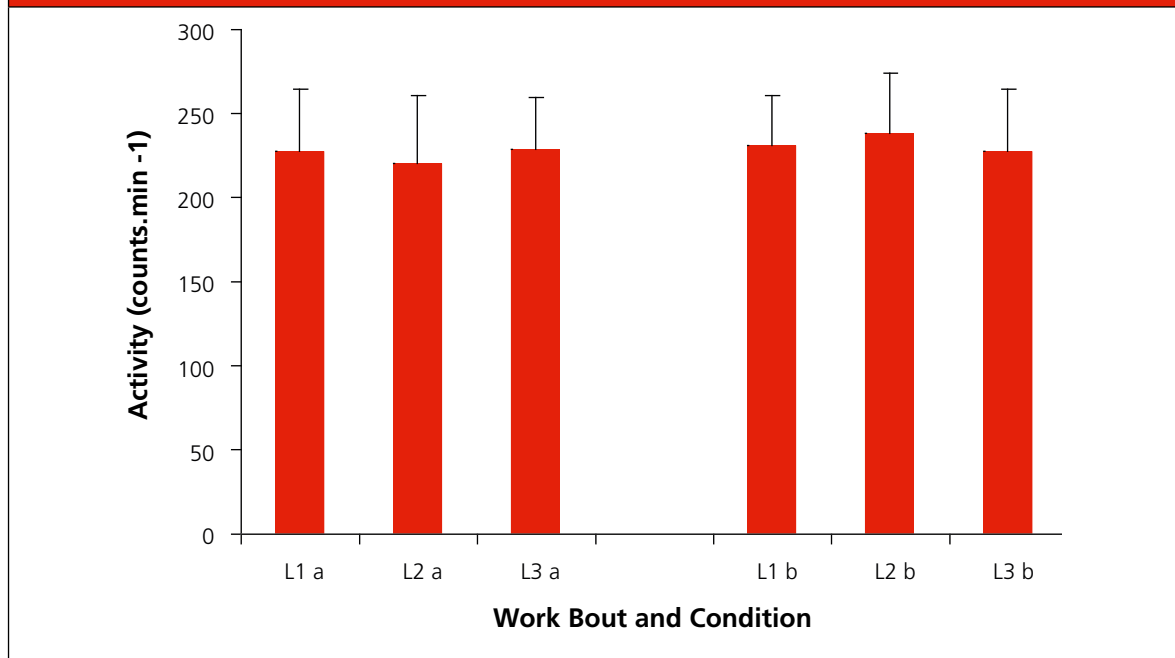
Figure 5.7. Mean ventilation by condition and work bout

⁹ Telecons Kerry Donovan (OPL) with Dave Mannings & Malcolm Stanton (LFB) & Mark Rayson (OPL) with Tom ore (Draeger).

5.8 Activity rate

There was a differences in total activity counts (derived from accelerometry) between work bouts (a: 4436 ± 874 , b: 3836 ± 754 , $p < 0.01$) and conditions, with L2 (3709 ± 799 counts) being lower than both L1 (4254 ± 783 counts, $p < 0.01$) and L3 (4446 ± 867 counts, $p < 0.01$). There was also a trend for an interaction effect ($p = 0.07$) with the total activity count remaining similar between work bouts in L1 and L2, but decreasing during the re-deployment in L3 (4981 ± 663 counts to 3911 ± 713 counts, $p < 0.01$). However, when work duration was accounted for these differences disappeared. There were no differences in activity rates between work bouts ($p = 0.18$) or conditions ($p = 0.91$) and no interaction. The activity data are shown in Figure 5.8 and Table C7 in Appendix C.

Figure 5.8. Mean activity rate by condition and work bout



5.9 Summary of Phase 2 findings

1. The success rate of the Firefighting, Search and Rescue Scenario performed under live fire conditions, was moderate (L2a 50%) to high (L1a, L3a 75%) during the initial deployment. Following the recovery period, 30 minutes cold was the only condition to record a 100% success rate in the re-deployment (L1b), with 30 minute warm recovery (L2b) recording a 50% success rate and 120 minute warm recovery (L3b) a 75% success rate.
2. All failures (7 of 24 tests – 29%) were a result of teams withdrawing early due to the firefighters falsely assuming that all casualties had been recovered following fire extinguishing.

3. Air use averaged 50 litres per minute ($5.7 \text{ bar}\cdot\text{min}^{-1}$), which equates to 125% of the use assumed in the BA Entry Tables. There was no difference in air use between work bouts or between experimental conditions. Assuming a starting cylinder pressure of 200 bar (1674 l) and the low cylinder pressure warning whistle sounding at 50 bar (419 l), and with this ventilation rate, firefighters had approximately 25 minutes of wear time. Actual work durations were 19.9 ± 3.3 min and 16.6 ± 2.0 min for the initial deployment (a) and re-deployment bouts (b), respectively.
4. The rate of rise of core temperature was similar between initial deployment and re-deployment work bouts ($0.035 \pm 0.017^\circ\text{C}\cdot\text{min}^{-1}$) and did not differ between experimental conditions. No teams had to withdraw early due to core temperatures exceeding 39.5°C and / or suspected exertional heat stress during either work bout. Assuming a baseline core temperature of 37.5°C , it would have taken firefighters on average 43 minutes to reach Graveling's proposed upper limit for trainers of 39°C ¹⁰. Using the more valid curvilinear rates of rise calculated in section 6, this time would be reduced to 30 minutes before reaching 39°C .
5. The rates of decline of core temperature were similar over the three recovery periods, when compared after 30 min of recovery ($-0.017 \pm 0.011^\circ\text{C}\cdot\text{min}^{-1}$). The similarity in cooling rates between 30 minute cold (L1r) and both warm recovery periods (L2r and L3r) over the first 30 min is most likely due to the firefighters keeping their PPE on during the shorter rest durations, negating the cooling influence of the ambient air in the latter conditions. The 120 warm recovery resulted in a significantly lower baseline re-deployment core temperature (L3b: 37.4 ± 0.4) compared to both 30 minute recovery conditions (L1b, L2b: 37.8 ± 0.3), potentially reducing the wear time after the 30 minute recoveries by 11 minutes.
6. There was no difference between conditions in the mean skin temperature response during the initial deployment (a). A greater rate of mean skin temperature decline (L1r: $-0.222 \pm 0.046^\circ\text{C}\cdot\text{min}^{-1}$) in the 30 minute cold recovery period resulted in a significantly lower baseline mean skin temperature (L1b: $30.1 \pm 1.6^\circ\text{C}$) in the 30 minute cold re-deployment bout compared to both warm recovery conditions (L2b: $32.0 \pm 0.6^\circ\text{C}$, L3b: $31.4 \pm 1.1^\circ\text{C}$). This established a greater temperature gradient between body core and periphery in the cold recovery condition.

¹⁰ Graveling et al (2001). *Firefighter Training: Physiological and Environmental Factors*. Fire Research Report Number 1/2001. Institute of occupational Medicine.

7. The rate of rise of mean skin temperature during the work bouts did not differ between experimental conditions. However, rate of mean skin temperature rise was significantly greater during the re-deployment (b: $0.405 \pm 0.084^{\circ}\text{C}\cdot\text{min}^{-1}$) compared to the initial deployment (a: $0.326 \pm 0.062^{\circ}\text{C}\cdot\text{min}^{-1}$). This, in part, would have been due to the significantly higher mean ambient temperatures experienced by the firefighters in the re-deployment (b: $63 \pm 9^{\circ}\text{C}$) compared to the initial deployment (a: $48 \pm 12^{\circ}\text{C}$).
8. The heart rate data, providing an index of cardiovascular strain, indicated that firefighters were working 'hard', averaging 70% of their Heart Rate Reserve across all conditions. A minority worked 'moderately'. There was a difference in heart rate response between work bouts, with firefighters experiencing greater cardiovascular strain in the re-deployment (b: $72 \pm 11\%$) compared to the initial deployment (a: $68 \pm 9\%$), probably due to the higher thermal load during the re-deployment.
9. The heart rate response did differ between conditions, with a lower response in the 120 minute warm recovery work bouts (L3: $67 \pm 11\%$) compared to the corresponding work bouts in both 30 minute recovery conditions (L1: $72 \pm 9\%$, L2: $70 \pm 10\%$). This indicates that firefighters were working at a lower level of cardiovascular strain following the 120 minute warm recovery (L3b). Given that the rate of activity were similar between work bouts and conditions, averaging 229 ± 34 counts per minute, the lower cardiovascular strain probably reflects the lower baseline core temperature and resulting thermal strain.
10. Fluid loss through sweating averaged 1.0 ± 0.54 litres and was not different between conditions. The rate of sweat loss averaged 0.6 litres per hour, and was lower in the 120 minute warm condition (L3: -0.36 litres per hour) compared to both 30 minute conditions (L1, L2: -0.75 litres per hour). Fluid intake averaged 0.77 ± 0.42 litres and, although not significant, was highest in the 120 minute warm recovery period (L3: 1.0 ± 0.5 litres) and lowest in the 30 minute cold recovery period (L1: 0.5 ± 0.1 litres). This may explain, in part, why the rate of core temperature decline was similar between 30 minute cold recovery (L1) and both warm recovery periods (L2 and L3).

5.10 Conclusions

The following conclusions are drawn:

1. The scenarios were shorter during the firefighting, search and rescue scenarios performed under live fire conditions (L) compared with those performed under ambient conditions (A), possibly due to the smaller building used. The thermal response was greater during both the initial (La) and re-deployment (Lb) with live fires and there was less recovery during the recovery periods (r), compared to the ambient conditions. Under live fire conditions, the rates of rise and decline in core temperature were more marked and skin temperature rates of rise were threefold and rates of decline twofold those reported for the ambient scenario. Lack of success in achieving the scenario objectives through the firefighters failing to locate all the casualties was the only source of failure, which occurred in 29% of deployments.
2. Within these live fire trials, the outcomes and physiological performance on the re-deployment were not substantially degraded relative to the initial deployments, with more successful outcomes occurring during the re-deployments than the initial deployments. However, the redeployments were shorter than the initial deployments and the firefighters undertook less total physical activity.
3. A few differences were noted between experimental conditions:
 - relatively little further decline in core temperature was achieved beyond the first 45 minutes in the 120 minute recovery period
 - the final core temperature at the end of the re-deployment was higher in the 30 minute recovery conditions (L1b & L2b) compared to the 120 minute recovery condition (L3b).
4. No differences were noted in ventilation, rate of rise of core or mean skin temperature, activity rate or body mass loss between experimental conditions in the re-deployment work bout.
5. In 9% of cases firefighters exceeded Graveling's proposed upper limit for core temperature in trainers of 39°C; three of these seven cases occurred during a re-deployment, one was in the 30 minute cold condition (L1b) and two were in the 30 minute warm condition (L2b).
6. Taken as a whole, all recovery conditions appeared adequate to allow firefighters to recover sufficiently between work bouts.

Chapter 6

Modelling the Core Temperature Response

This section models the core temperature responses to the initial deployment, recovery and re-deployment in both ambient and live fire conditions. The modelling permits estimation of the core temperature response to be made to varying durations of initial deployment, recovery and re-deployment, based on the underlying assumptions of the model.

The model is based on a four phase approach to the core temperature responses reported in Sections 4 and 5. The first phase models the rise in core temperature during initial deployment in either ambient or live fire conditions. The rise in the mean core temperature response to both ambient and live fire conditions are best described by a second order polynomial (quadratic) function:

$$T_c(t) = a + b(t) + c(t)^2$$

Where $T_c(t)$ = core temperature at time t , (t) = time, a = initial core temperature at the start of deployment (which can be varied), b = constant, c = constant.

As theoretically there should be no difference in the rise in T_c during the initial deployments (they should be independent of the three recovery conditions – 30 minute cold, 30 minute warm and 120 minute warm) these data have been combined to give a common quadratic function for the rise in T_c during ambient conditions ($a = 37.63^\circ\text{C}$, $b = 0.02107$, $c = 0.00040$) and live fire conditions ($a = 37.48^\circ\text{C}$, $b = 0.01437$, $c = 0.00111$).

Following the firefighters exiting from the building, there is a continued rise in the mean core temperature response for approximately seven (ambient) to nine (live fire) minutes before T_c begins to decrease. Although 'exit temperature' varies greatly between individuals (by up to 0.5°C), the mean time course for T_c to return to exit temperature is fairly constant at approximately 14 minutes in the ambient scenarios and 17 minutes in the live fire scenarios. The mean T_c response from exit temperature, to peak T_c , and back down again to exit temperature can also be modelled with a common quadratic function, and although the individual temperatures reached may be $\pm 0.5^\circ\text{C}$ different with the common model for ambient and live fire conditions, the similar time course to return to exit temperature makes a common quadratic function suitable to describe the initial recovery temperature profile (the second phase). The quadratic function for ambient is $b = 0.01801$ and $c = -0.00162$ (a = exit temperature) with a time course of 14 minutes and for live fire, $b = 0.06716$ and $c = -0.00412$ (a = exit temperature) with a time course of 17 minutes.

Once T_c has fallen to the same level as the initial deployment exit temperature (the second phase described above), the remaining decline in T_c (the third phase) can be modelled with an exponential function:

$$T_c(t) = c + \text{amplitude} (1 - e^{-(t/\tau)})$$

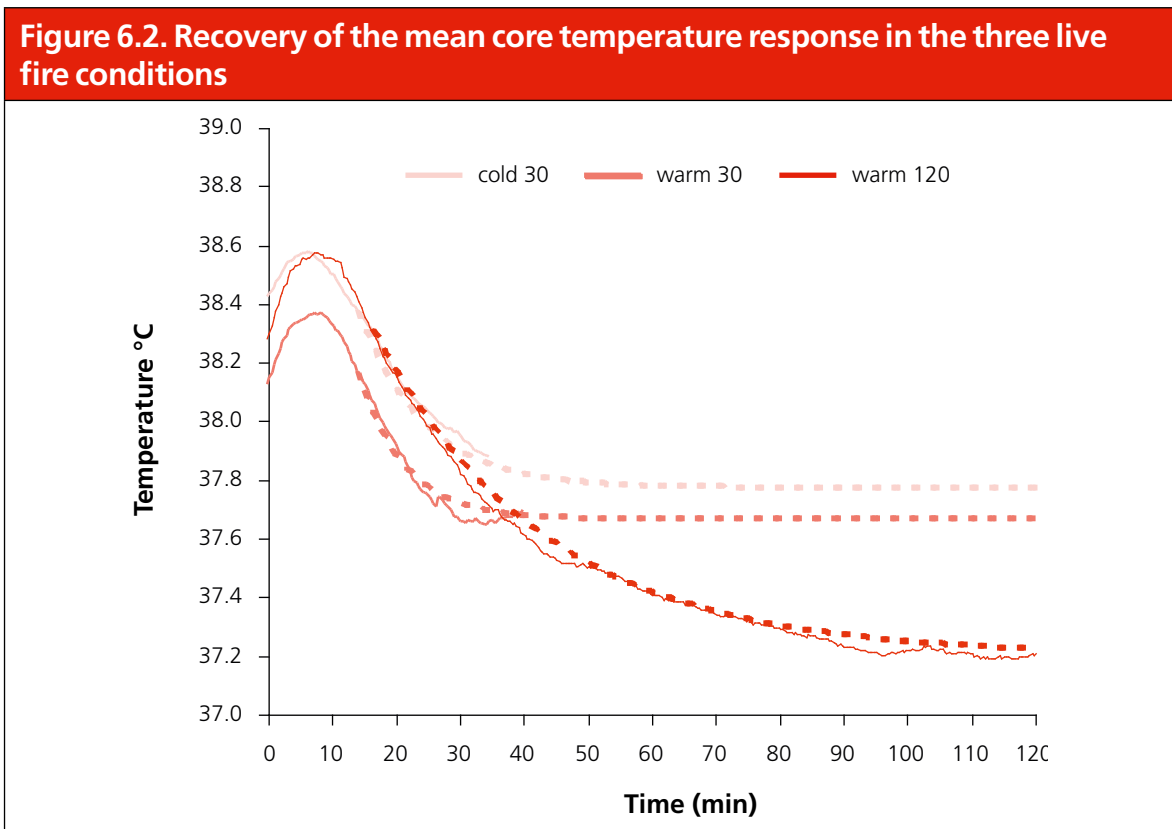
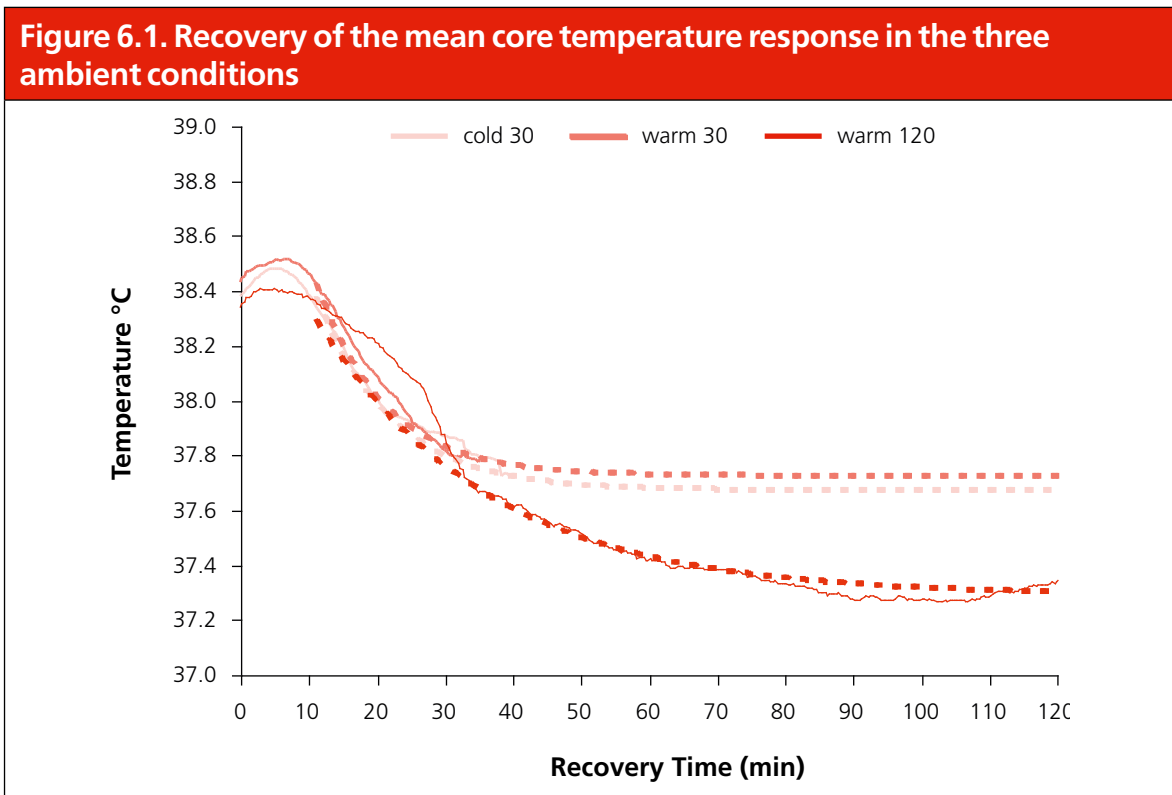
Where $T_c(t)$ = core temperature at time t , (t) = time, c = initial core temperature at the start of this recovery period, amplitude is the final T_c reached when thermal equilibrium is re-established during the recovery period and τ is the time constant.

The time constant is the time required for T_c to reach 63% of its final amplitude. Approximately 86% of this final amplitude will be reached in 2τ , 95% in 3τ and 98% in 4τ where the response will essentially be complete. Therefore a time constant of 10 min will mean that final recovery temperature will be reached in approximately 40 min.

Figures 6.1 and 6.2 show the mean core temperature recovery profiles for the three recovery conditions in ambient and live fire conditions respectively, fitted with exponential functions (dotted lines) after 14 minute (ambient) and 17 minute (live fire) of recovery. Although exponential functions have been fitted to the three recovery responses, only in the 120 minute warm recovery condition has the fall in T_c been recorded long enough to be confident in the final amplitude of the response. If we accept this extrapolation beyond the 30 minutes of data collected for the 30 minute recovery periods, all recovery profiles seem to fit the exponential function well, except the 120 minute warm recovery in ambient conditions, which may overestimate the rate of fall of T_c between 10 and 30 minute (Figure 6.1).

As only the 120 min recovery periods provide sufficient data to be confident of the exponential function fitted, and theoretically the warm recovery reflects "worst case scenario", the following model uses the recovery profiles from the ambient and live fire 120 min recovery scenarios. In ambient, $c = 37.20^\circ\text{C}$, $\tau = 27.7$ min and in live fire, $c = 37.14^\circ\text{C}$, $\tau = 29.8$ min. The amplitude (a) is calculated as the difference between the temperature at the end of phase 2 of the model and c . Note that these amplitudes will only be valid in similar recovery conditions to those experienced in the 120 min recovery periods. It is interesting to note that although based upon extrapolation, the predicted amplitudes in both 30 minute recovery conditions are some 0.5°C higher than in the 120 minute recovery. This is probably due to the firefighters keeping most of their outer PPE on during the shorter recovery periods, especially in the cold condition outside. However, these higher resting temperatures in the 30 min recovery periods appear reasonable, as they are almost identical to the mean resting temperatures experienced at the start of the trials ($\sim 37.5 - 37.6^\circ\text{C}$). Hence, the greatest total cooling occurs in the 120 minute warm condition, and suggests that given sufficient recovery time, re-deployment initial core temperatures may be lowered by removal of outer PPE during the recovery period. This of course assumes that firefighters could lie down and rest (as done in this study), which may

not be realistic in operational situations. The estimation of a baseline recovery temperature of ~37.2°C may therefore be too optimistic in reality.



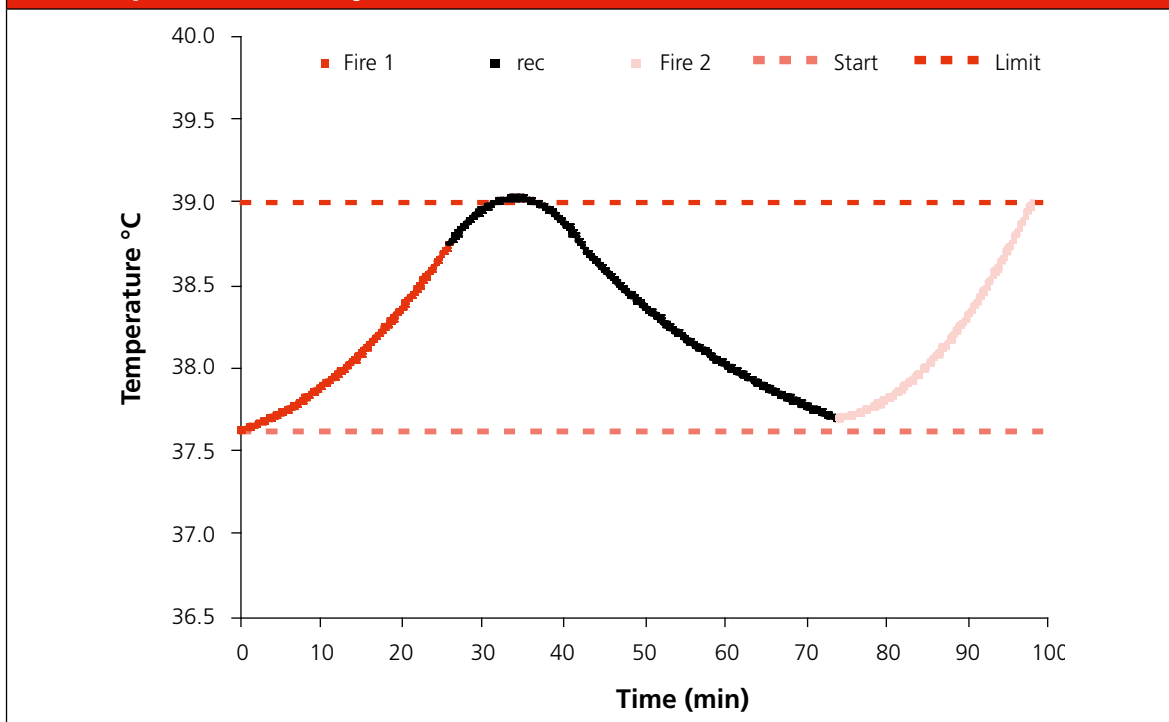
The fourth and final phase models the mean T_c responses to re-deployment, which again can be done using a quadratic function. Unlike the initial deployment, the T_c responses to re-deployment may well be dependant on the recovery condition and so independent quadratic functions have been developed for each condition (Table 6.1).

Table 6.1 Quadratic constants used to describe the core temperature response to re-deployment in ambient and live fire conditions						
Quadratic Constants	Ambient Conditions			Live Fire Conditions		
Recovery	30 cold	30 warm	120 warm	30 cold	30 warm	120 warm
a	37.78	37.80	37.44	37.90	37.78	37.31
b	0.00869	0.01617	0.02417	0.00189	-0.00166	0.00665
c	0.00071	0.00059	0.00059	0.00161	0.00291	0.00197

The data demonstrate that after 20 minute of re-deployment in the live fire condition, the difference in the mean rise in T_c between 30 minute cold and 30 minute warm recovery would be approximately 0.45°C.

The following example shows how the model can be used to manipulate the duration of the initial deployment, the recovery period and re-deployment period to determine the T_c response to the scenario. The example uses an initial T_c of 37.6°C, the common model for initial deployment in the live fire condition, the common model for the initial rise in core temperature during recovery (with a 17 minute duration), the 120 minute warm recovery exponential function and the specific model for re-deployment following 120 minute warm recovery. It is assumed in this example that the upper safe T_c for firefighters is 39°C and that air supply limits the duration of the deployments to 26 and 24 minutes respectively for the initial and re-deployments (150 bar reduction in pressure, from full pressure to the operation of the low cylinder pressure warning whistle, at the mean rates used during live fire conditions). Figure 6.3 shows the four phase model with the recovery period manipulated to achieve a mean maximum core temperature of 39°C on exit of the re-deployment.

Figure 6.3. A model of the T_c response to live fire conditions with warm (120 minute profile) recovery



The live fire model predicts that on average, 50 minutes of recovery is needed to perform an initial deployment for 26 minutes and a re-deployment for a further 24 minutes (the mean predicted durations of the SDBA with the mean ventilation measured during these trials) with a warm recovery (with outer PPE removed), if a T_c upper limit of 39°C was deemed desirable during the deployments. It is important to note that this model predicts the mean response for the firefighters, and hence using this set of assumptions, 50% of firefighters would finish below 39°C and 50% would finish above 39°C. The ambient model predicts that on average, a 23 minute recovery would suffice between deployments under thermo-neutral conditions, using the same set of ambient specific assumptions.

To protect the majority of the workforce in the absence of personal core temperature monitors, the model can be extended to include the 95th percentile confidence limits on the mean responses reported above. This was achieved by modelling the standard deviation (SD) of the residuals around the mean response, as a function of deployment time during the first and second fire. The upper 95th percentile response was then calculated as the mean response + (1.64*SD). The residuals were calculated based upon the temperature change from the initial core temperature for each individual firefighter, to minimise the effect of inter-individual variability on the confidence intervals during short deployments. Note, the 120 min recovery model used was that of the mean response, as it would be too conservative to assume that the firefighter with the fastest rates of rise in core temperature also had the slowest rate of recovery.

Using the same parameters described above for ambient and live fire conditions, the following calculations can be made to estimate minimum recovery durations to protect 95% of the workforce (Table 6.2).

Table 6.2 Minimum recovery durations required for two example durations of deployment and re-deployment to protect 95% of firefighters under a) ambient and b) live fire conditions			
a) Ambient Conditions			
Recovery	Maximum time (min) for initial deployment before 5% of firefighters exceed 39°C	Minimum recovery time (min) required to achieve a 26 min initial deployment and a 24 min re-deployment ¹¹	Minimum recovery time (min) required to achieve a 20 min initial deployment and a 20 min re-deployment ¹²
All recovery conditions	27 ¹³	45 ¹⁴	28 ¹⁵
b) Live Fire Conditions			
Recovery	Maximum time (min) for initial deployment before 5% of firefighters exceed 39°C	Minimum recovery time (min) required to achieve a 21 min initial deployment and a 22 min re-deployment ¹⁵	Minimum recovery time (min) required to achieve a 20 min initial deployment and a 20 min re-deployment ¹³
All recovery conditions	21 ¹⁶	120 ¹⁷	65 ¹⁷

In summary, in ambient conditions a core temperature of 39°C will be reached by 5% of firefighters after approximately 27 min in an initial deployment and 24 min in a re-deployment. These times correspond approximately to the times that air supply will become limiting for the average firefighter (~26 min and ~24 min for initial deployment and re-deployment, respectively). The re-deployment duration of 24 minutes assumes approximately 45 min rest is taken between deployments (see Table 6.2a). If the deployments are limited to a more typical 20 minutes duration, then the required recovery time is reduced to ~28 min.

¹¹ Projected air supply limitations of 26 min and 24 min for the deployment and redeployment, respectively.

¹² Typical BA wear durations.

¹³ This compares with 22 minutes wearing SDBA in previous trials in ambient conditions (Rayson et al, 2004; calculated from Table B3, page 58).

¹⁴ Based on the mean times from all three recovery models.

¹⁵ The initial deployment of 21 min is limited by the core temperature response. With a 120 min recovery period (the maximum recovery duration investigated in this study), firefighters could deploy for 22 min on the redeployment before 5% exceed 39.0 °C.

¹⁶ This compares with 20 minutes wearing EDDBA (SDBA was not worn during the live fire trials) in previous live fire trials (Rayson et al, 2004; calculated from Table C3, page 61).

¹⁷ Based on the 120 min warm recovery model.

In live fire conditions, a core temperature of 39°C will be reached by 5% of firefighters before mean air supply becomes limiting during the initial deployment (ie at ~21 min). Given 120 min of warm recovery involving quiet rest in working dress, a core temperature of 39°C will be reached after ~22 min by 5% of firefighters in the re-deployment, before mean air supply becomes limiting (at ~24 min) (see Table 6.2b).

In reality, given these recovery conditions are unlikely to be encountered during operations and end of recovery core temperatures are likely to be similar to those at the start of the initial deployment (37.6°C), these maximum redeployment times may be reduced in practice by some 3-4 min. Figures 6.1 and 6.2 suggest that irrespective of the recovery condition, this higher resting temperature will be achieved with about 40 min of recovery.

Chapter 7

Recommendations

Based on the findings from this study, the following recommendations are made to optimise recovery between deployment bouts, to prolong work duration, and to maximise performance and health and safety.

1. For search and rescue activities conducted under thermo-neutral ambient conditions and continued to the operation of the low cylinder pressure warning whistle, the average firefighter should have at least 23 minutes of recovery, ideally, but not necessarily in a cool environment, with their PPE removed, and to consume a minimum of 500 ml cold water. This recovery duration should be extended to at least 28 min to prevent 95% of firefighters from reaching a core temperature of 39°C on more typical 20 min deployments and redeployments, thereby protecting the majority of firefighters during most of the deployments.
2. For firefighting, search and rescue activities conducted under conditions of live fire and continued to the operation of the low cylinder pressure warning whistle, the average firefighter should have at least 50 minutes of recovery, ideally, but not necessarily in a cool environment, with their PPE removed, and to consume a minimum of 1000 ml cold water. This recovery duration should be extended to at least 65 min to protect 95% of firefighters engaged in more typical 20 min deployments and redeployments.
3. Given that some firefighters exceeded a core temperature of 39.0°C during a single wear of an SDBA under both ambient and live fire conditions, the wearing of personal core temperature monitors is recommended to allow their withdrawal before critical core temperatures are reached.
4. Simple cooling strategies should be reinforced in firefighters to optimise the cooling process during recovery. These include the complete removal of outer PPE at the earliest opportunity, relocation to a cool, shaded place ideally with air movement, the consumption of reasonable volumes of cool fluid, and potentially the use of other active cooling strategies such as forearm cooling.

Chapter 8

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Appendix A

Fitness Data

Table A1. Phase 1 cohort physiological characteristics

FF	FF	Age	Height	Mass	HR max	VO _{2max} †	VO _{2max} †
No.*	Sex	(y)	(cm)	(kg)	(beats .min ⁻¹)	(mL. kg ⁻¹ . min ⁻¹)	(L.min ⁻¹)
1	m	35	170	78.4	193	50.2	3.937
2	m	35	174	71.7	191	50.0	3.587
3	f	26	168	60.6	186	33.1	2.004
4	m	28	180	105.8	191	42.4	4.486
5	m	39	175	88.1	186	40.5	3.568
6	f	31	175	78.4	188	40.5	3.173
7	m	24	177	65.2	197	44.9	2.929
8	m	27	182	96.0	193	41.4	3.973
9	f	29	177	74.1	171	40.2	2.977
10	f	40	166	88.3	173	30.2	2.668
11	m	35	177	86.5	183	47.1	4.074
12	f	28	173	73.6	196	47.4	3.487
13	m	38	184	84.6	197	43.3	3.662
Mean		31.9	175.2	80.9	188.1	42.4	3.425
SD		5.3	5.2	12.4	8.4	5.9	0.666

Table A2. Phase 2 cohort physiological characteristics							
FF	FF	Age	Height	Mass	HR max	VO_{2max} †	VO_{2max} †
No.*	Sex	(y)	(cm)	(kg)	(beats .min⁻¹)	(mL. kg⁻¹. min⁻¹)	(L.min⁻¹)
1	m	38	178	84.2	195	46.5	3.914
2	m	35	177	86.1	183	47.1	4.057
3	m	35	174	71.5	191	50	3.577
4	f	28	172	66.2	182	45.8	3.032
5	m	42	179	77.6	193	54.5	4.231
6	f	40	166	86.5	173	30.2	2.612
7	m	39	175	87.5	186	40.5	3.544
8	m	38	184	84.1	197	43.3	3.643
9	f	31	175	78.3	188	40.5	3.171
10	m	27	182	98.3	193	41.4	4.068
11	m	28	180	105.7	191	42.4	4.483
12	m	24	177	65.3	197	44.9	2.932
13	f	26	169	58.6	195	47.4	2.779
14	m	38	181	94.0	194	48.3	4.539
15	f	29	177	74.8	171	40.2	3.006
16	f	28	175	74.0	196	47.4	3.509
Mean		32.9	176.3	80.8	189.1	44.4	3.569
SD		5.8	4.7	12.5	8.1	5.4	0.608

*The firefighter numbers in Table A1 and A2 do not correspond with each other.

† Estimated from multistage fitness test.

Appendix B

Phase 1: Ambient Scenario Results

Table B1. Mean ambient temperature and humidity by condition

	Initial Deployment (a)			Recovery Period (r)			Re-Deployment (b)		
	A1	A2	A3	A1	A2	A3	A1	A2	A3
Mean T (°C)	23.97	23.60	23.16	13.31	25.45	22.42	22.69	24.28	25.02
SD T (°C)	3.75	5.15	7.32	2.15	3.22	1.11	5.40	6.02	4.18
Mean RH (%)	28.6	36.2	40.5	55.1	42.9	48.4	31.4	42.3	43.0
SD RH (%)	6.9	7.9	10.4	9.2	4.7	4.3	7.7	10.0	7.7

Where T refers to ambient temperature, SD refers to standard deviation and RH refers to relative humidity.

Table B2. outcomes by condition

	Success	Temp	Safety	Air	Totals
A1 a	3	0	0	1	4
A2 a	2	0	0	2	4
A3 a	3	0	0	1	4
A1 b	4	0	0	0	4
A2 b	2	0	0	2	4
A3 b	2	0	0	2	4
Totals	16	0	0	8	24

Table B3. Core temperature response by condition (mean \pm SD)						
C	n	Mean Duration (min)	Core Temperature			
			"Start" ($^{\circ}$ C)	"Stop" ($^{\circ}$ C)	Rise ($^{\circ}$ C)	Rate of Rise ($^{\circ}$ C.min $^{-1}$)
A1 a	11	24.7 \pm 1.6	37.6 \pm 0.2	38.3 \pm 0.3	0.7 \pm 0.3	0.029 \pm 0.011
A2 a	11	28.2 \pm 4.6	37.6 \pm 0.3	38.4 \pm 0.4	0.8 \pm 0.3	0.029 \pm 0.013
A3 a	11	23.5 \pm 1.8	37.6 \pm 0.3	38.3 \pm 0.3	0.7 \pm 0.3	0.030 \pm 0.009
T a	33	25.5 \pm 3.5	37.6 \pm 0.3	38.4 \pm 0.4	0.7 \pm 0.3	0.029 \pm 0.011
A1 r	11	41.7 \pm 2.2	38.3 \pm 0.3	37.8 \pm 0.2	-0.6 \pm 0.3	-0.017 \pm 0.014
A2 r	11	41.5 \pm 3.8	38.4 \pm 0.4	37.8 \pm 0.4	-0.6 \pm 0.4	-0.017 \pm 0.009
A3 r	11	129.9 \pm 4.1	38.3 \pm 0.3	37.4 \pm 0.4	-0.9 \pm 0.3	-0.016 \pm 0.017
T r	33	71.0 \pm 42.4	38.4 \pm 0.4	37.7 \pm 0.3	-0.7 \pm 0.4	-0.017 \pm 0.013
A1 b	11	23.6 \pm 5.9	37.8 \pm 0.2	38.3 \pm 0.3	0.5 \pm 0.3	0.021 \pm 0.014
A2 b	11	23.5 \pm 1.4	37.8 \pm 0.4	38.5 \pm 0.4	0.7 \pm 0.3	0.030 \pm 0.012
A3 b	11	26.1 \pm 7.9	37.4 \pm 0.3	38.4 \pm 0.3	0.9 \pm 0.4	0.036 \pm 0.011
T b	33	24.4 \pm 5.7	37.7 \pm 0.3	38.4 \pm 0.3	0.7 \pm 0.4	0.029 \pm 0.013

Where T refers to the mean core temperature response across all three conditions (A1, A2 and A3) combined. During recovery (rows A1r, A2r, A3r), the rate of rise is determined over the first 30 min only for all conditions.

Table B4. Skin temperature response by condition (mean \pm SD)						
C	n	Mean Duration (min)	Skin Temperature			
			"Start" ($^{\circ}$ C)	"Stop" ($^{\circ}$ C)	Rise ($^{\circ}$ C)	Rate of Rise ($^{\circ}$ C.min $^{-1}$)
A1 a	8	24.6 \pm 1.6	32.0 \pm 1.2	35.2 \pm 1.2	3.2 \pm 1.1	0.133 \pm 0.052
A2 a	8	28.3 \pm 4.2	32.9 \pm 0.9	35.7 \pm 0.8	2.8 \pm 1.0	0.100 \pm 0.038
A3 a	8	23.2 \pm 1.9	32.7 \pm 0.6	35.5 \pm 0.9	2.9 \pm 0.8	0.124 \pm 0.038
T a	24	25.4 \pm 3.5	32.5 \pm 1.0	35.5 \pm 0.9	3.0 \pm 0.9	0.119 \pm 0.044
A1 r	8	41.6 \pm 2.3	35.2 \pm 1.2	29.2 \pm 2.1	-6.0 \pm 1.8	-0.146 \pm 0.043
A2 r	8	42.0 \pm 4.0	35.7 \pm 0.8	34.2 \pm 1.2	-1.5 \pm 1.4	-0.037 \pm 0.037
A3 r	8	129.4 \pm 4.6	35.5 \pm 0.9	32.5 \pm 1.2	-3.0 \pm 1.6	-0.023 \pm 0.012
T r	24	71.0 \pm 42.4	35.5 \pm 0.9	32.0 \pm 2.6	-3.5 \pm 2.5	-0.069 \pm 0.064
A1 b	8	23.3 \pm 6.4	29.2 \pm 2.1	34.4 \pm 1.5	5.2 \pm 1.3	0.232 \pm 0.064
A2 b	8	23.8 \pm 1.3	34.2 \pm 1.2	34.8 \pm 1.5	0.6 \pm 2.1	0.028 \pm 0.087
A3 b	8	25.6 \pm 8.5	32.5 \pm 1.2	35.7 \pm 0.7	3.2 \pm 1.0	0.137 \pm 0.062
T b	24	24.2 \pm 6.0	32.0 \pm 2.6	35.0 \pm 1.3	3.0 \pm 2.4	0.132 \pm 0.109

Table B5. Heart Rate Response by condition (mean \pm SD)

	Mean HR (bpm) (n)		Percentage HRR (%)	
	Initial deployment	Re-deployment	Initial deployment	Re-deployment
A1	149 \pm 15 (12)	144 \pm 13 (12)	73 \pm 11	70 \pm 9
A2	147 \pm 16 (12)	150 \pm 18 (12)	72 \pm 11	74 \pm 12
A3	147 \pm 13 (12)	148 \pm 15 (12)	72 \pm 9	72 \pm 10
T	148 \pm 15 (36)	147 \pm 15 (36)	72 \pm 10	72 \pm 10

Where the number in parenthesis after each SD refers to the sample size.

Table B6. Air use by condition (mean \pm SD)

	n	Duration under Air (min)	Air Use (bar)	Rate of Air Use (bar.min ⁻¹)	Ventilation Rate (l.min ⁻¹)
A1 a	13	24.6 \pm 1.5	144 \pm 17	5.9 \pm 0.7	49.3 \pm 6.0
A2 a	13	28.1 \pm 4.2	150 \pm 16	5.5 \pm 1.2	45.7 \pm 9.8
A3 a	13	23.2 \pm 1.8	129 \pm 15	5.6 \pm 0.6	46.5 \pm 5.4
T a	39	25.3 \pm 3.4	141 \pm 18	5.6 \pm 0.9	47.1 \pm 7.3
A1 b	13	22.3 \pm 6.2	129 \pm 36	5.8 \pm 0.9	48.9 \pm 7.3
A2 b	13	23.7 \pm 1.3	137 \pm 12	5.8 \pm 0.7	48.6 \pm 6.2
A3 b	13	25.2 \pm 7.5	147 \pm 27	6.1 \pm 1.2	50.7 \pm 10.1
T b	39	23.7 \pm 5.7	138 \pm 27	5.9 \pm 0.9	49.4 \pm 7.9

Table B7. Activity by condition (mean \pm SD)

	Total Counts (n)		Activity Rate (counts.min ⁻¹)	
	Initial deployment	Re-deployment	Initial deployment	Re-deployment
A1	5167 \pm 800 (13)	4760 \pm 1784 (13)	209 \pm 23	209 \pm 35
A2	5510 \pm 732 (13)	4985 \pm 714 (13)	200 \pm 39	211 \pm 32
A3	4853 \pm 766 (13)	5210 \pm 1479 (13)	208 \pm 24	208 \pm 25
T	5176 \pm 794 (39)	4985 \pm 1375 (39)	206 \pm 29	209 \pm 30

Where the number in parenthesis after each SD refers to the sample size.

Appendix C

Phase 2: Live Fire Scenario Results

Table C1. Mean and peak ambient temperature and humidity by condition									
	Initial Deployment (a)			Recovery Period (r)			Re-Deployment (b)		
	L1	L2	L3	L1	L2	L3	L1	L2	L3
Mean T (°C)	37.9	52.4	50.4	7.6	25.7	19.4	65.3	64.6	61.6
SD T (°C)	8.4	11.8	11.9	2.5	2.3	1.1	4.7	8.3	11.2
Peak T (°C)	62.8	70.6	74.6				118.0	102.0	104.0
SD T (°C)	4.4	15.9	15.4				23.7	21.6	30.6
Mean RH (%)				58.8	36.6	29.3			
SD RH (%)				15.4	18.1	6.5			

Where T refers to ambient temperature, SD refers to standard deviation and RH refers to relative humidity. No humidity probes were taken into the fire compartments to allow RH to be quantified during the initial deployment and re-deployment bouts.

Table C2. outcomes by condition			
	Success	Failure	Totals
L1 a	3	1	4
L2 a	2	2	4
L3 a	3	1	4
L1 b	4	0	4
L2 b	2	2	4
L3 b	3	1	4
Totals	17	7	24

Table C3. Core temperature response by condition (mean \pm SD)

C	n	Mean Duration (min)	Core Temperature			
			"Start" (°C)	"Stop" (°C)	Rise (°C)	Rate of Rise (°C.min ⁻¹)
L1 a	13	20.6 \pm 2.4	37.6 \pm 0.6	38.3 \pm 0.4	0.7 \pm 0.3	0.033 \pm 0.016
L2 a	13	16.7 \pm 3.3	37.4 \pm 0.3	38.0 \pm 0.4	0.6 \pm 0.2	0.034 \pm 0.013
L3 a	13	21.6 \pm 2.0	37.5 \pm 0.3	38.3 \pm 0.5	0.8 \pm 0.4	0.037 \pm 0.018
T a	39	19.6 \pm 3.3	37.5 \pm 0.4	38.2 \pm 0.5	0.7 \pm 0.3	0.035 \pm 0.016
L1 r	13	38.6 \pm 5.5	38.3 \pm 0.4	37.9 \pm 0.4	-0.5 \pm 0.3	-0.014 \pm 0.007
L2 r	13	47.1 \pm 5.0	38.0 \pm 0.4	37.8 \pm 0.2	-0.2 \pm 0.2	-0.015 \pm 0.010
L3 r	13	134.0 \pm 1.6	38.3 \pm 0.5	37.4 \pm 0.4	-1.0 \pm 0.5	-0.022 \pm 0.015
T r	39	74.2 \pm 44.1	38.2 \pm 0.5	37.7 \pm 0.4	-0.5 \pm 0.5	-0.017 \pm 0.011
L1 b	13	17.0 \pm 0.8	37.9 \pm 0.4	38.4 \pm 0.5	0.5 \pm 0.3	0.027 \pm 0.015
L2 b	13	15.4 \pm 2.6	37.8 \pm 0.2	38.4 \pm 0.4	0.6 \pm 0.3	0.041 \pm 0.020
L3 b	13	16.9 \pm 1.4	37.4 \pm 0.4	38.0 \pm 0.5	0.7 \pm 0.3	0.039 \pm 0.018
T b	39	16.5 \pm 1.8	37.7 \pm 0.4	38.3 \pm 0.5	0.6 \pm 0.3	0.036 \pm 0.018

Where T refers to the mean core temperature response across all three conditions (L1, L2 and L3) combined. During recovery (rows L1r, L2r, L3r), the rate of rise is determined over the first 30 min only for all conditions.

Table C4. Skin temperature response by condition (mean \pm SD)

C	n	Mean Duration (min)	Skin Temperature			
			"Start" (°C)	"Stop" (°C)	Rise (°C)	Rate of Rise (°C.min ⁻¹)
L1 a	7	21.0 \pm 1.8	32.4 \pm 0.5	38.6 \pm 1.0	6.2 \pm 0.8	0.299 \pm 0.059
L2 a	7	16.2 \pm 3.4	33.0 \pm 0.6	38.5 \pm 1.0	5.5 \pm 1.3	0.341 \pm 0.059
L3 a	7	22.2 \pm 1.7	31.7 \pm 0.8	39.2 \pm 1.1	7.4 \pm 1.5	0.336 \pm 0.069
T a	21	19.8 \pm 3.5	32.4 \pm 0.8	38.8 \pm 1.0	6.4 \pm 1.4	0.326 \pm 0.062
L1 r	7	38.9 \pm 7.4	38.6 \pm 1.0	30.1 \pm 1.6	-8.5 \pm 1.4	-0.222 \pm 0.046
L2 r	7	45.9 \pm 5.1	38.5 \pm 1.0	32.0 \pm 0.6	-6.5 \pm 1.0	-0.143 \pm 0.020
L3 r	7	134.0 \pm 1.6	39.2 \pm 1.1	31.4 \pm 1.1	-7.7 \pm 1.6	-0.057 \pm 0.011
T r	21	73.1 \pm 44.9	38.8 \pm 1.0	31.2 \pm 1.4	-7.6 \pm 1.5	-0.141 \pm 0.074
L1 b	7	17.2 \pm 1.2	30.1 \pm 1.6	37.3 \pm 0.7	7.1 \pm 1.7	0.414 \pm 0.093
L2 b	7	14.6 \pm 2.3	32.0 \pm 0.6	37.9 \pm 0.6	5.9 \pm 0.8	0.407 \pm 0.046
L3 b	7	16.8 \pm 1.4	31.4 \pm 1.1	38.1 \pm 1.3	6.6 \pm 2.0	0.393 \pm 0.110
T b	21	16.2 \pm 2.0	31.2 \pm 1.4	37.8 \pm 0.9	6.6 \pm 1.6	0.405 \pm 0.084

Table C5. Heart Rate Response by condition (mean \pm SD)				
	Mean HR (bpm) (n)		Percentage HRR (%)	
	Initial deployment	Re-deployment	Initial deployment	Re-deployment
L1	148 \pm 12 (16)	152 \pm 12 (16)	71 \pm 9	74 \pm 9
L2	143 \pm 11 (16)	151 \pm 14 (16)	68 \pm 8	73 \pm 11
L3	141 \pm 13 (16)	144 \pm 16 (16)	66 \pm 9	68 \pm 12
T	144 \pm 12 (48)	149 \pm 15 (48)	68 \pm 9	72 \pm 11

Where the number in parenthesis after each SD refers to the sample size.

Table C6. Air use by condition (mean \pm SD)					
	n	Duration under Air (min)	Air Use (bar)	Rate of Air Use (bar.min ⁻¹)	Ventilation Rate (l.min ⁻¹)
L1 a	16	20.4 \pm 2.3	123 \pm 17	6.0 \pm 0.8	50.5 \pm 6.4
L2 a	16	17.4 \pm 3.8	105 \pm 21	6.1 \pm 0.7	51.2 \pm 5.8
L3 a	16	22.0 \pm 1.9	122 \pm 18	5.6 \pm 1.0	47.1 \pm 8.2
T a	48	19.9 \pm 3.3	117 \pm 20	5.9 \pm 0.8	49.6 \pm 6.9
L1 b	16	17.4 \pm 1.2	97 \pm 20	5.6 \pm 1.0	46.7 \pm 8.4
L2 b	16	15.2 \pm 2.4	94 \pm 19	6.2 \pm 0.8	51.6 \pm 7.0
L3 b	16	17.2 \pm 1.6	103 \pm 20	6.0 \pm 1.0	50.3 \pm 8.3
T b	48	16.6 \pm 2.0	98 \pm 20	5.9 \pm 1.0	49.5 \pm 8.0

Table C7. Activity by condition (mean \pm SD)				
	Total Counts (n)		Activity Rate (counts.min ⁻¹)	
	Initial deployment	Re-deployment	Initial deployment	Re-deployment
L1	4555 \pm 862 (12)	3953 \pm 583 (12)	225 \pm 36	227 \pm 31
L2	3773 \pm 654 (12)	3645 \pm 948 (12)	221 \pm 38	238 \pm 34
L3	4981 \pm 663 (12)	3911 \pm 713 (12)	226 \pm 31	229 \pm 37
T	4436 \pm 874 (36)	3836 \pm 754 (36)	224 \pm 34	231 \pm 33

Where the number in parenthesis after each SD refers to the sample size.

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