# Physical Work Limits for Toronto Firefighters in Warm Environments: Defining the Problem and Creating Solutions

*WSIB Research Grant #01 005: Final Report*

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## Defence R&D Canada – Toronto

External Client Report
DRDC Toronto ECR 2003-112
September 2003

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This study, approved by the DRDC Toronto Human Research Ethics Committee, was conducted in conformity with the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans

# Abstract

This research project was divided into five parts. Part A examined the relationship between tolerance time (TT) and metabolic rate for three different environmental temperatures (25°C, 30°C, and 35°C, 50% R.H.), while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA). 37 Toronto firefighters (33 male and 4 female) were matched and divided into 4 work groups defined as Heavy (H - 4.8 $km \cdot h^{-1}$, 5% elevation; n=9), Moderate (M - 4.5 $km \cdot h^{-1}$, 2.5% elevation; n=9), Light (L - 4.5 $km \cdot h^{-1}$, 0% elevation; n=10), and Very Light (VL – 2.5 $km \cdot h^{-1}$, 0% elevation; n=9). Each group worked until rectal temperature ($T_{re}$) reached 39.0°C, heart rate (HR) reached 95% of maximum or exhaustion. Following work at each environmental temperature, subjects were monitored for 30-minutes of recovery. Part B examined the reduction in heat stress by replacing pants with shorts while wearing FPC and SCBA. Twenty-four firefighters from part A repeated their 35°C trial replacing their station pants with shorts. Part C examined active and passive cooling during intermittent work and Part D examined different levels of rehydration (0, 1/3rd, 2/3rd, and Full) while wearing FPC and SCBA. Fifteen and twelve subjects were tested for the cooling (C) and hydration (D) trials, respectively. Subjects performed an intermittent work (4.5 $km \cdot h^{-1}$, 0% elevation )/rest cycle. Reasons for termination were similar to phase I, except the $T_{re}$ cut-off was raised to 39.5°C. In part A significant differences in TT were observed across all group comparisons, excluding M versus L at 30°C and 35°C and H versus M at 35°C. During passive recovery at 35°C, $T_{re}$ continued to increase 0.5°C above $T_{re\ final}$, whereas HR declined significantly. Replacing pants with shorts had no impact on $T_{re}$ or HR when TT was less than 1 hour (H and M). In contrast, as TT were extended during lighter exercise (L and VL) $T_{re}$ was reduced by as much as 0.4°C after 80 min, and TT were significantly increased. In part C & D, TT and work time (WT) were significantly increased with both methods of active cooling when compared to all levels of hydration with passive cooling. By the end of the second rest period, $T_{re}$ was 0.9°C lower for forearm submersion (FS) compared to mister (M) cooling. Fluid restriction significantly elevated $T_{re}$ after 27 min of work and significantly reduced TT and WT when compared to full hydration. These findings illustrate the differential impact of environmental conditions at various metabolic rates on TT while wearing FPC and SCBA, as well as the importance of encorporating even partial fluid replacement strategies while wearing FPC and SCBA in the heat. In addition, passive recovery may not be sufficient to reduce $T_{re}$ below pre-recovery levels when working at higher metabolic rates and high ambient conditions. As such, the utilization of active cooling, specifically FS, can provide a definite physiological advantage while wearing FPC and SCBA in the heat. Furthermore, it appears that replacing pants with shorts under FPC reduces the heat stress associated with wearing the protective ensemble and extends TT approximately 10-15% during light exercise. The final part of the project (Part E) involved the generation of a sliderule for use by the Toronto Fire Service. This sliderule incorporated the findings from the four studies outlined above together with mathematically modeled predictions of work times in different environmental temperatures and relative humidities.

# Résumé

Ce projet de recherche a été divisé en cinq parties. Dans la partie A, nous avons examiné la relation entre le temps de tolérance (TT) et l'énergie métabolique pour trois températures ambiantes différentes (25 °C, 30 °C et 35 °C, 50 % H.R.), chez des sujets portant des vêtements de protection contre les incendies (VPI) et un appareil respiratoire autonome (ARA). Trente-sept pompiers de Toronto (33 hommes et 4 femmes) ont été appariés et divisés en quatre groupes définis selon l'intensité du travail, soit : élevée (É = 4,8 $km \cdot h^{-1}$, pente 5 %; n = 9), modérée (M = 4,5 $km \cdot h^{-1}$, pente 2,5 %; n = 9), légère (L = 4,5 $km \cdot h^{-1}$, pente 0 %; n = 10) et très légère (TL = 2,5 $km \cdot h^{-1}$, pente 0 %; n = 9). Chaque groupe a travaillé jusqu'à ce que la température rectale ($T_{re}$) s'établisse à 39,0 °C, la fréquence cardiaque (FC) atteigne 95 % du maximum ou jusqu'à l'épuisement. Après avoir travaillé dans chaque température ambiante, les sujets ont fait l'objet d'un contrôle pendant une période de récupération de 30 minutes. Dans la partie B, nous avons examiné la réduction du stress thermique lorsqu'on remplaçait le pantalon par une culotte par-dessus laquelle les sujets portaient des VPI et un ARA. Vingt-quatre pompiers ayant participé à la partie A ont répété leur essai à 35 °C en remplaçant leur pantalon par une culotte. Dans la partie C, nous avons examiné le refroidissement actif et passif durant le travail intermittent alors que dans la partie D, nous avons examiné différents niveaux de réhydratation (0, 1/3, 2/3 et totale) tandis que les sujets portaient des VPI et un ARA. Quinze et douze sujets respectivement ont participé aux essais sur le refroidissement (C) et l'hydratation (D), Les sujets exécutaient un cycle intermittent de travail (4,5 $km \cdot h^{-1}$, pente 0 %)/repos. Les critères utilisés pour mettre fin à l'essai étaient les mêmes que dans la phase I, sauf que la limite de la $T_{re}$ a été relevée à 39,5 °C. Dans la partie A, des différences significatives du TT ont été observées dans l'ensemble des groupes comparés, à l'exception du groupe M par rapport au groupe L à 30 °C et 35 °C, et dans le groupe L par rapport au groupe M à 35 °C. Durant la récupération passive à 35 °C, la $T_{re}$ a continué à augmenter de 0,5 °C au-dessus de la $T_{re\ finale}$, alors que la fréquence cardiaque (FC) a diminué de façon significative. Le fait de remplacer le pantalon par la culotte n'a eu aucun effet sur la $T_{re}$ ou la FC lorsque le TT était inférieur à une heure (L et M). En revanche, lorsque le TT était prolongé durant l'exercice plus léger (L et TL), la baisse de la $T_{re}$ pouvait atteindre 0,4 °C après 80 minutes, et les TT étaient augmentés de façon significative. Dans les parties C et D, le TT et le temps de travail (WT) ont été augmentés de façon significative avec les deux méthodes de refroidissement actif par rapport à tous les niveaux d'hydratation avec un refroidissement passif. À la fin de la deuxième période de repos, la $T_{re}$ était inférieure de 0,9 °C dans le cas de la submersion de l'avant-bras (SA) comparativement au refroidissement par pulvérisateur (P). La restriction liquidienne augmentait la $T_{re}$ de façon significative après une période de travail de 27 minutes et réduisait significativement le TT et le WT par rapport à l'hydratation totale. Ces résultats mettent en lumière les effets différents des conditions ambiantes à différents niveaux d'énergie métabolique sur le TT chez des sujets portant des VPI et un ARA de même que l'importance de prévoir des stratégies de réhydratation même partielle chez les sujets portant des VPI et un ARA dans la chaleur. En outre, la récupération passive n'est peut-être pas suffisante pour abaisser la $T_{re}$ en deçà du niveau qu'elle atteignait avant la récupération, quand les sujets travaillent à des niveaux d'énergie métabolique supérieurs et dans des conditions de chaleur ambiante élevée. En soi, l'utilisation du refroidissement actif, en particulier la SA, peut constituer un net avantage physiologique chez un sujet portant des VPI et un ARA dans la chaleur. En outre, il semble que le fait de remplacer le

pantalon par une culotte en-dessous des VPI réduit le stress thermique associé au port des vêtements protecteurs et prolonge le TT d'environ 10 à 15 % durant un exercice léger. La dernière partie du projet (partie E) consistait à produire une règle à calcul pour le Service des incendies de la ville de Toronto. Cette règle à calcul intégrait des résultats des quatre études décrites précédemment ainsi que des prédictions établies au moyen de modèles mathématiques de temps de travail dans différentes conditions de température et d'humidité relative ambiantes.

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# Executive summary

Firefighters face a trade-off between personal protection and cardiovascular and thermal strain when performing firefighting activities. As a result, there is a requirement to develop methods for keeping firefighters' cardiovascular and thermal strain below critical levels during work in firefighting protective clothing (FPC). Although the heat-stress of wearing FPC has been described, no one has attempted to define safe work limits for firefighters in different ambient conditions. This research study was designed in conjunction with the Toronto Fire Service to establish safe work guidelines for Toronto firefighters wearing FPC and SCBA (self-contained breathing apparatus) at ambient temperatures representative of summer conditions in Toronto. In addition, active and passive cooling strategies combined with different levels of hydration were examined. In total, 85 medical screenings, and 339 various heat stress trials were performed during the course of the two-year grant. All heat-stress trials were conducted in the climatic facility at DRDC Toronto. In part A, three different ambient temperatures (25°C, 30°C and 35°C, 50% R.H.) were examined over four different work intensities (Heavy, Moderate, Light, and Very Light) in order to define the physiolgoical strain associated with wearing FPC and SCBA. For part B, an additional trial at 35°C was completed during each of the workloads in part A with station pants replaced with shorts. Parts C and D utilized an ambient temperature of 35°C with 50% R.H. and the Light workload defined in part A. Findings revealed significant differences in tolerance times across the various workrates and ambient temperatures. Furthermore, during recovery heart rate was not an accurate indicator of the extent of heat strain. Mathematical hyperbolic functions relating tolerance time and metabolic rate diverged at lower metabolic workrates and converged as metabolic workrates increased. These functions illustrated that even under resting conditions at 30°C and 35°C the body would continue to store heat, and thus, implementation of a work and rest schedule while remaining encapsulated would not increase work times. Replacing station pants with shorts significantly reduced heat strain and increased TT during light exercise. There were no significant improvements during moderate or heavy exercise. The incorporation of active cooling during scheduled rest significantly reduced the heat strain associated with any given task. Hydration was found to play a role in reducing both the cardiovascular and thermal strain while wearing FPC and SCBA in the heat. It appears that even partial fluid replacement can have benefitial effects, increasing TT and WT. Ultimately, the implementation of active cooling (forearm submersion) and hydration strategies will help to reduce the occurrence of heat related injury and possibly myocardial infarction in active firefighters.

Selkirk, G.A. and T.M. McLellan. 2003. Physical Work Limits For Toronto Firefighters In Warm Environments: Defining the Problem and Creating Solutions. DRDC Toronto ECR 2003-112 DRDC Toronto.

# Sommaire

Les pompiers doivent faire un compromis entre leur protection personnelle et le stress cardiovasculaire et thermique lorsqu'ils combattent des incendies. Aussi faut-il mettre au point des méthodes permettant de réduire le stress cardiovasculaire et thermique des pompiers en deçà des niveaux critiques pendant les périodes où ils portent des vêtements de protection contre les incendies (VPI). S'il est vrai que le stress thermique lié au port de VPI a déjà été décrit, personne n'a tenté de définir des limites de travail sûres pour les pompiers dans différentes conditions ambiantes. Cette étude de recherche a été préparée de concert avec le Service des incendies de la ville de Toronto dans le but d'établir des lignes directrices pour assurer la sécurité au travail des pompiers de Toronto portant des VPI et un ARA (appareil respiratoire autonome) dans des conditions de température ambiante représentatives des conditions estivales à Toronto. En outre, des stratégies de refroidissement actif et passif combinées à différents niveaux d'hydratation ont été examinées. En tout, 85 examens médicaux et 39 essais divers de détection du stress thermique se sont déroulés pendant la période de deux ans couverte par la subvention. Tous les essais sur le stress thermique ont eu lieu à l'installation climatique de RDDC Toronto. Dans la partie A, trois températures ambiantes différentes (25 °C, 30 °C et 35 °C, 50 % H.R.) ont été examinées pour quatre intensités de travail différentes (Élevée, Modérée, Légère et Très Légère) afin de définir le stress physiologique lié au port de VPI et d'ARA. Dans la partie B, un autre essai à 35 °C a été effectué pour chacune des intensités de travail prévues à la partie A, mais dans laquelle on avait remplacé le pantalon par une culotte. Dans les parties C et D, la température ambiante s'élevait à 35 °C et l'humidité relative à 50 %, et les sujets devaient exécuter un travail d'intensité Légère définie dans la partie A. Les résultats ont mis en lumière des différences significatives du temps de tolérance pour diverses intensités de travail et températures ambiantes. En outre, durant la récupération, la fréquence cardiaque n'était pas un indicateur exact de l'importance du stress thermique. Les fonctions hyperboliques mathématiques mettant en corrélation le temps de tolérance et l'énergie métabolique divergeaient à des niveaux d'énergie métabolique inférieurs et convergeaient à mesure que cette énergie augmentait. Ces fonctions montrent que même au repos à 30 °C et 35 °C, l'organisme continuerait d'emmagasiner de la chaleur et donc que la mise en œuvre d'un plan d'alternance des périodes de travail et des périodes de repos chez des sujets qui sont toujours enfermés dans leurs VPI ne permettrait pas d'augmenter le temps de travail. Le fait de remplacer le pantalon par une culotte réduisait significativement le stress thermique et augmentait le TT durant l'exercice léger. On n'a noté aucune augmentation significative durant les périodes d'exercice d'intensité modérée ou élevée. Le recours au refroidissement actif durant les périodes de repos prévues réduisait de façon significative le stress thermique lié à une tâche quelconque. Il a été démontré que l'hydratation joue un rôle dans la réduction du stress cardiovasculaire et thermique chez des sujets portant des VPI et un ARA dans la chaleur. Il semble qu'un réhydratation même partielle puisse avoir des effets significatifs en augmentant à la fois le TT et le WT. En fin de compte, la mise en œuvre d'un refroidissement actif (submersion de l'avant-bras), et les stratégies d'hydratation aideront à réduire la survenue de lésions dues à la chaleur et éventuellement l'incidence des infarctus du myocarde chez les pompiers qui sont toujours en activité.

Selkirk, G.A. and T.M. McLellan. 2003. Physical Work Limits For Toronto Firefighters In Warm Environments: Defining the Problem and Creating Solutions. DRDC Toronto ECR 2003-112 DRDC Toronto.

# Table of contents

# List of figures

# List of tables

# Acknowledgements

The authors would like to express thanks to the personnel from the Toronto Fire Services who participated in the heat-stress trials. Their time and effort in this investigation were crucial to its success. Thank-you to our Toronto Fire Services liaison, Captain Tim Metcalfe, for all of your help with subject recruitment and scheduling. In addition, thank you to John Lane, David Ross and the Toronto Professional FireFighters Association, for their continued help and support. The assistance and technical support of Mrs. I Smith, Mr. J. Pope, Mrs. D. Kerrigan-Brown, Mr. R. Limmer and Mr. J. Hilton were crucial to the successful completion of these trials. Additional thanks to Dr. P. Tikuisis for his mathematical analysis and Dr. Gonzalez (USARIEM) for conducting thermal manikin testing.

This Project was funded by a research grant provided by the Workplace Safety and Insurance Board (Ontario).

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# Introduction

### Physical Work Limits

Traditionally, it has been perceived that a firefighter's primary responsibility is to fight fires; however, in actuality, only a small percentage of time is spent on this task [1, 2]. Other aspects of a fire call include overhaul, ventilation, search and rescue and salvage [2-5]. Additional types of calls can include emergency responses which encorporate the risk of exposure to unknown agents and/or poor air quality, such as hazardous material spills, suspected terrorist activity and industrial incidents. Although these environments do not involve direct live fire exposure, they do produce the neccessity to protect firefighters against hazardous agents by wearing firefighting protective clothing (FPC) and self contained breathing apparatus (SCBA) regardless of the ambient temperature. In addition to wearing FPC and SCBA during such tasks, a firefighter is expected to be active (ie. walking, running, lifting and/or pushing objects), creating an increase in metabolic heat production and potential heat storage [2, 6, 7].

In 1987, changes in legislation lead to the National Fire Protection Agency's (NFPA) development of new protective clothing standards [5]. With these changes, comes a new era of firefighter protective ensembles, which offers an increased protection from both hazardous materials and extreme environmental heat for short periods of time. Since the new clothing is typically heavy, thick, multi-layered and bulky, it exacerbates the challenge of thermoregulation because of limited water vapor permeability across the clothing layers, which decreases the rate of heat exchange [8, 9].

Typical bunker gear configurations, with SCBA, weigh approximately 23 kg [4, 10, 11]. The increased bulk and mass can alter both gait mechanics and the efficiency of movement, increasing the metabolic cost of work by up to 50% [4]. Furthermore, when protective clothing ensembles restrict evaporative heat loss through decreased water vapor permeability, the evaporative heat loss required to maintain a thermal steady state ($E_{req}$) can exceed the maximal evaporative capacity of the environment ($E_{max}$), creating a condition of uncompensable heat-stress [12]. In these situations, trapped metabolic heat produced by working muscles, as well as heat gained from the local environment produce an increased thermoregulatory strain [10, 13]. As well, increased skin perfusion in response to the thermal strain during work creates an additional demand on the cardiovascular system.

It is common to record near maximal heart rates in firefighters for prolonged periods of time[4, 5, 14-16]. Unfortunately, in respect to firefighting many in-line deaths from heart attack have been documented each year. The most recent statistics in the United States reported that 46% (52 of 112) of firefighter deaths in 1999 were due to heart attack [17]. Although the majority of these deaths were in firefighters over 50 years of age, 20 were due to heart attack for firefighters under 50. The number of deaths due to heart attack fluctuates slightly from year to year; however, heart attacks consistently represent the most frequent cause of in-line deaths for firefighters [3, 18]. In light of the inherent physiologic strain associated with performing fire fighter duties in protective clothing, the gear is a necessary tool for firefighter safety in the modern firefighting scene. Considering the advantages and disadvantages of protective clothing ensembles, there appears to be a trade-off between personal protection and the negative impact of additional metabolic and thermal loads.

The relationship between tolerance time (TT) and metabolic rate is well defined by a hyperbolic function when military protective clothing is worn in hot environments [19, 20]. These relationships can be used to suggest safe work and rest schedules that can extend operations beyond those performed in a continuous fashion [21]. Similar information has not been generated for the firefighter although work time data are available for specific rates of heat production and environmental temperatures [16]. Given that the cardiovascular and thermal strain is substantiated for firefighters [4, 13, 15, 22, 23], there is a need to establish safe work guidelines that can be applied for different environmental temperatures over a range of metabolic rates that encompass firefighting duties and can create an uncompensable heat-stress situation. In addition, following firefighting activity, it has been found that rectal temperature ($T_{re}$) [4, 5, 15] and mean skin temperature ( $\overline{T}_{sk}$ ) [4] continue to rise 5 to 10 min into recovery, increasing the risk of heat injury after work in FPC. These findings pose the following questions. Are designated rest periods long enough for $T_{re}$ to return to pre-recovery levels? And, at what environmental conditions does a rest period become ineffective?

**Pants versus Shorts**

While protective clothing is being continually improved and lightened, the requirement for adequate environmental protection is generally contradictory to the desire for adequate ventilation. For example, the requirement to meet National Fire Prevention Association (NFPA) standards for protective clothing has led to firefighting clothing ensembles that create greater heat stress for the individual than protective ensembles that were used before this standard was introduced in 1987 [5]. One option that has been implemented by the New York City Fire Department and is being considered for implementation by the Toronto Fire Service is the replacement of the pants that are worn under the protective overgarment with shorts. Malley et al.,[24] reported that treadmill exercise time at 50% $\dot{V}O_{2\,max}$ was increased approximately 10% when the long-sleeved shirt and pants were replaced by a T-shirt and shorts worn under the protective bunker pants and jacket. Rectal temperatures, however, were not significantly different following the 15-20 minutes of exercise that included 2-min warm-up and recovery phases in a comfortable hospital laboratory setting. Subjects did report that they felt less discomfort and less restriction of movement when the shorts and T-shirt were worn. A subsequent prospective analysis of New York City firefighters between May and August revealed that replacing the long-sleeved shirt and pants with a T-shirt and shorts did not compromise the protection for the firefighter but these changes did reduce the medical leave required to treat cases of heat exhaustion [25].

Replacing the pants with shorts does decrease the thermal resistance of the firefighter's protective ensemble approximately 10% from 0.249 to 0.225 $m^{s} \cdot {}^{o}C \cdot W^{-1}$ (R.R. Gonzalez personal communication) but whether this change impacts on the resultant cardiovascular and thermal strain is unknown. Evaluation of the thermal resistance with a dry and articulating heated manikin has shown that the removal of both the combat pants and jacket worn under the military's biological and chemical defence overgarment decreases the total thermal resistance of the ensemble approximately 18% from 0.291 to 0.239 $m^s \cdot {}^oC \cdot W^{-1}$ at a wind speed of 1.12 $m \cdot s^{-1}$ [26]. These changes have extended tolerance times up to 40% during exercise in environments between 30ºC and 40ºC [27-30]. One would expect a smaller improvement, therefore, with the removal of only the firefighter's duty uniform pants and replacement of this clothing with shorts. One might also expect that these improvements would be more evident during light exercise where the rates of heat production are low and exposure times are extended well beyond the 15-20 min protocol used by Malley et al.,[24]. Physiological manipulations such as heat acclimation [31, 32], endurance training [31, 33] and hydration [33] have all been shown to only exert an influence on exercise time in the heat while wearing protective clothing during lower metabolic rates where tolerance times are extended beyond 60 minutes.

Although the previous studies by Malley et al.,[24] and Prezant [25] provide useful information that ultimately affected current firefighting policy and guidance for commanders, data is not available that conclusively shows that the thermal and cardiovascular stress associated with wearing firefighting protective clothing is reduced when the duty uniform pants are replaced with shorts.

**Active versus Passive Cooling**

Work and rest schedules can be implemented to extend operations beyond those performed in a continuous fashion [21]. However, it has been found that with hot and/or humid conditions $T_{re}$ will not decrease during passive rest, and in fact, will continue to increase during the designated rest periods due to the environmental conditions[4, 5, 15, 34]. Thus, when ambient temperatures are high, the implementation of work and rest schedules will extend exposure time but not the total amount of work accomplished. If body cooling can occur during periods of rest, then implementing work and rest schedules can increase the total work time while reducing heat strain [35]. It has been postulated that in such instances, active cooling can be incorporated into the standard work and rest schedules to promote a negative heat balance(18).

Various methods for cooling have been suggested, including precooling [36, 37], liquid and air cooling systems [38-40], water immersion of the extremities, both hands [40-42] and feet [43], as well as fan cooling [7]. Liquid and air cooling systems offering continuous [38]and intermittent [39] microclimate cooling have been found to deliver sufficient cooling power to effectively reduce heat strain during moderate to heavy work. Depending on the working conditions, these methods have the potential to change an uncompensable working environment to compensable [39, 44]. Another approach is to adapt the technology of these devices into portable units. However, current portable cooling devices generally utilize complicated equipment, are expensive and cumbersome, and add to the already elevated metabolic demand for a given activity [39, 44, 45]. In addition, practicality and mobility could be limited with tethered systems or portable units where extended periods of exposure to harsh or dangerous environments are necessary. An alternative cooling method to personal mounted devices is extremity immersion [40, 42, 43, 45]. A comparison between an ice-vest configuration and hand immersion found that the small advantage acquired through constant cooling during work when using an ice vest was surpassed by hand immersion in 20°C water during scheduled rest periods [40].

Fan cooling has also been found to attenuate the increase in rectal temperatures during work and rest schedules; however, as rectal temperature approached 38.0°C, rectal temperature continued to rise during subsequent recovery periods[7]. Therefore, it remains to be seen how effective active fan cooling would be following additional bouts of work as firefighters approach critical limits. Portable misters utilizing the concept of flash evaporation have the potential to reduce elevated local ambient environmental conditions by approximately 20°C (Personal communication, Schaefer Ventilation Equipment, LLC). It is possible that additional cooling potential supplied by a fan and mist combination might have the potential to further decrease the rate of rectal temperature increase observed with fan cooling alone[7].

Given the reported benefits of limb submersion and fan/ mister cooling, these modalities were selected as the two most practical and cost effective cooling methods to be examined.

**Hydration**

Dehydration of 1-3% body mass (BM) is associated with performance decrements both psychologically [46, 47] and physiologically [48-50]. A core temperature increase of 0.1°C- 0.2°C has been reported for every percentage decrease in BM [50-52]. Decreases in blood volume during rest/ exercise, increased blood viscosity and decreased cardiac filling contribute to the decrease in physical work capacity. Furthermore, the combination of dehydration (~4%) and hyperthermia have been found to produce increases in HR for a given workload, resulting in an 8% decrease in stroke volume and subsequent 13% decrease in cardiac output [53]. Hyperosmolality produced by the loss of water from prolonged sweating decreases whole body sweat rate [52], sweat sensitivity threshold[54-57], and increases cutaneous vascular resistance [52, 54, 58, 59] decreasing the ability to dissipate heat and maintain thermoregulation [54]. Severe dehydration greater than 7% BM can result in collapse [60]. In addition, an elevated internal temperature may increase mental and cognitive impairments, such as an increasing decision time and decreasing working memory [50] and can lead to unsafe behaviour in the workplace [61]. Within certain occupational settings, it must be considered that as the complexity of tasks increase, the lower is the limit for unimpaired performance [62]

Fluid restriction [63-65] and hypohydration [63] have been shown to have detremental effects on tolerance time while wearing protective clothing [33, 63, 64]. In a uncompensable environment, evaporation of sweat is restricted, thus making the sweating response to elevated core temperatures an ineffective means to reduce elevated core temperatures. It has been suggested that due to the limited water vapour permeability through the protective clothing, the increased ability to produce sweat (such as in endurance trained or heat-acclimated individuals) may promote an increased rate of fluid loss (dehydration) without the added benefits of increased evaporative heat loss [66]. In fact, when the effects of acclimation and aerobic training have been examined with hypohydration and fluid restriction, fluid replacement has been suggested as a suitable alternative to heat acclimation while wearing NBC protective clothing [33].

The effectiveness of fluid replacement depends on the volume [54, 67] and temperature [65, 68] of the fluid ingested, the rate of gastric emptying from the stomach, the rate at which fluid is absorbed from the small intenstine [69, 70] and the type of exercise which is being performed [71]. As thermal strain and dehydration increase there is a decrease in the rate of gastric empting due to decreased stomach secretion and contraction [72]. Thus, exercise in the heat which produces elevated $T_{re}$ and SR has the potential to reduce the effectiveness of fluid replacement in maintaining plasma volume [69].

While working in the heat, an individual's thirst response does not accurately predict body fluid needs [61]. Mechanisms to drink are not activated until a dehydration of approximately 2% occurs [48], thus even when fluid is administered ad libium, the drive to drink is inadequate to maintain a euhydrated state during heat-exposures[48, 73]. This process has been coined voluntary dehydration [74, 75] which represents a complex process, incorporating both psychological and physiological stimuli [74, 75]. Given the importance of maintaining euhydration while working in the heat wearing protective clothing, forced hydration schedules must be examined in order to ensure proper fluid replacement.

The cardiovascular and thermoregulatory strain associated with firefighters working in temperate climates has been documented for exercise up to 1 hr [2] as well as for shorter durations in the heat [4, 11, 15] and during live-fires [10, 13, 76]. However, few, have examined the impact of hydration strategies either before or during rest periods on the cardiovascular and thermoregulatory responses while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA). One study, Carter et al., [7], reported administering 500mL of water during recovery, however, body weights still declined over 1 kg during the 40-min protocol. Clearly, this strategy did not ensure that euhydrated body weights were maintained.

Previously, McLellan and Cheung [65] reported that fluid replacement increased tolerance time during uncompensable heat stress because heat storage capacity, rather than evaporative heat loss, was increased compared with the no fluid condition. The fluid provided during this study [65] represented 67% of the fluid lost and their findings questioned whether maintianing an euhydrated condition might enhance TT further by an additional increase in heat storage capacity.

## Purpose

The purposes of this two-year WSIB research grant were to:

A. determine, how long personnel can continue to work before reaching unsafe physiological limits while wearing their protective clothing and SCBA at 25°C, 30°C and 35°C and 50% relative humidity (R.H.).

B. examine how rapidly the firefighter cools during a 30-min recovery period following work to exhaustion.

C. determine the relationship between TT and metabolic work rate.

D. compare the cardiovascular and thermal strain associated with wearing the duty uniform long pants or shorts under FPC.

E. compare active and passive cooling strategies during intermittent rest periods to determine whether one modality was more effective than another in aiding heat transfer from the body while wearing FPC.

F. examine the effects of different levels of fluid replacement during work in FPC and SCBA in the heat.

# A. Physical Work Limits For Toronto Firefighters in Warm Environments.

## Abstract

This study examined the relationship between time to reach critical end points (Tolerance Time, TT) and metabolic rate for three different environmental temperatures (25°C, 30°C, and 35°C, 50% R.H.), while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA). Thirty-seven Toronto firefighters (33 male and 4 female) were divided into 4 work groups defined as Heavy (H, n=9), Moderate (M, n=9), Light (L, n=10), and Very Light (VL, n=9). At 25°C, 30°C and 35°C, ET (min) decreased from 56 to 47 to 41 for H, 92 to 65 to 54 for M, 134 to 77 to 67 for L, and 196 to 121 to 87 for VL, respectively. Significant differences in TT were observed across all group comparisons, excluding M versus L at 30°C and 35°C, and H versus M at 35°C. Comparing 25°C to 30°C, M, L, and VL had significant decreases in TT, whereas only VL had a significant decrease when 30°C was compared to 35°C. For 25°C to 30°C, the relative change in TT was significantly greater for L (37%) and VL (41%) compared with H (16%) and M (26%). For 30°C to 35°C, the relative change among the groups was similar and approximately 17%. During passive recovery at 35ºC, $T_{re}$ continued to increase 0.5ºC above $T_{re\ final}$, whereas HR declined significantly. These findings show the differential impact of environmental conditions at various metabolic rates on TT while wearing FPC and SCBA. Furthermore, these findings reveal passive recovery may not be sufficient to reduce $T_{re}$ below pre-recovery levels when working at higher metabolic rates in hot environments.

**Keywords:** Uncompensable heat-stress, work tolerance, rectal temperature, metabolic rate, protective clothing.

# Methods

### Subjects

Following approval by the DRDC Toronto's Human Ethics Review Committee, 37 subjects (33 men and 4 women) were selected from a pool of 70 active Toronto Firefighters. Prior to participation, the subjects were medically screened and a full explanation of procedures, discomforts and risks were given prior to obtaining written informed consent. Medical screening consisted of a baseline 12-lead electrocardiogram, a medical history questionnaire, a pulmonary function assessment and a doctors' examination. Testing was performed in the climatic chamber at DRDC Toronto between October and May to limit heat acclimation through casual exposure to hot environments.

### Determination of $\dot{V}O_{2peak}$

Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured at a comfortable room temperature (22°C) using open-circuit spirometry on a motorized treadmill using an incremental protocol [19, 20]. $\dot{V}O_{2peak}$ was defined as the highest observed 30-sec value for oxygen consumption ($\dot{V}O_2$) together with a respiratory exchange ratio (RER) $\geq$ 1.15. Relative values for $\dot{V}O_{2peak}$ in $mL \cdot kg^{-1} \cdot min^{-1}$ were expressed in terms of total body mass for individual subjects. Heart rate (HR) was monitored during the treadmill protocol using a transmitter/ telemetry unit (Polar Vantage XL, Finland). The highest value recorded at the end of the exercise test was defined as peak HR ($HR_{peak}$). A physical activity profile was obtained from a verbal questionnaire to determine the presence or absence of regular involvement in aerobic activities. Body surface area ($A_D$) was calculated using the Dubois equation [77]. Body density was determined from underwater weighing using body plethysmography to determine residual lung volume [78, 79]. Body fatness was calculated using the Siri equation [80].

### Definition of Groups

Firefighters were divided into one of four groups (8-9 men and 1 woman in each group) that performed treadmill exercise defined as Heavy (H, 4.8 $km \cdot h^{-1}$, and 5% elevation, n=9), Moderate (M, 4.5 $km \cdot h^{-1}$, and 2.5% elevation, n=9), Light (L, 4.5 $km \cdot h^{-1}$, and 0% elevation; n=10), and Very Light (VL, 2.5 $km \cdot h^{-1}$, and 0% elevation; n=9) in accordance with guidelines established for military work efforts [26]. Subjects were allocated such that the average age, aerobic fitness and body fatness were similar across the groups (Table 1).

## Clothing Ensembles

During work, subjects wore their own NFPA standard protective firefighting turnout gear (Garment Model – BPR5442TK, Morning Pride, Dayton, OH), gloves (Shelby Firewall), Nomex® flash hood (Majestic Fire Apparel), helmet (Firedome PX Series, Bullard, Kentucky), and SCBA (MSA, Mine Safety Appliances Company, Pitts, Penn). Standard issue cotton station pants and Toronto fire T-shirt were worn beneath the turnout gear, along with underwear, shorts, socks and running shoes. The Canadian Forces nuclear biological and chemical (NBC) impermeable protective over-boot was worn in place of the standard rubber boot in order to simulate the impermeable characteristics of the rubber boot. The total weight of the ensemble approximated 22 kg. During all trials, subjects breathed room air as opposed to SCBA; however, full SCBA was carried to simulate the weight of the bottle. The total thermal resistance of the firefighter protective clothing ensemble, determined with a heated articulating copper manikin, at a wind speed of 0.85 $m \cdot s^{-1}$, was 0.240 $m^2 \cdot °C \cdot W^{-1}$ (1.55 clo). The Woodcock vapor permeability coefficient, determined with a completely wetted manikin, was 0.27 (R.R. Gonzalez, personal communication).

## Experimental Design

All subjects performed a familiarization exposure in the most severe environmental condition (35°C, 50% R.H., wind speed <0.1 $m \cdot s^{-1}$), at their designated work rate until attaining one or more of the specific end-point criteria (see below). The first experimental trial was at least 10 days after the familiarization trial to limit the acute effects of acclimation. Each subject then performed randomly assigned experimental sessions at their corresponding work rates, at ambient temperatures of 25°C, 30°C, and 35°C and 50% R.H., while wearing the full firefighting protective ensemble. Subjects were asked to refrain from hard exercise (i.e., running, swimming, cycling, and weight lifting), alcohol, nonsteroidal anti-inflammatories, and sleep medication 24 hours before each session and also to refrain from consumption of caffeine or nicotine 12 hours before each session. Donation of blood was prohibited within 30 days of any part of the experiment. The protocol timeline was broken into a work and recovery phase as is shown in Figure 1.

*Work phase.* Each work cycle was divided into a work portion and a simulated SCBA bottle change. The work portion consisted of walking at the assigned work rate for 20 min while wearing the protective ensemble and SCBA (Figure 2). At 20 min, the simulated SCBA bottle change portion began. Subjects walked at 2.5 $km \cdot h^{-1}$, for min 20-23 to simulate walking to a bottle change station. At 23 min, subjects straddled the treadmill while removing helmet, flash hood, SCBA face piece and gloves (Figure 3). At 26 min, subjects were asked to don their SCBA, flash hood, helmet and gloves and to resume walking at 2.5 $km \cdot h^{-1}$, for min 27-30, thus simulating the return to the work area. At 30 min, subjects began another 20-min work portion, repeating the cycle until one or more of the specific end-point criteria were reached.

*Recovery phase.* Recovery time zero was defined as the time at which the subject reached one of the specific end-point criteria. After recording a dressed weight, helmet, flash hood, gloves, jacket, tanks and SCBA face piece were removed and the subject was seated for the remainder of the 30-min recovery period exposed to the same environmental conditions.  Although bunker pants were not taken off, the subjects were allowed to undo the Velcro® on the front of the pant.

*Specific End-Point Criteria.* End-point criteria for the work phase included, 4 hours of continuous work, $T_{re}$ reaching 39.0°C, HR reaching or exceeding 95% of maximum for 3 min, dizziness or nausea precluding further exercise, subject exhaustion or discomfort due to the encapsulation of the clothing ensemble and respirator, or the investigator terminating the trial.  End-point criteria for the recovery phase were similar to the work phase except that the $T_{re}$ ceiling was raised to 40°C. Tolerance time was defined, for all trials, as the elapsed time from the beginning of the first work phase to the attainment of one or more of the end-point criteria that resulted in the termination of the work phase and the start of the 30-min recovery phase.

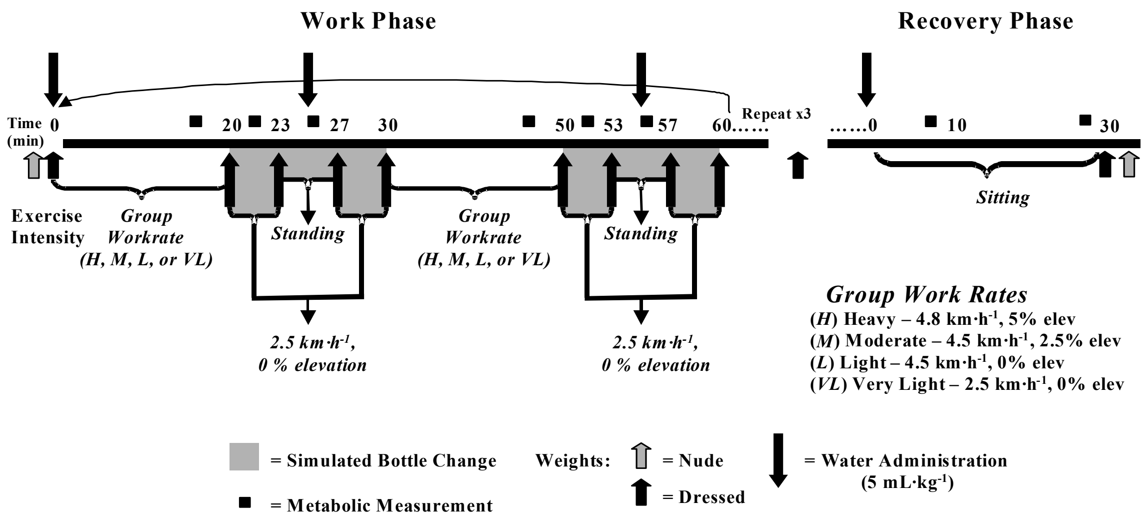


*__Figure 1.__ Protocol Timeline for heat-stress trials at 25°C, 30°C and 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus.*

## Dressing and Weighing Procedures

To control for the effects of circadian rhythm on $T_{re}$ , all trials began at 7:30 am [81]. Upon arrival, subjects inserted a rectal probe and were weighed nude on an electronic scale, sensitive to the nearest 0.05 kg (Serta Systems Inc., SuperCount, Acton, MA). Skin thermistors and HR monitor were applied, and then subjects were dressed in

***Figure 2.*** *20-min work pahse walking at assigned group workrate wearing full firefighting protective ensemble and self-contained breating apparatus.*

station pants and T-shirt followed by bunker pants, jacket, flash hood, running shoes, and NBC over-boot (Figure 4). Following water administration, subjects donned SCBA tanks and their respirator facepiece, pulled over their flash hoods and put on helmet and gloves, to obtain full encapsulation. Subjects' were then led into the climatic chamber where a final dressed weight was obtained, and skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer, Pitts, PA). Subjects straddled the treadmill walking surface and specific treadmill speed and grade were set prior to the first 20-min work portion.

Upon completion of the recovery phase, a final dressed weight was obtained to encompass all gear and subjects were removed from the climatic chamber. The subjects' nude weight was recorded within 5 min after subjects undressed and towelled dry.

***Figure 3.*** *Standing rest period during work cycle, simulated SCBA bottle change.*

### Fluid Replacement

Prior to entering the climatic chamber, at min 25 of each 30-min work + SCBA bottle change cycle, and at the beginning of the recovery period subjects were given 5 $mL \cdot kg^{-1}$ of cool water (~15°C) to drink. If $T_{re}$ exceeded 38.5°C or if the subject felt that he or she could not continue for at least another 15 min, water was not administered for the remainder of the work phase. This procedure was implemented to prevent an unabsorbed bolus of water from remaining in the gut after trial termination and effecting subsequent sweat rate calculations.

## Physiologic Measurements

### Temperature Measurements

Mean values over 1-min periods for $T_{re}$, and a 7-point weighted $\overline{T}_{sk}$ [82] were calculated, recorded, and printed by the computerized data-acquisition system. $T_{re}$ was measured using a flexible vinyl-covered rectal thermistor (YSI Precisions 4400 Series, Yellow Springs Instrument Co. Inc. Yellow Springs, OH)

(A) (B)

***Figure 4.*** *Dressing procedures – running shoes (A), and NBC overboot (B).*

inserted approximately 15 cm beyond the anal sphincter. $\overline{T}_{sk}$ was obtained from 7 temperature thermistors (Mallinckrodt, Medical Inc, St. Louis, MO) taped on the forehead, abdomen, deltoid, hand, upper anterior thigh, shin and foot.

### Heart Rate Measurements

Heart rate was monitored using a transmitter (Polar Vantage XL), attached with an elasticized belt fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually every 5 min during both the work and recovery phases of the heat-stress trial.

### Gas-Exchange Measurements

Details of the open-circuit spirometry used to determine expired minute ventilation ($\dot{V}_E$), $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$) have been presented previously [20]. Measurements were made during min 17-20 and 20-23 of each 30-min work + bottle change cycle and during min 7-10 and 27-30 of the recovery phase. Values were averaged from a 2-min sampling period for each subject following a 1-min washout period.  The current SCBA face piece outtake valve was modified to incorporate the attachment of an adaptor that allowed expired gases to be collected (Figure 5).

### Sweat Measurements

During the trials, all nude and dressed masses were corrected for respiratory [83] and metabolic mass losses [84], as well as for fluid intake.  The rate of sweat production (SR) incorporated both the work and recovery phases.

### Blood Sampling and Measurements

A 5 mL blood sample was obtained by venipuncture (Figure 6), prior to the dressing procedures, to determine osmolality using the Advanced[TM] Micro-Osmometer (Model 3300, Advanced Instruments, Norwood, Massachusetts).

***Figure 5.*** *Modified SCBA facepiece outtake valve with hose adaptor*

***Figure 6.*** *Blood sampling using venipuncture*

## Statistical Analyses

A one factor between (group) and one factor within (environmental temperature) ANOVA was used to compare the dependant measures of osmolality, TT, SR and $\dot{V}O_2$. An ANOVA with one between factor (group) and 2 repeated factors (environmental temperature and time of exposure) were performed on the various dependant measures sampled over time (ie., $\Delta T_{re}$, $\overline{T}_{sk}$, and HR) for the work and recovery phases. To correct for violations in the assumption of sphericity with the repeated factors, the Huynh-Feldt correction was applied to the F-ratio. When a significant F-ratio was obtained, post-hoc analyses utilized a Newman-Keuls procedure to isolate differences among the treatment means. In addition, the relationship between TT and the average metabolic rate over the duration of the heat exposure was fit with a hyperbolic function [19, 20, 35]. All ANOVA's were performed using statistical software (SuperAnova V. 1.11 (1991), Abacus Concepts, Inc.). For all statistical analyses, an alpha level of 0.05 was used.

# Results

### Subjects

Anthropometric measures, $HR_{peak}$ and $\dot{V}O_{2peak}$ are listed in Table 1. There were no significant differences among groups for any of these measurements. Although group averages suggest moderate fitness levels, it is important to note that $\dot{V}O_{2peak}$ ranged between 40 and 60 $mL \cdot kg^{-1} \cdot min^{-1}$ and subjects activity levels ranged from sedentary to highly trained in each group.

***Table 1.*** *Anthropometric measurements of age, height, mass, surface area ($A_D$), maximal heart rate ($HR_{peak}$), peak aerobic power ($\dot{V}O_2$ in $mL \cdot kg^{-1} \cdot min^{-1}$) and body fatness (BF) for Heavy (H), Moderate (M), Light (L) and Very Light (VL) groups and overall sample mean. Values are means (±SE).*

| Group | Age (y) | Height (cm) | Mass (kg) | $A_D$ ($m^2$) | $HR_{peak}$ ($b \cdot min^{-1}$) | $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) | BF (%) |
|---|---|---|---|---|---|---|---|
| **H (n=9)** | 40.2 (0.8) | 181.6 (2.2) | 85.6 (3.4) | 2.06 (0.05) | 184.2 (2.8) | 51.8 (1.9) | 17.3 (2.0) |
| **M (n=9)** | 39.0 (1.5) | 177.1 (3.5) | 83.12 (4.0) | 2.00 (0.07) | 189.8 (3.6) | 51.7 (2.0) | 16.1 (1.6) |
| **L (n=10)** | 40.0 (1.3) | 178.9 (3.0) | 83.63 (3.3) | 2.02 (0.05) | 189.3 (2.4) | 51.3 (2.1) | 16.9 (1.3) |
| **VL (n=9)** | 39.2 (1.0) | 180.3 (1.3) | 88.23 (3.1) | 2.08 (0.04) | 186.0 (3.4) | 50.5 (2.0) | 17.2 (0.6) |
| **Over-all** | 39.6 (0.6) | 179.4 (1.3) | 85.1 (1.7) | 2.04 (0.03) | 187.4 (1.5) | 51.31 (1.0) | 16.9 (0.7) |

There were no significant differences observed between the groups.

### Pre-Osmolality and Fluid Replacement

There were no significant differences in osmolality within or between the groups with values ranging from 287-293 $mOsm \cdot kgH_2O^{-1}$ well within the accepted range for a normal hydrated state [85]. During the heat-stress trials, subjects consumed 93% of the fluid they were administered. The average rate of consumption was $0.788 \pm 0.05\ L \cdot h^{-1}$ during the heat-stress trials and there were no significant differences observed within or between groups.

## Work Phase

### Gas Exchange

After 20 min of work, there were no significant differences in $\dot{V}O_2$ observed within each group across the three ambient temperatures (25°C, 30°C and 35°C) and there were no further changes with time during the heat-stress. A significant main effect of $\dot{V}O_2$ was observed between all group comparisons. After 20 min of work $\dot{V}O_2$ was 2.09 ± 0.06, 1.62 ± 0.06, 1.29 ± 0.06, and 0.99 ± 0.06 $L{\cdot}min^{-1}$ for H, M, L, and VL respectively. These values approximated 47%, 38%, 30%, and 21% $\dot{V}O_{2peak}$ for H, M, L and VL respectively.

### Heart Rate

Figure 7 presents the HR response for the four groups during exposure to the three environmental conditions. Between group comparisons (H vs. M, L, and VL; M vs. L, and VL; L vs. VL) showed that there were significant differences in HR for all group comparisons following the first 5 min of work for all three temperature conditions (25°C, 30°C, 35°C). Within group comparisons for the 25°C and 30°C conditions revealed that HR was significantly higher in H and M at 30°C after 25 min of work, L after 15 min and VL after 20 min of exposure. Comparisons between 30°C and 35°C revealed that exercise HR values were significantly higher in VL at 35°C after 20 min and after 40 min for M. There were no significant differences observed for H or L.

### Rectal Temperature

The values for initial rectal temperature ($T_{re\ initial}$), final rectal temperature ($T_{re\ final}$), and the rate of $T_{re}$ increase ($\frac{T_{reFinal} - T_{reInitial}}{TT}$) are given in Table 2.

*$T_{re\ initial}$.* We did not expect any differences for $T_{re\ initial}$ either within or between groups since group allocation was matched for fitness and the presentation of the experimental sessions was randomized. $T_{re\ initial}$ varied by less than 0.2°C between the groups and within the sessions. However, VL was significantly higher compared with H at 25°C, and in addition, M was significantly higher compared to the other groups at 35°C. There were also significant within group differences. For example, $T_{re\ initial}$ at 30°C was significantly greater than 25°C and 35°C for H. In addition, at 25°C $T_{re\ initial}$ for M was significantly lower than 30°C and 35°C and L at 30°C was significantly greater compared to L at 35°C.

*$T_{re\ final}$.* H was significantly lower than M for all exposures, and lower than L, and VL at 35°C. Furthermore, $T_{re\ final}$ for VL was significantly lower than M and L at 25°C. When comparing the groups' $T_{re\ final}$ response across the three different

temperatures, VL at 25°C had a significantly lower $T_{re\ final}$ compared with 30°C and 35°C.

***Table 2.*** *Initial, final, and rate of rectal temperature ($T_{re}$) increase ($\uparrow$) during the work phase of the heat-stress trials at 25°C, 30°C, and 35°C and 50% relative humidity while wearing full firefighting protective clothing and self-contained breathing apparatus for the Heavy (H), Moderate (M), Light (L), and Very Light (VL) work groups. Values are means (±SE).*

| Group | $T_{re\ initial}$ (°C) | | | $T_{re\ final}$ (°C) | | | Rate $T_{re}$ $\uparrow$ (°C·h$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 25°C | 30°C | 35°C | 25°C | 30°C | 35°C | 25°C | 30°C | 35°C |
| H (n=9) | 36.94 (0.10) | 37.06[F] (0.07) | 36.94 (0.11) | 38.65[D] (0.15) | 38.69[D] (0.12) | 38.53[D] (0.15) | 1.78 (0.08) | 2.04 (0.10) | 2.31 (0.17) |
| M (n=9) | 36.92[G] (0.11) | 37.05 (0.09) | 37.04[B] (0.10) | 39.00 (0.00) | 39.00 (0.002) | 38.88 (0.10) | 1.41 (0.09) | 1.81 (0.08) | 2.03(0.07) |
| L (n=10) | 36.95 (0.09) | 37.02[H] (0.12) | 36.88 (0.11) | 38.91 (0.05) | 38.93 (0.05) | 38.83 [E] (0.10) | 0.92 (0.07) | 1.50 (0.11) | 1.75 (0.10) |

Between significance: [A] VL > H ; [B] M > H, L and VL ; [C] VL < M and L ; [D] H < M ; [E] L > H. Within significance: [F] H-30°C > H-25°C and H-35°C ; [G] M-25°C < M-30°C and M-35°C ; [H] L-30°C > L-35°C ; [I] VL-25°C < VL-30°C and VL-35°C. For the rate of $T_{re}$ $\uparrow$ all comparisons, both within and between were signficantly different.

*Rate of $T_{re}$ increase.* All within and between group comparisons were significantly different for the rate of $T_{re}$ increase during the heat-stress trials.
*$T_{re}$ response over time.* To normalise the differences in $T_{re\ initial}$ data are shown as $\Delta T_{re}$ ($\Delta T_{re} = T_{re\ t} - T_{re\ initial}$) in Figure 8. Group differences in the $\Delta T_{re}$ response were evident generally after 10-20 min of exposure. In addition, group differences became evident earlier as the environmental temperature increased. Within group comparisons revealed that approximately 30 min of exposure was neccessary before significant differences were found between the 25°C and 30°C exposures or between the 30°C and 35°C exposures.

### Mean Skin Temperature

After 10 minutes of exercise, between group comparisons revealed significant increases in $\overline{T}_{sk}$ as work rate increased from VL to M at 25°C. As environmental temperature increased to 30°C and 35°C, similar differences were observed after 15 and 20 min, respectively. There were no significant differences observed between H and M as temperature increased from 25°C to 35°C. Within group comparisons between 25°C and 30°C revealed a significant increase in $\overline{T}_{sk}$ for VL throughout the trial, for M and L after 5 min of work, and for H after 20 min. For 30°C and 35°C, a significant increase in $\overline{T}_{sk}$ at 35°C was observed after 15 min for H, 20 min for M and for VL and 27 min for L. All significant differences remained for the duration of the trial.

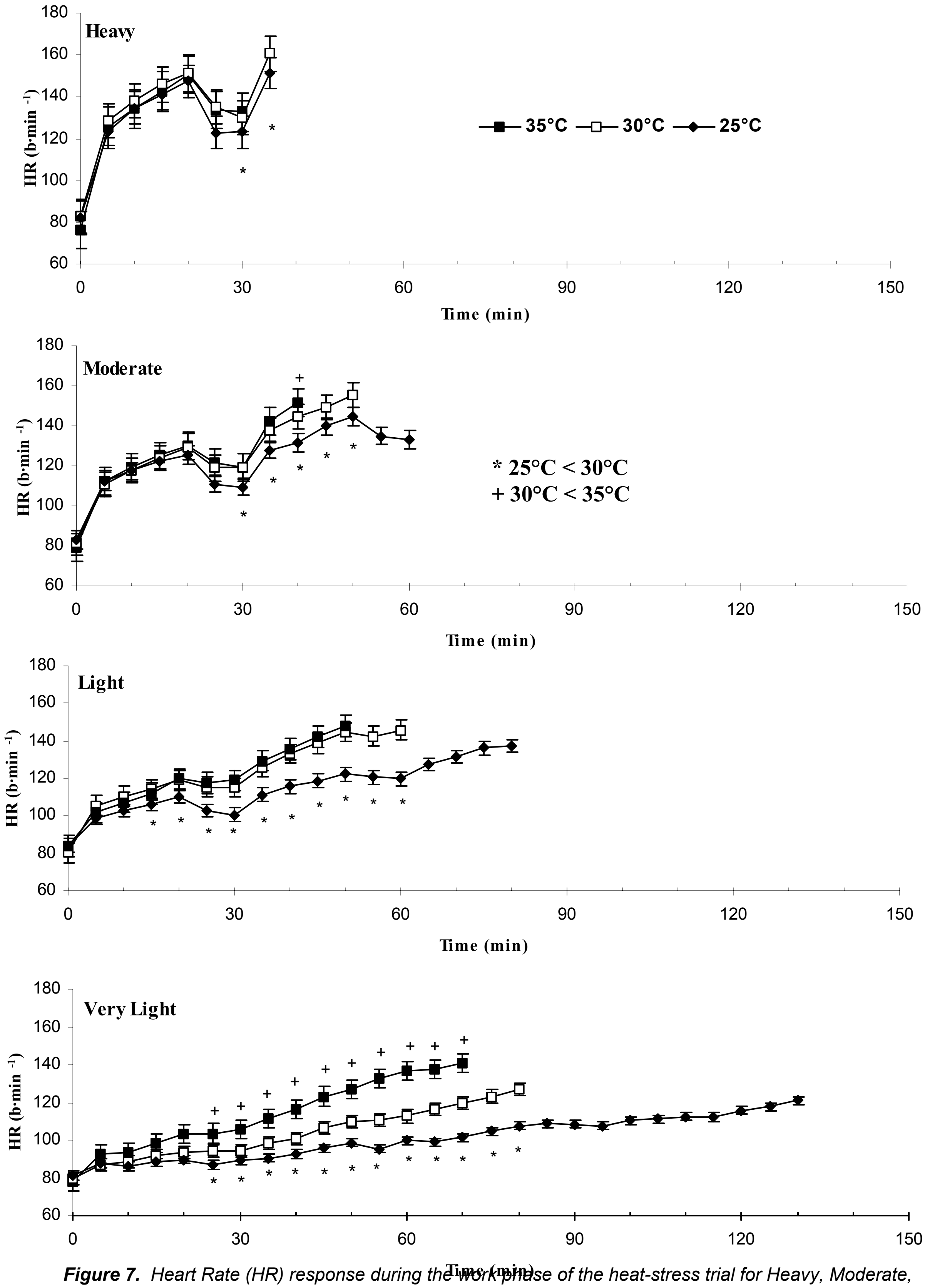


***Figure 7.*** *Heart Rate (HR) response during the work phase of the heat-stress trial for Heavy, Moderate, Light and Very Light groups at 25°C, 30°C and 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

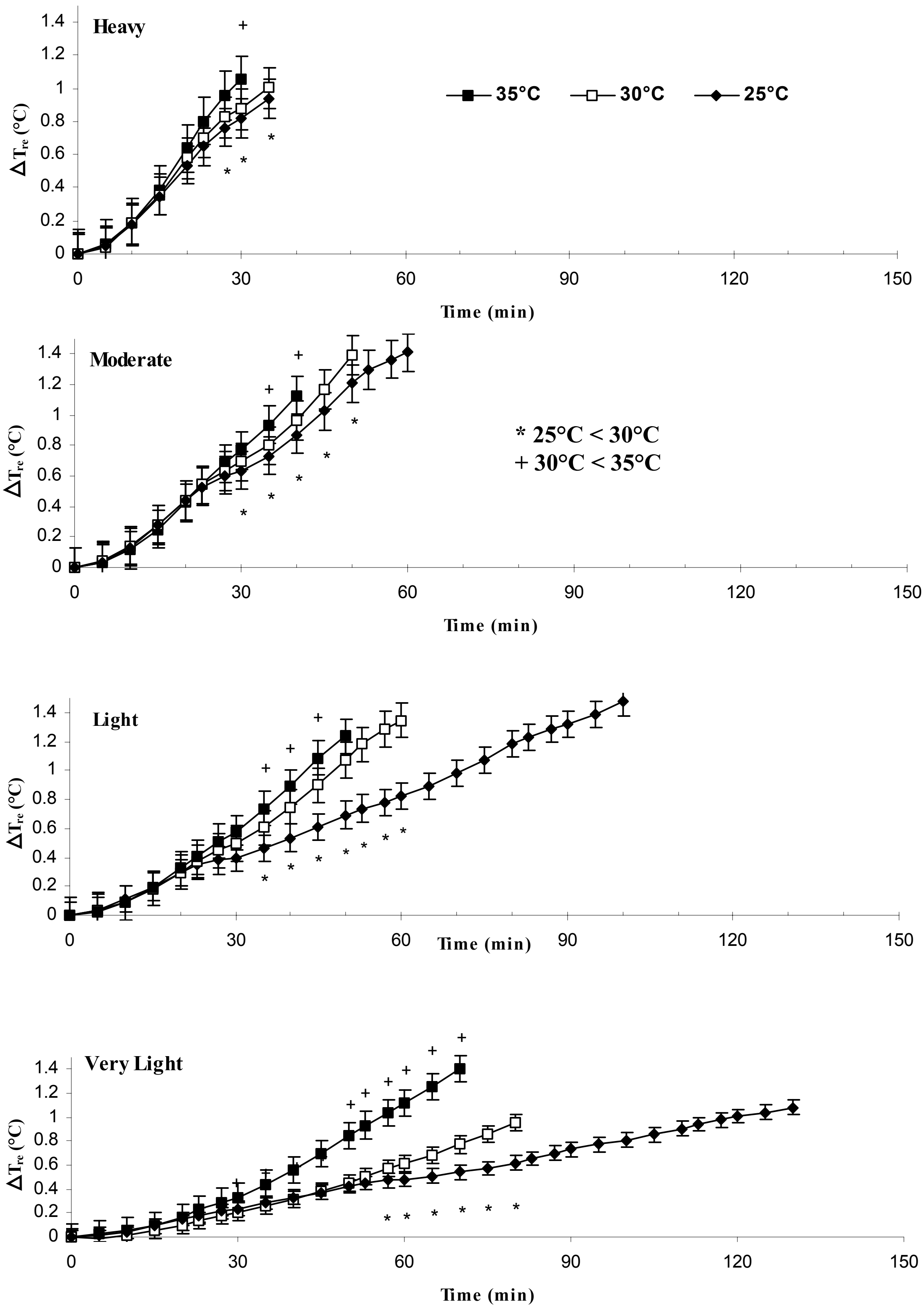


***Figure 8.*** *Delta Rectal temperature ($\Delta T_{re}$) response during the work phase of the heat-stress trial for Heavy, Moderate, Light and Very Light groups at 25°C, 30°C and 35°C and 50% relative humidity with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

## Tolerance Time

There were significant differences in the TT observed across all group comparisons, excluding M versus L at 30°C and 35°C and H versus M at 35°C (Table 3). M, L and VL had significant decreases in TT when ambient temperature increased from 25°C to 30°C, whereas only VL had a significant decrease when comparing the change in ambient temperature from 30°C to 35°C. The decrease in TT from 25°C to 30°C expressed as a percentage was significantly greater for L (40.5 ± 3.9%) and VL (37.3 ± 3.8%), compared with H (15.6 ± 3.6%) and M (26.4 ± 3.7%). However, the % change in TT from 30°C to 35°C was not different among the groups (17.3 ± 2.1%). Reasons for trial termination of the sessions are illustrated in Table 4 for the various groups. Of the 111 experimental sessions, 63% were terminated because $T_{re}$ reached 39.0°C during the work phase. A further 19% were terminated with subjects complaining of exhaustion, with half of these sessions occuring in the VL group. Eighty percent of all sessions terminated for HR occurred with heavy work. All subjects completed the 30 min of recovery during the recovery phase.

***Table 3.*** *Tolerance Time expressed in min during the heat-stress trials conducted at 25°C, 30°C and 35°C and 50% relative humidity with subjects wearing full firefighter protective ensemble and self-contained breathing apparatus for the Heavy (H), Moderate (M), Light (L) and Very Light (VL) work groups. Values are means (± SE).*

| Group | 25°C | 30°C | 35°C |
|---|---|---|---|
| **H (n=9)** | 56.4 $^{A}$ (4.4) | 47.4 $^{A}$ (3.3) | 40.7 $^{D}$ (2.3) |
| **M (n=9)** | 91.9 $^{B}$ (8.5) | 65.4 $^{E}$ (3.7) | 54.0 $^{E}$ (3.5) |
| **L (n=10)** | 134.0 $^{C}$ (9.3) | 77.1 $^{C}$ (3.1) | 67.3 $^{C}$ (3.0) |
| **VL (n=9)** | 196.1 (12.9) | 121.2 (8.4) | 86.8 (5.1) |

Significant differences: Between groups- $^{A}$ H < M, L, VL; $^{B}$ M < L, VL; $^{C}$ L < VL; $^{D}$ H < L, VL; $^{E}$ M < VL. Within groups – 25°C-30°C – M, L, VL significantly different; 30°C-35°C only VL significant.

***Table 4.*** *Reasons for termination of the heat-stress at 25°C, 30°C and 35°C with 50% relative humidity for the Heavy (H), Moderate (M), Light (L), and Very Light (VL) work groups. Values represent the number of subjects during each trial that attained a rectal temperature ($T_{re}$) of 39.0°C, ended due to exhaustion (Exh), reached or exceeded a heart rate (HR) of 95% $HR_{peak}$ for 3 min, ended due to dizziness or nausea or attained the time limit of 4 hours of work.*

| Reason for Termination | H (n=9) | | | M (n=9) | | | L (n=10) | | | VL (n=9) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25°C | 30°C | 35°C | 25°C | 30°C | 35°C | 25°C | 30°C | 35°C | 25°C | 30°C | 35°C |
| **$T_{re}$** | 5 | 4 | 3 | 9 | 8 | 6 | 6 | 8 | 7 | 3 | 5 | 6 |
| **Exh** | 1 | 1 | 1 | - | 1 | 2 | 3 | 1 | 1 | 3 | 4 | 3 |
| **HR** | 3 | 4 | 5 | - | - | - | 1 | 1 | 1 | - | - | - |
| **Dizziness/ Nausea** | - | - | - | - | - | 1 | - | - | 1 | - | - | - |
| **Time** | - | - | - | - | - | - | - | - | - | 3 | - | - |

## Recovery Phase

### Gas Exchange

After 10 min of recovery $\dot{V}O_2$ was similar among all groups and temperatures (0.43 ± 0.02 $L \cdot min^{-1}$), and remained similar for the duration of the recovery period (0.36 ± 0.01 $L \cdot min^{-1}$).

### Heart Rate

Heart rates responses during the 30 min of recovery are depicted in Figure 9. Between group comparisons revealed that HR was significantly lower for VL compared to the other groups throughout recovery at 25°C and 30°C. At 35°C, however, although HR was different at time 0 among the groups there were no other differences for the remainder of the recovery period. Within group comparisons revealed significantly lower HR for all groups after 10 min of recovery at 25°C compared with 30°C. In contrast, only group VL displayed lower HR during recovery at 30°C compared with 35°C.

### Rectal Temperature

Delta $T_{re}$ during the recovery phase is depicted in Figure 9. Between group comparisons revealed that $\Delta T_{re}$ for H and M were signficantly greater than L and VL after approximately 15 min of recovery. Significant differences in the $\Delta T_{re}$ response were also observed for all groups following 10 min of recovery for the comparisons between 25°C and 30°C and between 30°C and 35°C.

### Sweat Rate

There was a significant main effect of temperature on sweat rates. Sweat rates at 25°C (0.39 ± 0.02 $kg \cdot m^{-2} \cdot h^{-1}$) were significantly lower compared to 30°C (0.49 ± 0.03 $kg \cdot m^{-2} \cdot h^{-1}$) and 35°C (0.51 ± 0.03 $kg \cdot m^{-2} \cdot h^{-1}$).

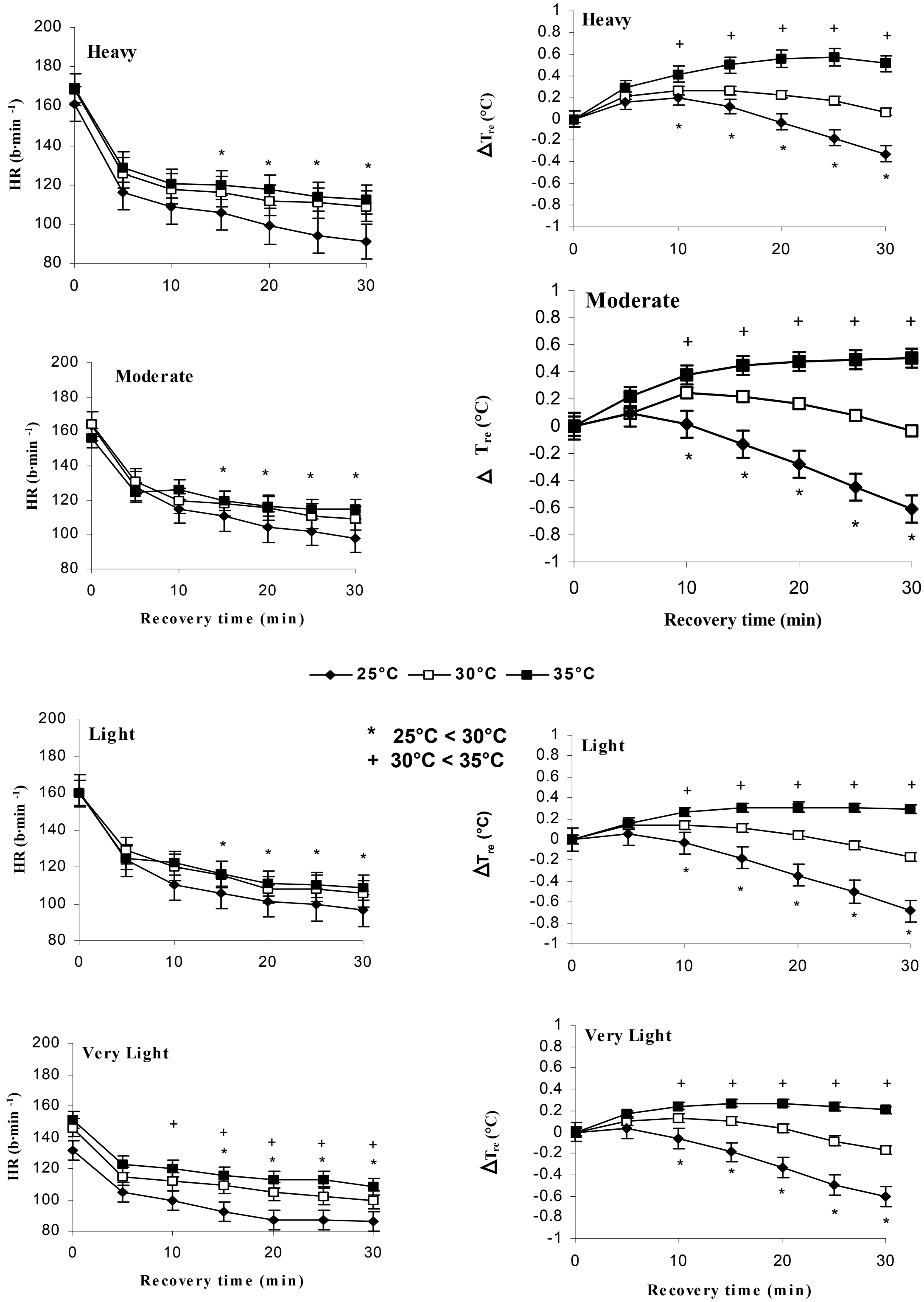


***Figure 9.*** *Heart Rate (HR) and Delta Rectal temperature ($\Delta T_{re}$) response during the 30-min recovery phase of the heat-stress trial for Heavy, Moderate, Light and Very Light groups at 25°C, 30°C and 35°C and 50% relative humidity, with subjects sitting wearing boots, bunker pants and T-shirt. Values are means (±SE).*

## Curve Fitting

The relationship between the average $\dot{V}O_2$ and TT throughout the work phase fit with a hyperbolic function for each of the three environmental conditions is shown in Figure 5. Convergence of the curves can be seen at higher work rates, whereas there is a divergence in TT at lower metabolic rates. The mathematical functions describing these relationships are also presented in Figure 10.

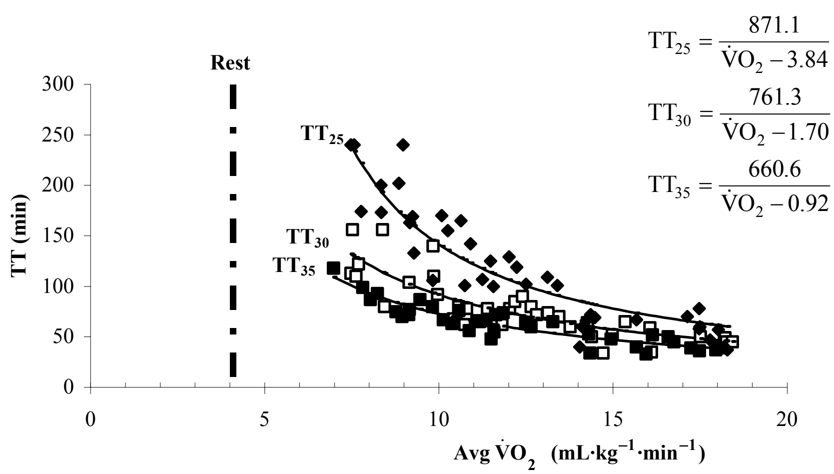


***Figure 10.*** *Curvilinear relationships between tolerance time (TT) and the average metabolic rate (Avg $\dot{V}O_2$) for all subjects at 25°C (◆), 30°C (□), and 35°C (■) and 50% relative humidity while wearing full firefighting protective clothing and self-contained breathing apparatus. Mathematical hyperbolic functions describing the relationship are also shown for the three ambient conditions. An average resting metabolic rate equivalent to 4.0 mL·kg$^{-1}$·min$^{-1}$ is also presented.*

## Discussion

The purpose of the present study was to further define the physiological strain associated with wearing FPC and SCBA at various ambient temperatures. Although, we could not simulate the radiant heat of direct fire exposure in our climatic chambers we recognized that many firefighting activities do not involve direct exposure to a fire (e.g. overhaul, toxic spills). Indeed, it has been documented that a significant proportion of the firefighter's time is spent in a non-fire environment wearing their protective ensemble and using their SCBA [3]. As such, we realized the importance to document the heat-stress associated with wearing firefighting protective ensemble during ambient conditions that are representative of the warm summer months in temperate climate regions such as Toronto.

To ensure that our findings would be applicable to all members of the Toronto Fire Service, a large sample size was recruited in order to encompass a full spectrum of active Toronto Fire Services personnel. We also attempted to control or match for many factors that might influence the thermoregulatory and cardiovascular responses during heat-stress. For example, the percentage of female firefighters in the Toronto Fire Service is less than 10%, justifying the placement of one female in each group. Elevation in $T_{re\ initial}$ in female subjects has been found during the mid-luteal phase compared to the early follicular phase [38], and thus would affect TT. In light of these findings, female subjects were tested at the same time during each 28-day firefighter shift cycle. It is important to note that the subjects in the present study were matched for age since aging can be associated with a decrease in cardiovascular function, manifested as a decrease in $HR_{peak}$, and a lowering of $\dot{V}O_{2peak}$. Variations in clothing fit were minimized by having subjects wear their own properly fitted bunker gear [86]. In addition, subjects were matched for aerobic fitness and body fatness, two important factors contributing to tolerance of uncompensable heat-stress [87, 88]. It has been documented that gender is a non-issue when dealing with tolerance to uncompensable heat-stress where subjects are matched for $\dot{V}O_{2peak}$ and body fatness [87]. Special attention was given to ensure that females in the present study had comparable anthropometric values both between and within each group. Furthermore, considering that TT for the participating females were comparable to group averages and that firefighter recruitment standards within the Toronto Fire Services are independent of gender, active firefighters should have comparable fitness levels, and thus similar responses to those seen in the present work regardless of gender.

Hypohydration is associated with increased cardiovascular and thermoregulatory strain during exercise [89, 90] and can lead to a decreased tolerance to uncompensable heat-stress, regardless of fitness levels [33]. Fluid replacement decreases physiological strain during exercise in the heat [91] and has also been shown to produce a decreased cardiovascular strain while exercising in protective clothing [63]. In the present study, pre-osmolality values were well within the range for normal hydration [85]. In addition, subjects were given 5 $mL \cdot kg^{-1}$ of water every 30 min during the exposure, equating to approximately 0.6 - 1.0 $L \cdot h^{-1}$. Sweat rates averaged 0.94 $L \cdot h^{-1}$ across the three temperatures, and thus, the percentage of body mass lost due to dehydration was less than 0.5%.

It has been well documented that certain firefighting activities incorporate a large amount of heavy upper body work for short durations [22, 23]. However it is important to realize that firefighters self-pace and work in pairs using work and rest schedules in order to continue these activities until their SCBA alarms sound. Since heat storage is a function of the absolute rate of heat production [92], it was inconsequential for the purpose of our study whether the firefighters' metabolic heat was generated using arm, leg, or a combination of arm and leg exercise. Physiologically, cardiovascular strain from leg exercise would be lower compared to arm exercise, at the assigned work rates, due to the size of the recruited muscle mass. Therefore, in the present study, continuous arm exercise was not used to simulate firefighting duties since the smaller muscle mass and local muscle fatigue would limit heat exposure times. As a result, treadmill walking was selected in order to recruit a large muscle mass and to produce TT ranging between 30 and 90 min in the highest ambient environmental temperature of 35ºC, 50% R.H.

Tolerance time in the present study was dependent on both the work rate and the environmental conditions present. For example, comparisons between H and VL showed that TT increased 2- and 4-fold at 35°C and 25°C, respectively. In contrast, within the H group there were no significant differences observed in TT as temperatures increased from 25°C to 30°C to 35°C. Final core temperatures were significantly lower for H (~38.6°C) in the present study compared to the other groups, as 3, 4 and 5 subjects ended because of high HR at 25°C, 30°C and 35°C, respectively. The lower $T_{re\ final}$ and higher HR observed demonstrate the cardiovascular limitation on TT at these higher metabolic rates lasting between 15-30 min. Similar findings were made by Smith et al.,[5] and White and Hodus[93], using work rates of 2.5 $L \cdot min^{-1}$ and 2.0 $L \cdot min^{-1}$, respectively. During these work rates, $T_{re}$ at exhaustion was less than 38.5°C after 30 min of moderate work [93] and less than 38.0°C [5] after 15 min of heavy work. Thus, it appears that firefighters' performing heavy work may succumb to physical exhaustion before heat-stress becomes a critical issue. However, the firefighter that has difficulty due to cardiovascular limitations may likely have a lower fitness level as well, and thus may tolerate a much lower rectal temperature [87].

Following firefighting activity, it has been found that $T_{re}$ [4, 5, 15] and $\overline{T}_{sk}$ [4] continue to rise 5 to 10 min into recovery increasing the risk of heat injury after work in FPC. The present study shows that HR should not be used as an index of the heat strain being experienced by the firefighter during recovery. Clearly, as evident when comparing Figure 4, the fall in HR during recovery would not predict or indicate the continued rise in $T_{re}$ during exposure to 35°C. Similarly, the comparable HR following 30 min of recovery at 30°C and 35°C for groups H, M and L, for example, do not reflect $T_{re}$ differences (approximately 0.5°C) between these environmental conditions. Our data would not recommend that firefighters be permitted to don their protective clothing and SCBA and begin a subsequent exercise phase at 35°C following this passive recovery period. It would appear that other cooling strategies such as fans[7] or hand and forearm submersion in cool water[41, 42] may be necessary to reduce the heat strain and allow subsequent work schedules to be completed.

When working with protective clothing in an occupational setting, a major issue of contention is the length of time that an individual can work before succumbing to heat exhaustion. In fact, the main goal should be to set work limits in such a way that the individual approaches but never reaches this state. However, given the vast differences in physical characteristics among working populations this is not an easy task.

The equations representing the curvilinear relationships can be used to predict TT for various work and rest schedules. The value of the vertical asymptote for these equations signifies an infinite TT and delineates compensable and uncompensable heat-stress. Thus, an infinite work time for $TT_{25}$ would be predicted at an average metabolic rate of 3.84 $mL \cdot kg^{-1} \cdot min^{-1}$. Since this value is representative of a resting metabolic rate implementing work and rest schedules while remaining fully encapsulated at 25°C should allow more total work to be accomplished [21]. However, the vertical asymptotes of 1.70 and 0.92 $mL \cdot kg^{-1} \cdot min^{-1}$ for the equations representing 30°C and 35°C, respectively, are physiologically unattainable. Even under resting conditions at 30°C and 35°C the body would continue to store heat, thus implementing work and rest schedules while remaining fully encapsulated at these higher ambient temperatures would not allow more total work to be accomplished.

It is recognized that the length of a bottle will depend on a variety of factors such as physical characteristics (fitness, body composition, and mass) and work intensity. However, in order to allow comparisons between the different work rates, SCBA bottle length needed to be standardized in the present work. Our curves that predict TT could easily accommodate different bottle durations (15-45 min) since they are based on a time weighted average for metabolic rate. Based on the assumption that an average air cycle lasts 30 min (20 min work + 10 min SCBA bottle change), our data predicts that a firefighter performing heavy work at 25°C would last, 2 work cycles (SCBA bottles) or a TT of 56 min. However, working at 35°C, that same firefighter would only make it partially through the second bottle (40 min) before succumbing to exhaustion. Comparatively, during light work at 25°C, on average, the firefighters could continue for at least 4 bottles (120 min) before succumbing to exhaustion. At 35°C, however, that same firefighter should last only slightly more than 2 bottles or 67 min. Therefore, based on these examples, a conservative guideline to limit heat related illness while performing light work would be 4 bottles or 120 min at 25°C and 2 bottles or 60 min at 35°C before going to a recovery station. A similar guideline of 2 and 1 bottles could be set for the heavy group in regards to continuous work for 25°C and 35°C, respectively. Based on these two examples, our prediction equations could be used to establish guidelines for each of the remaining conditions and work rates. Furthermore, for metabolic rates which are higher than group H in the present study it is likely that the firefighter would succumb to physical exhaustion during continuous work before significant elevations of $T_{re}$ are achieved.

If body cooling can occur during periods of rest, then implementing work and rest schedules can increase the total work time while reducing the heat strain [35]. Group M had an average metabolic rate of 13 $mL \cdot kg^{-1} \cdot min^{-1}$ throughout each of the heat-stress exposures. Based on the prediction equation $TT_{25}$, continuous work at this average metabolic rate would produce a TT of 90 min. If an intermittent work and rest cycle involving 15 min work and 15 min of rest was implemented, the average metabolic work rate for M would be reduced to 8.5 $mL \cdot kg^{-1} \cdot min^{-1}$ which assumes a resting $\dot{V}O_2$ of 4 mL·kg$^{-1}$·min$^{-1}$. Thus, this lower average metabolic work rate would increase TT to 190 min and the total work performed to 100 min. In contrast, at 35°C, continuous work for M would produce a TT of 55 min based on equation $TT_{35}$. Incorporating a similar intermittent work and rest cycle would increase total TT to 90 min while reducing total work time to 45 min. Thus, in the latter situation, at 35°C, an intermittent schedule would not be optimal for maximizing total work while remaining fully encapsulated.

What would be the effect of an intermittent work and rest cycle where protective clothing was removed during recovery? Consider an intermittent schedule, with recovery periods similar to the present study. Firefighters working in group H had rectal temperatures of approximately 38.0°C for both the 25°C and 35°C conditions after 30 min of exposure (see Figure 3 and Table 2). Thus, assuming a 30-min work and rest cycle, following 30 min of work the firefighters would then go to recovery for 30 min. $T_{re}$ after the 30 min of recovery would theoretically be 37.7°C and 38.5°C for 25°C and 35°C, respectively (see Figure 4). Thus, if it is recommended that $T_{re}$ not exceed a critical temperature of 39.0°C when performing work in FPC [15], the firefighter working at 25°C would be able to return to work for at least one more work cycle (SCBA bottle). However, the firefighter working in the ambient temperature of 35°C would not be able to complete a second bottle of air before reaching a potentially dangerous heat-stress situation. Thus, during the recovery period even removing some parts of the protective clothing ensemble may not be sufficient to extend work times in warm environments.

Clearly, these findings have illustrated the importance of developing methods for keeping active firefighters' $T_{re}$ below a critical level. There are many ways this can be accomplished. In cooler ambient conditions, implementing work and rest cycles could increase total work time while slowing the rise in $T_{re}$. Furthermore, if operational requirements permit Commanders to rotate duties this may be another effective method to reduce the average metabolic rate and thereby extend TT. At higher environmental temperatures, a work and rest schedule that incorporates some form of active cooling during the recovery period may be the only viable option available to extend work times. For instance, forearm submersion [41, 42] or fan cooling [7] have been suggested as modalities for active cooling. However, the effectiveness of these modalities during subsequent work periods has not been conclusively addressed. The restriction of fluid or beginning work in a hypohydrated state has been shown to have detrimental effects when exposed to uncompensable heat-stress for longer than 60 min [94], yet there are presently no known guidelines for firefighters. Further examination of such factors need to be elucidated in order to maximize firefighter performance and safety.

## Conclusions

The present findings document the differential impact of environmental conditions at various metabolic rates on TT while wearing FPC and SCBA. Implementation of work and rest schedules at lower metabolic rates and environmental temperatures may be sufficient to extend work times. However, at higher ambient temperatures passive recovery may not be sufficient to reduce $T_{re}$ below pre-recovery levels. Furthermore, during passive recovery in hot environments, HR may not be used as an indicator for the extent of heat strain being experienced by the firefighter. Thus, combining the relationship between TT and metabolic rate and potential active cooling modalities, safe work limits can be developed for firefighters working in various ambient conditions while wearing FPC and SCBA.

# B. Heat Stress While Wearing Long Pants Or Shorts Under Firefighting Protective Clothing.

## Abstract

It was the purpose of this study to examine whether replacing pants (P) with shorts (S) would reduce the heat stress of wearing firefighting protective clothing during exercise in a warm environment. Twenty-four Toronto Firefighters were allocated to one of four groups that performed heavy (H, 4.8 $km \cdot h^{-1}$, 5% grade), moderate (M, 4.5 $km \cdot h^{-1}$, 2.5% grade), light (L, 4.5 $km \cdot h^{-1}$) or very light (VL, 2.5 $km \cdot h^{-1}$) exercise while wearing their full protective ensemble and self-contained breathing apparatus. Subjects performed a familiarization trial followed by two experimental trials at 35ºC and 50% relative humidity wearing either P or S under their bunker pants. Replacing P with S had no impact on the rectal temperature ($T_{re}$) or heart rate response during heavy or moderate exercise where tolerance times were less than 1 hour (40.8 ± 5.8 and 53.5 ± 9.2 min for H and M, respectively while wearing P, and 43.5 ± 5.3 and 54.2 ± 8.4 min, respectively while wearing S). In contrast, as tolerance times were extended during lighter exercise $T_{re}$ was reduced by as much as 0.4ºC after 80 min of exercise while wearing S. Tolerance times were significantly increased from 65.8 ± 9.6 and 83.5 ± 11.6 min during L and VL, respectively while wearing P to 73.3 ± 8.4 and 97.0 ± 12.5 min, respectively while wearing S. It was concluded that replacing P with S under the firefighting protective clothing would reduce the heat stress associated with wearing the protective ensemble and extend exposure times approximately 10-15% during light exercise. However, during heavier exercise where exposure times were less than 1 hour replacing P with S was of little benefit.

**Keywords:** Uncompensable heat stess, rectal temperature, metabolic rate, exercise tolerance

# Methods

### Subjects

Following approval from DRDC Toronto's Human Ethics Review Committee, volunteers from the Toronto Fire Service were informed of all details of the experimental procedures and the associated risks and discomforts. After a medical examination to ensure that there were no medical contraindications to their participation in the experiment, each volunteer gave their written informed consent prior to the first day of data collection. Twenty-two males and two women were selected from a larger pool of volunteers to give a range for fitness and body composition that would be representative of the members of the Toronto Fire Service.

### Baseline Measurements

Following the medical screening and informed consent procedures, subjects were tested for aerobic fitness and body fatness. Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured at a comfortable room temperature (22°C) using open-circuit spirometry on a motorized treadmill [29]. The test consisted of 3 minutes of steady-state running (0% elevation; wind speed <0.1 $m \cdot s^{-1}$) on a motorized treadmill (Quinton Instruments., Q65, Seattle Washington) at a self-selected pace, that was dependent on the aerobic fitness level of each subject. Thereafter, treadmill grade was increased $1\% \cdot min^{-1}$, up to 10% elevation. At this point, an alternating increase in speed (0.22 $m \cdot s^{-1}$) and elevation (1%) each minute was implemented until the subject could no longer continue. $\dot{V}O_{2peak}$ was defined as the highest observed 30-s value for oxygen consumption ($\dot{V}O_2$) together with a respiratory exchange ratio ≥ 1.15. Heart rate (HR) was monitored during the treadmill protocol using a transmitter/ telemetry unit (Polar Vantage XL, Finland). The highest value recorded at the end of the exercise test was defined as $HR_{peak}$. Body density was determined from underwater weighing (UWW) using helium dilution to determine residual lung volume and body fatness was then calculated using the Siri equation [80].

### Definition of Groups

Subjects were matched for fitness and body composition and equally divided into four groups that performed treadmill exercise defined as heavy (H, 4.8 $km \cdot h^{-1}$ and a 5% elevation), moderate (M, 4.5 $km \cdot h^{-1}$ and a 2.5% elevation), light (L, 4.5 $km \cdot h^{-1}$ and 0% elevation) and very light (VL, 2.5 $km \cdot h^{-1}$ and 0% elevation). One female subject was assigned to H and M.

### Experimental Design

All sessions were conducted in the fall and winter months. In addition, to control for the effects of circadian rhythm on rectal temperature, all sessions began in the morning around 0800 hours [81]. Subjects performed a familiarisation session and two experimental sessions in a climatic chamber controlled at 35ºC and 50% relative humidity with a wind speed less than 0.1 $m \cdot s^{-1}$. These sessions were separated by a minimum of 14 days with most trials scheduled once during a 28-day cycle. Subjects were asked to refrain from hard exercise (ie., running, swimming, cycling, and weight lifting), alcohol, nonsteroidal anti-inflammatories, and sleep medication 24 h before each session and also to refrain from ingesting caffeine or nicotine 12 h before each session. Donation of blood was prohibited within 30 days of any part of the experiment.

### Clothing

Subjects wore their own NFPA standard protective firefighting turnout gear, gloves, Nomex® flash hood, helmet, respirator and self-contained breathing apparatus (SCBA). Standard issue cotton station pants (P) or shorts (S) and a cotton T-shirt were worn beneath the turnout gear, along with underwear, socks and running shoes. The Canadian Forces nuclear biological and chemical impermeable protective over-boot was worn in place of the standard rubber boot in order to simulate the impermeable characteristics of the rubber boot, while minimising discomfort due to prolonged walking on the treadmill. Subjects wore P during their familiarisation session. The total weight of the ensemble approximated 22 kg. The respirator was adapted to allow subjects to breathe room air, however, the SCBA was carried during all trials.

### Exercise and Recovery Phases

Each trial was divided into an exercise and recovery phase. The exercise phase consisted of repeated 30-minute cycles that involved 20 minutes of exercise at the prescribed H, M, L or VL metabolic rate followed by a 10-min walk and rest period to simulate a bottle change. This simulation consisted of 3 min of level treadmill walking at 2.5 $km \cdot h^{-1}$, followed by 4 min of standing and a subsequent 3 min of walking at 2.5 $km \cdot h^{-1}$. During the 4 min of standing subjects removed their helmet, flash hood, SCBA, respirator and gloves. The exercise phase continued until $T_{re}$ reached 39.0ºC, HR reached or exceeded 95% of $HR_{peak}$ for 3 min, nausea or dizziness precluded further exercise or the investigator or subject terminated the trial. Upon the attainment of one of these end-point criteria, a dressed weight was obtained. Subjects then removed their helmet, flash hood, gloves, SCBA, jacket and respirator and were seated at 35ºC for a 30-min recovery period or until one of the end-point criteria were reached. However, for the non-encapsulating recovery period the end-point criterion for $T_{re}$ was 40ºC. Although the protective overpants were not removed during this recovery period, subjects were allowed to undo the Velcro® on the front of the pant.

Exercise time was defined, for all trials, as the elapsed time from the beginning of the exercise to the attainment of one or more of the end-point criteria that resulted in the termination of the exercise phase and placement into the 30-minute recovery phase. Immediately prior to entering the climatic chamber and beginning the exercise phase, during each 4-min period of standing during the simulated bottle change and at the beginning of the seated recovery period, subjects were given 5 $mL \cdot kg^{-1}$ of cool water at approximately 15ºC to consume. If $T_{re}$ was greater than 38.5°C during the exercise phase or if the subject felt that they could not continue for another 10 minutes, water was not administered for the remainder of the exercise period.

### Dressing Procedures

Subject preparation, insertion of the rectal thermistor and placement of skin thermistors have been detailed previously [31]. Upon entering the chamber, the subject's thermistors and rectal thermistor monitoring cables were connected to a computerized data acquistion system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer) and the session began. Mean values over 1-min periods for $T_{re}$ and skin temperature were recorded and printed by the data acquisition system. A 7-point weighted mean skin temperature ( $\overline{T}_{sk}$ ) [82] was subsequently calculated. HR was recorded every 5 min from the display on the telemetry receiver (Polar® CE0537).

Differences in nude and dressed weights before and after each trial were corrected for respiratory and metabolic weight loss (see below). The rate of sweat production was calculated as the difference between the corrected pre-trial and post-trial nude weights, divided by exercise time. Evaporative sweat loss was calculated separately for the exercise and recovery phases from the differences in pre- and post-phase corrected dressed weights. The dressed weight recorded at the end of the exercise phase represented the post-exercise and pre-recovery dressed weight.

### Gas Exchange

Open-circuit spirometry was used to determine expired minute ventilation ( $\dot{V}_E$ ), $\dot{V}O_2$ and carbon dioxide production ( $\dot{V}CO_2$ ) for corresponding metabolic measurement periods during the exercise (min 17-20 and min 20-23) and recovery (min 7-10 and min 27-30) phases. An additional metabolic measurement was taken during the first 4-minute standing period of the simulated bottle change to determine a resting metabolic value for the trial. Values were averaged from a 2-minute sampling period for each subject following a 1-minute washout period. In order to determine $\dot{V}_E$ , the current SCBA facepiece exhaust valve was modified to incorporate the attachment of an adaptor which directed expired air to a 5L-mixing box and then through a ventilation module (Alpha Technologies VNN 110 Series, Laguna Hill, CA). An aliquot of dried expired gases was pumped via a sampling line to an $O_2$ and $CO_2$ analyser (Ametek Instruments S-3A/I and CD-3A, respectively, Pitts, PA). Gas analyzers were calibrated before each trial using precision-analysed gas mixtures of known concentrations of oxygen and carbon dioxide, and the ventilation meter was calibrated using a 3-L syringe. After analogue-to-digital conversion (Hewlett Packard 59313A A/D converter, Pitts, PA), $\dot{V}_E$ and, $\dot{V}O_2$ and $\dot{V}CO_2$ gas fractions were calculated and displayed on-line at one minute intervals. Two minute averages of $\dot{V}_E$ , $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated and recorded. Respiratory water loss was calculated using the $\dot{V}O_2$ measured during the trial and the equation presented by

Mitchell et al.[83]. Metabolic weight loss was calculated from $\dot{V}O_2$ and the respiratory exchange ratio using the equation described by Snellen[84].

### Ratings of Perceived Exertion and Thermal Comfort

Following the gas exchange measurement, subjects were asked to provide a rating of perceived exertion (RPE) between 6 and 20 for the whole body [95] and a rating of thermal comfort (RTC) between 1 (so cold I am helpless) and 13 (so hot I am sick and nauseous) for the whole body [96].

### Blood sampling and measurement

Prior to beginning the dressing procedure, but after the insertion of the rectal thermistor, a 5 ml venous blood sample was taken while the subject was in the supine position and the serum was later analyzed for osmolality (Advance Micro Osmometer, Model 3300, Advanced Instruments Inc., Norwood, MA).

### Statistical Analyses

Data are presented as mean values and the standard error of the mean. A one factor between (group) and one factor within (clothing) ANOVA was used to compare the dependant measures of osmolality, exercise time and sweat rate. Due to differences in exercise time among the groups a two factor within (clothing and time) ANOVA was performed separately for each group for the other dependant measures including $T_{re}$, $\overline{T}_{sk}$ , HR, RPE, RTC and $\dot{V}O_2$ . However, since the recovery period was constant for all groups, a one factor between (group) and two factor within (clothing and time) ANOVA was performed on these same dependant measures during the recovery period. To correct for the violation of the sphericity assumption with the repeated factors, a Huynh-Feldt correction was applied to the F-ratio. When a significant F-ratio was obtained, a Newman-Keuls post-hoc analysis was used to isolate differences among treatment means. For all statistical analyses, the 0.05 level of significance was used.

# Results

## Physical Characteristics of Subjects

There was no difference among the groups for any of the physical characteristics shown in Table 5.

***Table 5.*** *Age, height, mass, surface area ($A_D$), peak heart rate ($HR_{peak}$), peak aerobic power ($\dot{V}O_{2peak}$) and body fatness (BF) for the Heavy (H), Moderate (M), Light (L) and Very Light (VL) groups and for all subjects combined. Values are means (±SE).*

| Group | Age (y) | Height (cm) | Mass (kg) | $A_D$ ($m^2$) | $HR_{peak}$ ($b \cdot min^{-1}$) | $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) | BF (%) |
|---|---|---|---|---|---|---|---|
| H (n=6) | 40.2 (0.9) | 183.3 (3.0) | 84.7 (4.7) | 2.07 (0.07) | 184.8 (2.4) | 51.4 (2.0) | 18.3 (1.7) |
| M (n=6) | 39.0 (1.9) | 174.5 (4.3) | 83.0 (5.7) | 1.98 (0.09) | 189.5 (5.5) | 49.6 (2.4) | 17.8 (1.6) |
| L (n=6) | 39.0 (2.0) | 183.9 (3.5) | 88.8 (4.1) | 2.11 (0.06) | 190.8 (3.7) | 51.1 (1.5) | 17.2 (1.8) |
| VL (n=6) | 38.3 (1.0) | 180.2 (0.9) | 90.1 (3.7) | 2.10 (0.04) | 189.2 (3.6) | 52.6 (2.4) | 17.1 (0.9) |
| Over-all (n=24) | 39.1 (0.7) | 180.5 (1.7) | 86.6 (2.2) | 2.06 (0.03) | 188.6 (1.9) | 51.2 (1.0) | 17.6 (0.7) |

## Osmolality

Osmolality was similar among the groups during both sessions and averaged 290.1 ± 0.8 and 288.2 ± 0.8 $mosmol \cdot kg^{-1} H_2O$ for P for S, respectively.

## Gas Exchange

Wearing S had no effect on the $O_2$ cost of treadmill walking for any of the groups. After 20 min of exercise, $\dot{V}O_2$ in $l \cdot min^{-1}$ was 1.97 ± 0.11, 1.63 ± 0.06, 1.24 ± 0.06 and 0.96 ± 0.03 for H, M, L and VL, respectively for P and 2.00 ± 0.12, 1.61± 0.08, 1.33 ± 0.05 and 0.99 ± 0.04 for H, M, L and VL, respectively for S. These values approximated 46%, 40%, 29% and 21% $\dot{V}O_{2peak}$ for H, M, L and VL, respectively.

### Heart Rate

As shown in Figure 11, replacing P with S had not effect on the HR response during exercise for groups H and M. However, as exercise time was extended with groups L and VL, HR was significantly lower while wearing S. There was a main effect of clothing for L where overall HR was reduced from 119.6 ± 2.7 $b \cdot min^{-1}$ while wearing P to 113.3 ± 2.7 $b \cdot min^{-1}$ while wearing S. During VL, the impact on S was even more evident with HR being reduced approximately 10-15 $b \cdot min^{-1}$ throughout the exercise.

There was no effect from replacing P with S on the HR response during the 30-min recovery period. Heart rate decreased from 160.9 ± 3.7 $b \cdot min^{-1}$ at time 0 to 112.8 ± 2.8 $b \cdot min^{-1}$ after 30 min of recovery for P and from 164 ± 3.3 $b \cdot min^{-1}$ at time 0 to 113.8 ± 3.1 $b \cdot min^{-1}$ at the end of the recovery period.

### Rectal Temperature

Figure 12 presents the changes in $T_{re}$ during exercise for the four groups. Data are shown as a delta $T_{re}$ to normalise small differences in $T_{re}$ at the beginning of exercise. Shorts had no impact on the increase in $T_{re}$ for groups H or M but wearing S was associated with a significantly slower increase in $T_{re}$ for both groups L and VL. For group L a lower $T_{re}$ was evident after 30 minutes of exercise whereas for group VL the differences between P and S were significant after 35 minutes. Although S slowed the rate of increase in $T_{re}$ for groups L and VL, wearing S had no effect on the $T_{re}$ recorded at the end of the exercise period for any group (Table 6).

The impact of wearing S during the recovery period is shown in Figure 13. There was a significant clothing and time interaction that revealed a lower $T_{re}$ while wearing S during the last 15 min of recovery.

### Mean Skin Temperature

Figure 14 depicts the $\overline{T}_{sk}$ response during exercise for the four groups. For H and M wearing S did not affect $\overline{T}_{sk}$. However, for both L and VL there was a significant main effect of wearing S during exercise. During recovery, wearing S also significantly lowered $\overline{T}_{sk}$. Values decreased from 38.4 ± 0.1ºC at time 0 to 37.8 ± 0.1ºC after 30 min of recovery for P and from 38.2 ± 0.1ºC at time 0 to 37.5 ± 0.1ºC at the end of recovery for S. The major contributor to the lower $\overline{T}_{sk}$ while wearing shorts occurred on the lower leg where skin temperature was significantly reduced by 0.5ºC during exercise for L and VL and 0.7ºC for all groups during recovery. The upper leg skin temperature was also significantly reduced by 0.4ºC for group VL throughout exercise.

### Sweat Rate

There was a small but significant increase in sweat rate for all groups while wearing S (0.52 ± 0.03 $kg \cdot m^{-2} \cdot h^{-1}$) compared with P (0.49 ± 0.03 $kg \cdot m^{-2} \cdot h^{-1}$).

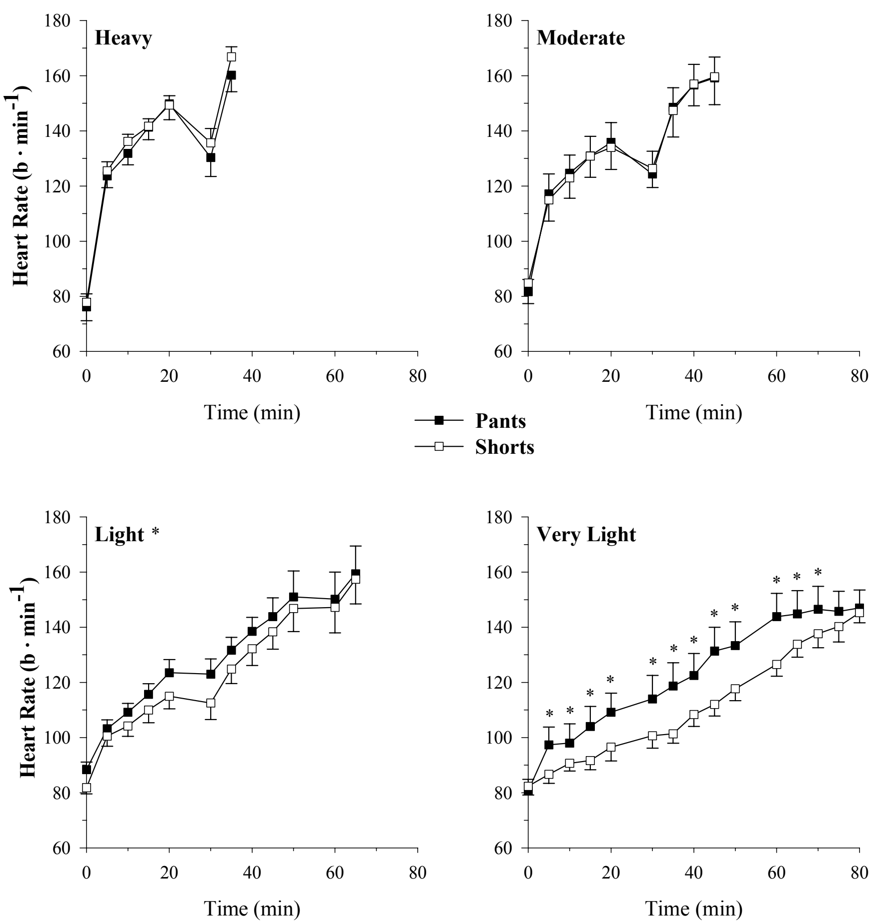


***Figure 11.*** *Heart rate responses for firefighters while wearing either pants or shorts under the bunker pants during very light, light, moderate or heavy exercise at 35ºC. The asterisk indicates a significant difference when pants or shorts are worn. Values are mean ± SE and represent n = 6 to 30 min and n = 5 at 35 min for heavy exercise, n = 6 to 40 min and n = 5 at 45 min for moderate exercise, n = 6 to 45 min and n = 5 from 50 to 65 min for light exercise, and n = 6 to 70 min and n = 4 at 75 and 80 min for very light exercise.*

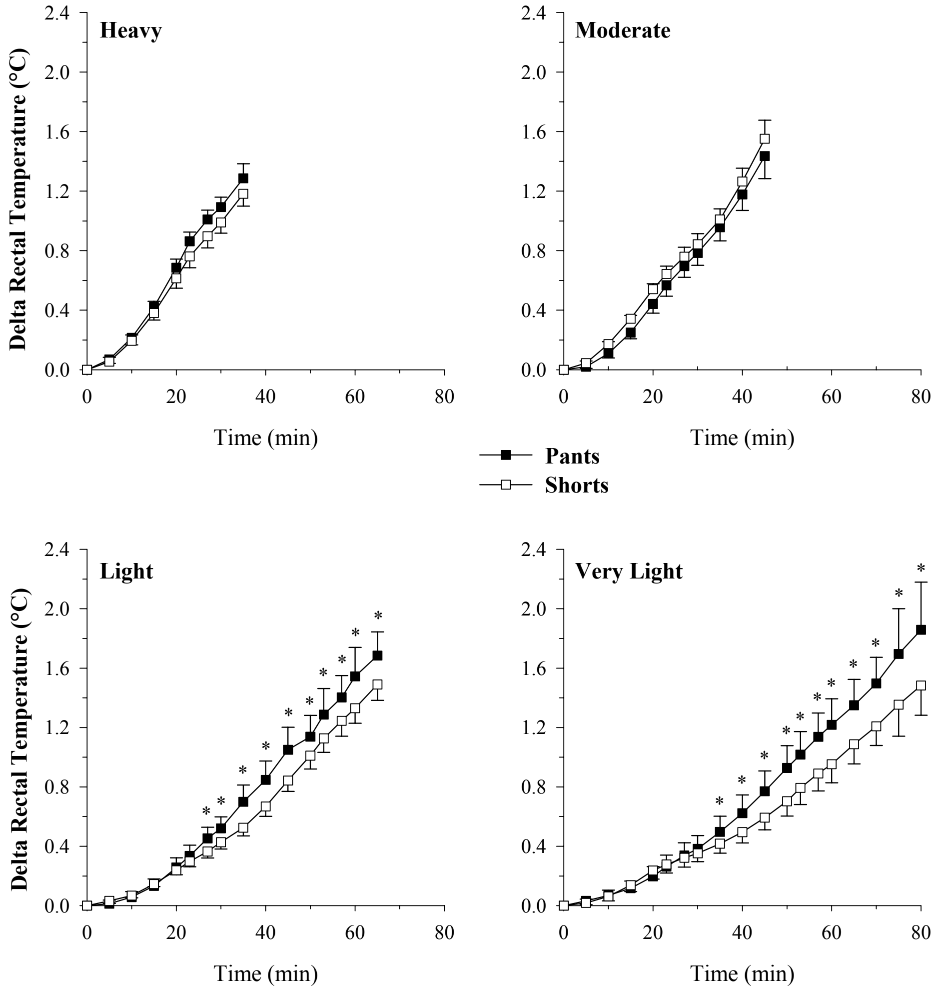


***Figure 12.*** *Delta rectal temperature responses for firefighters while wearing either pants or shorts under the bunker pants during very light, light, moderate or heavy exercise at 35ºC. The asterisk indicates a significant difference when pants or shorts are worn. Values are mean ± SE and subject numbers are as described for Figure 11.*

*__Table 6.__ Final exercise rectal temperature ($T_{re}$), exposure time and reasons for termination of the sessions for the heavy (H),moderate (M), light (L) and very light (VL) exercise groups while wearing either pants (P) or shorts (S) under the protective overpants. Values are mean ± SE.*

| | H | | M | | L | | VL | |
|---|---|---|---|---|---|---|---|---|
| | **P** | **S** | **P** | **S** | **P** | **S** | **P** | **S** |
| Final Exercise $T_{re}$ (ºC) | 38.55 (0.20) | 38.60 (0.20) | 38.94 (0.05) | 39.00 (0.00) | 38.79 (0.15) | 38.89 (0.11) | 38.85 (0.10) | 38.77 (0.11) |
| Exposure Time (min) | 40.8 (2.4) | 43.5 (2.2) | 53.5 (3.7) | 54.2 (3.4) | 65.8 (3.9) | 73.3 * (3.4) | 83.5 (4.7) | 97.0 * (5.1) |
| Reasons for Termination of Trial | HR (4) $T_{re}$ (2) | HR (4) $T_{re}$ (2) | $T_{re}$ (4) Exh (2) | $T_{re}$ (6) | HR (1) $T_{re}$ (4) Exh (1) | HR (1) $T_{re}$ (4) Exh (1) | $T_{re}$ (4) Exh (2) | $T_{re}$ (3) Exh (3) |

### Ratings of Perceived Exertion and Thermal Comfort

Wearing shorts had no impact on RPE during exercise and no impact on RTC during either exercise or recovery. Values for both RPE and RTC differed among the groups after 20 min of exercise. However, during recovery the decrease in RTC from 10.8 ± 0.2 at time 0 to 8.4 ± 0.2 after 30 min was similar for all groups.

### Exposure Time

There was a significant clothing and group interaction for exposure time as shown in Table 6. Whereas replacing P with S had no effect on exposure time for groups H and M, wearing S significantly prolonged exposure time for the groups performing lighter exercise. There was no indication that wearing S altered the reasons for termination of the session for any group. With the heaviest exercise more subjects terminated their session having attained a HR that reached or exceeded 95% of their peak value, whereas in the other exercise groups the majority of subjects terminated their sessions due to exhaustion or because $T_{re}$ reached 39.0ºC. All subjects completed the 30 min of recovery in the 35ºC environment.

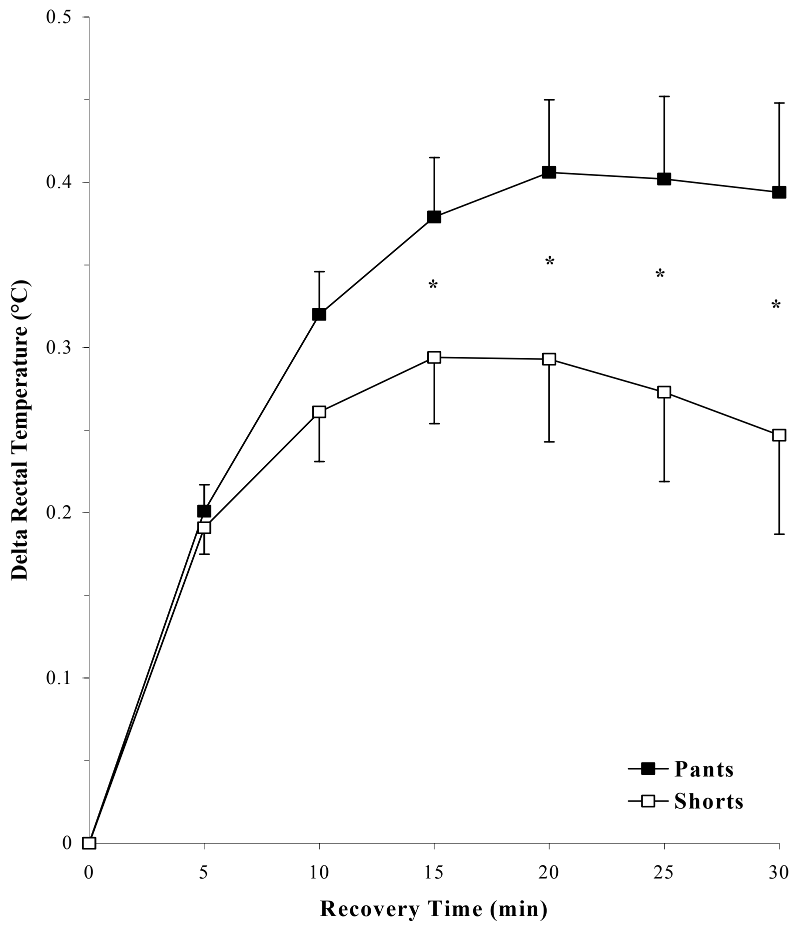


***Figure 13.*** *Delta rectal temperature responses for firefighters while wearing either pants or shorts under the bunker pants during 30 minutes of recovery following very light, light, moderate or heavy exercise at 35ºC. The helmet, face shield and respirator, breathing apparatus, flash hood, gloves and jacket were removed during this recovery period. The asterisk indicates a significant difference when pants or shorts are worn. Values are mean ± SE for 24 subjects.*

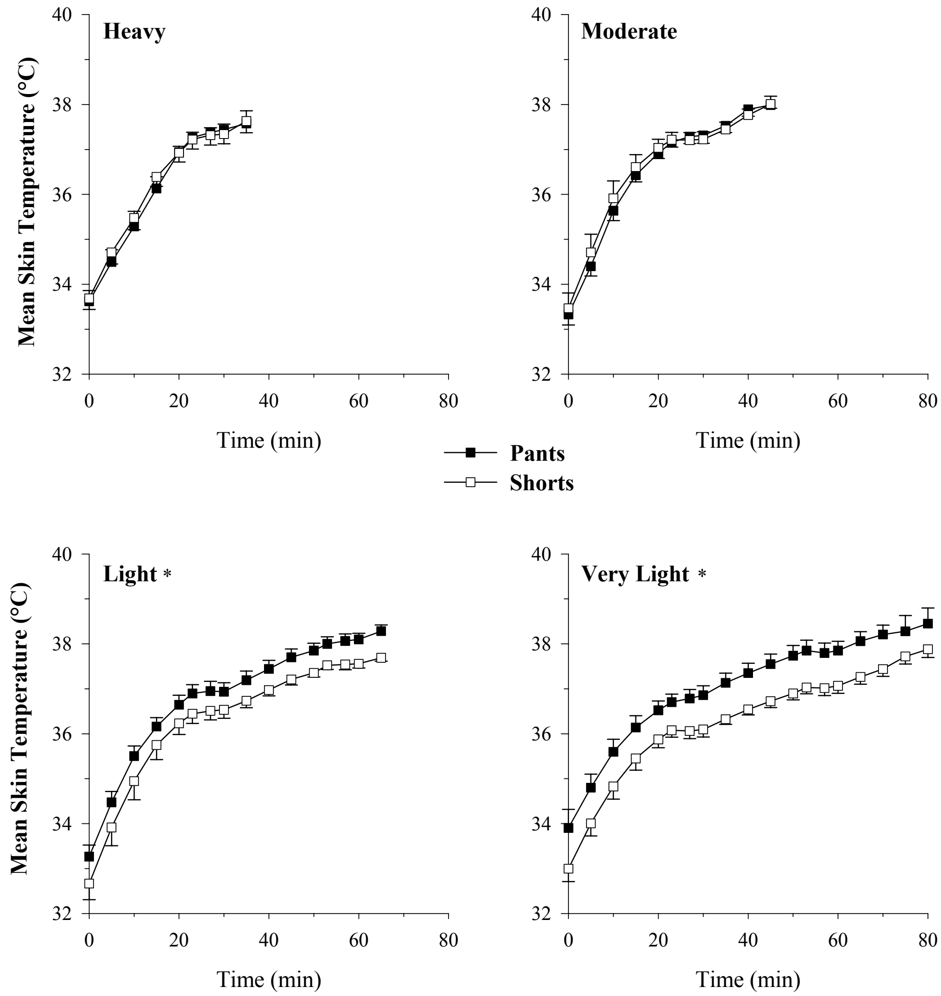


***Figure 14.*** *Mean skin temperature responses for firefighters while wearing either pants or shorts under the bunker pants during very light, light, moderate or heavy exercise at 35ºC. The asterisk indicates a significant difference when pants or shorts are worn. Values are mean ± SE and subject numbers are as described for Figure 12.*

# Discussion

The firefighter's protective clothing and SCBA is designed to minimise the risk of injury from burns and inhalation of toxic fumes during live fire suppression, building and area clean-up, and emergency response. The protective ensemble, however, creates considerable heat stress for the firefighter [16] that limits the duration of their effectiveness. One option to reduce this heat stress is the replacement of the pants that are worn under the protective bunker pants with shorts. This option has been implemented by the New York City Fire Department and is being considered for implementation by the Toronto Fire Service. A similar option has also been shown to effectively reduce the heat stress and extend tolerance times for military personnel wearing biological and chemical protective clothing [27-30]. To our knowledge the findings from the present study are the first to document the reductions in cardiovascular and thermal strain for firefighters with the wearing of shorts under their protective bunker pants during exercise in a warm environment.

Recent studies by Malley et al.[24] and Prezant et al.[25] have provided support for the decision to replace the duty uniform with shorts and a T-shirt for the New York City Fire Department. In the former study, Malley et al.[24] had firefighters exercise on a treadmill at room temperature at workrates that led to exhaustion in 15-20 minutes. Although exercise time was significantly extended from 15 to 17 minutes when shorts were worn there was no effect on the core temperature increase over this short duration of activity. The findings from the present study would extend this null effect to include moderate and heavy workrates that lead to exhaustion in less than 60 minutes. Under this set of conditions where the $E_{req}$ is high because of high rates of heat production, small changes in the $E_{max}$ of the environment that result from changes in the thermal resistance of the clothing ensemble have a very small impact on the overall heat stress index or ratio of $E_{req}$ to $E_{max}$. In addition, approximately 30 minutes is required before the microenvironment within the clothing layers is similar to the $E_{max}$ defined for the environment [29]. Thus under conditions where exhaustion has occurred because of a cardiovascular limitation for oxygen delivery [24] it is likely that replacing P with S would have a negligible impact on the thermal strain associated with this type of exercise. In contrast, limits for work while performing light exercise and wearing protective clothing in hot environments are related more to the core temperature that can be tolerated [87]. Thus as tolerance times are extended because of lower rates of heat production there is a greater opportunity for changes in the thermal resistance of the clothing ensemble to impact on the heat loss to the environment. As a result, thermal strain is reduced and tolerance times are extended as they were for groups L and VL in the present study. Physiological manipulations such as heat acclimation [31, 32] endurance training [31, 33] and hydration [63] have all been shown to only exert an influence on exercise time in the heat while wearing protective clothing during lower metabolic rates where tolerance times are extended beyond 60 minutes.

If the benefits for replacing P with S are only evident during activities that last beyond 60 minutes is this relevant for firefighters? Firefighting activities can demand a very high percentage of $\dot{V}O_{2\,max}$ [22, 23] that can lead to exhaustion in less than 20 minutes. However, self-pacing and the implementation of work and rest schedules could easily extend the involvement of the firefighter well beyond 20 minutes. Commanders might also rotate personnel between heavier and lighter duties following exchange of air bottles every 20 minutes to maximize their availability. Further there are numerous situations where firefighters are required to wear their protective ensemble with or without their SCBA that does not involve fire suppression activity. In these situations such as emergency response, accident investigation and building clean-up following fire suppression the intensity of the work effort may be equal to or lower than those involved with the demands of fire suppression. In all of these situations where exposure time while wearing the firefighting protective ensemble would be extended beyond 60 minutes, the current findings would suggest that the replacement of P with S would reduce the thermal and cardiovascular strain and extend tolerance time approximately 10-15%. These are not huge improvements but they are comparable to the relative improvements noted following heat acclimation [32] or fluid replenishment [63] when protective clothing is worn while performing light exercise in a hot environment.

Of perhaps greater concern for those responsible for authorizing the replacement of P with S is whether the protection of the ensemble is in any way compromised such that the firefighter would be at greater risk to injury. The recent prospective analyses of New York City firefighters would suggest that the burn incidence and severity were not affected by replacing P with S [25]. Indeed, this prospective analysis also suggested that days lost for medical leave due to heat exhaustion were significantly reduced when S was worn [25]. Taken collectively, therefore, the findings from the present study and those from Malley et al.[24] and Prezant et al.[25] would support the recommendation to replace P with S.

It is interesting that the reductions in thermal and cardiovascular strain noted for groups L and VL in the present study were not paralleled by reductions in RTC and RPE during the exercise. Recent studies have suggested that the use of these perceptual ratings might be an effective means to indicate the physiological strain [2, 97] during exercise and heat-stress. The present findings would suggest that perceptual ratings are not sensitive enough to discern the physiological changes that were observed for this group of firefighters. This is somewhat surprising given the magnitude of the HR and $T_{re}$ reductions (see Figures 11 and 12) for group VL. It is possible that our decision to record RPE and RTC only in conjunction with gas exchange measurements was insufficient, especially during the latter stages of the heat-stress exposure, and did not allow changes in perceptual ratings to be noted that would be consistent with the more frequent recordings of HR and $T_{re}$.

The subjects in the present study were selected from a larger pool of volunteers to be representative for the age and fitness level of firefighters within the Toronto Fire Service. Our sample varied in age from 33 to 45 years, 11 to 25% body fat and had $\dot{V}O_{2\,max}$ values that varied from 42 to 62 $ml \cdot kg^{-1} \cdot min^{-1}$ indicating a variety of active and inactive lifestyle behaviour choices for our participants. Interestingly, our sample population was quite similar to those New York City firefighters who volunteered for the study by Malley et al. [24] although we would not allow participation of firefighters who were over the age of 45 because of medical safety concerns. We also purposely assessed our subjects' responses over a range of metabolic rates that would allow us to address the issue of heat stress while wearing P or S. We were not interested in assessing metabolic rates that would lead to exhaustion in less than 15 minutes since cardiovascular rather than thermal strain would be the main factor involved in the termination of the exercise. We were also not interested in performing arm exercise to simulate certain firefighting duties since the smaller muscle mass and local muscle fatigue would have again limited exposure times. Heat storage is a function of the absolute and not the relative rate of heat production [92]. Thus, treadmill walking was selected to recruit a large muscle mass such that tolerance times could be manipulated between 30 and 90 minutes in this warm environment of 35ºC. We feel that our conclusions are valid for any set of environmental conditions and rates of heat production that require firefighters to remain encapsulated in their protective ensemble for durations in excess of 60 minutes.

## Conclusion

In conclusion, the present study has shown that replacing the duty uniform pants that are worn under the bunker pants with shorts will reduce the cardiovascular and thermal strain during exercise that lasts in excess of 60 minutes. Together with the previous work conducted in support of the New York City Fire Department [24, 25] we would recommend the implementation of this practice for the Toronto Fire Service and other fire departments considering this option.

# C. Active Versus Passive Cooling During Work in Warm Environments While Wearing Firefighting Protective Clothing.


## Abstract

This study examined whether active or passive cooling during intermittent work reduced the heat strain associated with wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA) in the heat (35°C, 50% R.H.). Fifteen male Toronto firefighters participated in the heat-stress trials. Subjects walked at 4.5 $km \cdot h^{-1}$ with 0% elevation on an intermittent work (50 min) and rest (30 min) schedule. Work continued until rectal temperature ($T_{re}$) reached 39.5°C, or heart rate (HR) reached 95% of maximum or exhaustion. One of three cooling strategies, forearm submersion (FS), mister (M), and passive cooling (PC) were employed during the rest phases. Tolerance time (TT) and total work time (WT) (min) were significantly increased during FS (178.7 ± 13.0 and 124.7 ± 7.94, respectively) and M (139.1 ± 8.28 and 95.1 ± 4.96, respectively) compared with PC (108.0 ± 3.59 and 78.0 ± 3.59). Furthermore, TT and WT were significantly greater in FS compared to M. Rates of $T_{re}$ increase, HR and $\overline{T}_{sk}$ were significantly lower during active compared to passive cooling. In addition, HR and $T_{re}$ values in FS were significantly lower compared to M after the first rest phase. During the first rest phase, $T_{re}$ dropped significantly during FS (~0.4°C) compared to M (~0.08°C) while PC increased (~0.2°C). By the end of the second rest period $T_{re}$ was 0.9°C lower in FS compared to M. The current findings suggest that there is a definite advantage when utilizing forearm submersion compared to other methods of active or passive cooling while wearing FPC and SCBA in the heat.



**Keywords:** Uncompensable heat stress, exercise tolerance, rectal temperature, metabolic rate, protective clothing, cooling strategies..

# Methods

## Subjects

Following approval by the DRDC Toronto's Human Ethics Review Committee, 15 subjects were selected from a pool of 40 active Toronto Firefighters to participate in the cooling trials described below. Baseline testing was completed in August and the trials were conducted in the climatic chamber at DRDC Toronto between September and January to limit heat acclimation through casual exposure to hot environments. All subjects were medically screened and a full explanation of procedures, discomforts and risks were given prior to obtaining written informed consent. Subjects were selected such that the age, aerobic fitness and body fatness covered a wide spectrum of individuals who were representative of the Toronto Fire Service.

## Determination of $\dot{V}O_{2peak}$

Peak oxygen consumption ( $\dot{V}O_{2peak}$ ) was measured at a comfortable room temperature (22°C) using open-circuit spirometry on a motorized treadmill using an incremental protocol [20, 98]. $\dot{V}O_{2peak}$ was defined as the highest observed 30-s value for oxygen consumption ( $\dot{V}O_2$ ) together with a respiratory exchange ratio (RER) $\geq$ 1.15. Heart rate (HR) was monitored during the treadmill protocol using a transmitter/ telemetry unit (Polar Vantage XL, Finland). The highest value recorded at the end of the exercise test was defined as peak HR ($HR_{peak}$).
Body surface area ($A_D$) was calculated using the DuBois equation (1915) [77]. Body density was determined from underwater weighing (UWW) using body plethysmography to determine residual lung volume [78, 79]. Body fatness was calculated using the Siri equation [80].

## Clothing Ensembles

During work, subjects wore their own NFPA standard protective firefighting turnout gear (Garment Model – BPR5442TK, Morning Pride, Dayton, OH), gloves (Shelby Firewall), Nomex® flash hood (Majestic Fire Apparel), helmet (Firedome PX Series, Bullard, Kentucky), and self-contained breathing apparatus (SCBA) (MSA, Mine Safety Appliances Company, Pitts, Penn). Standard issue cotton station pants and a Toronto fire T-shirt were worn beneath the turnout gear, along with underwear, shorts, socks and running shoes. The Canadian Forces nuclear biological and chemical (NBC) impermeable protective over-boot was worn in place of the standard rubber boot in order to simulate the impermeable characteristics of the rubber boot. The total weight of the ensemble approximated 22 kg. During all trials, subjects breathed room air as opposed to SCBA; however, full SCBA was carried to simulate the weight of the bottle. The total thermal resistance of the firefighter protective clothing ensemble, determined with a heated articulating copper manikin, at a wind speed of 0.85 $m \cdot s^{-1}$, was 0.240 $m^2 \cdot °C \cdot W^{-1}$ (1.55 clo). The Woodcock vapor permeability coefficient, determined with a completely wetted manikin, was 0.27 (R.R. Gonzalez, personal communication).

## Experimental Design

All subjects performed a familiarisation exposure (35°C, 50% relative humidity, wind speed <0.1 m·s$^{-1}$), at the designated work rate (4.5km·h$^{-1}$, 0% incline) until attaining one or more of the specific end-point criteria (see below). The familiarization trial was at least 10 days before their first experimental trial to limit the acute effects of acclimation. Each subject then performed randomly assigned experimental sessions at 35°C and 50% R.H., while wearing FPC and SCBA. The protocol timeline was broken into work and rest phases as shown in Figure 1.

*Work phase.* Each work cycle was divided into a work portion and a simulated SCBA bottle change, which have been previously described in detail (Study A) [34]. The work portion consisted of walking at 4.5 km·h$^{-1}$ for 20 min while wearing the protective ensemble and SCBA. Following 20 min of work a 10 min simulated SCBA bottle change occurred (see Figure 15). Following the 10 min

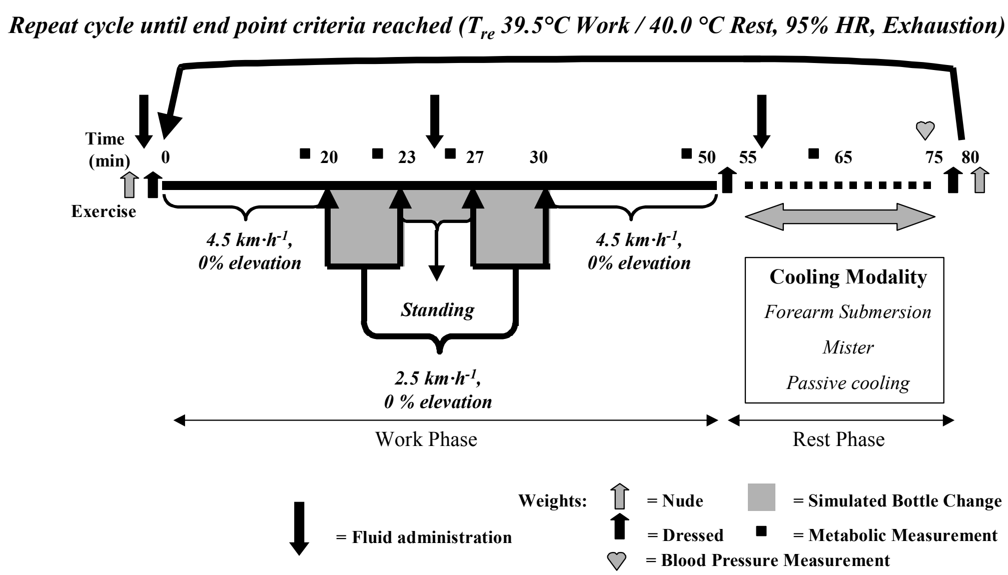


***Figure 15.*** *Protocol Timeline for passive cooling, mister and forearm submersion heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus.*

simulated bottle change subjects began another 20-min work portion.

*Rest phase.* Following the second 20-min work portion, a 30-min rest phase began at 50 min. The first 5 min of the rest phase was allotted for disconnecting the data acquisition system, obtaining a dressed weight, and removing helmet, flash hood, gloves, jacket, tanks and SCBA facepiece. At min 55, subjects received one of three 20-min cooling strategies. Following either active or passive cooling a second 5-min transition period allowed subjects to reencapsulate, obtain a dressed weight, and reconnect to the data acquisition system before beginning another work phase starting at 80 min.

The intermittent work and rest phases (50/30 min) were repeated until one or more of the following end-point criteria were reached; $T_{re}$ reaching 39.5°C, HR reaching or exceeding 95% of maximum for 3 min, dizziness or nausea precluding further work, subject exhaustion or discomfort, completing 4 cycles of work (290 min), or the investigator terminating the trial. End-point criteria for the rest phase were similar to the work phase except that the $T_{re}$ ceiling was raised to 40°C. If $T_{re}$ had not decreased below 39.5°C by the end of a rest phase, subsequent work was not performed. Tolerance time (TT) was defined, for all trials, as the elapsed time from the beginning of the work to the attainment of one or more of the end-point criteria that resulted in the termination of the trial. Total work time (WT) was defined as TT minus the time spent during rest.

## Cooling strategies

*Passive Cooling (PC).* Following transition between phases, subjects remained seated in the climatic chamber for 20 min. Although bunker pants were not taken off, the subjects were allowed to undo the Velcro® on the front of the pant.

*Forearm Submersion (FS) (active)* (Figure 16). Forearm submersion was accomplished using a insulated calorimetry tank (16.2cm H x 27.5cm W x 82.5cm L) placed at one end of the climatic chamber. The tank was temperature controlled (17.4 ± 0.2°C) prior to submersion in order to simulate hose-line water temperature. During submersion, subjects leaned over the tank with hands and arms submerged to the elbow joint for 20 min. During submersion, the tank was manually stirred, and water temperature was recorded every 5 min. The amount of heat (Q in watts) transferred from the hands and forearms to the calorimeter was determined using the following equation[23]:

$$Q = (mc \cdot t^{-1})(T_i - T_f - \Delta T_c) \quad (1)$$

where, m is the mass of water ($3.6 \times 10^4$ g), c is the specific heat of water ($4.2\ J \cdot g^{-1} \cdot °C^{-1}$), t is time ($1.2 \times 10^3$ s), $T_i$ is the water temperature when hands and forearm were submerged (°C), $T_f$ is the water temperature when the hands and forearms were removed, and $\Delta T_c$ is the change in calorimeter water temperature due to environmental conditions when hands and forearms are not submerged.


***Figure 16.*** *Forearm submersion during rest period*

*Mister (M) (active)* (Figure 17). A Versa Mist™ cooling system (Thermal Dyn, LLC) was used for the mister cooling trials which delivered fan propelled fine mist vapor at a rate of 2000 cubic feet per min. Subjects were seated approximately 5 feet in front of the mister in the climatic chamber for 20 min. The wind speed at the point of contact for the subjects was 1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$). Local ambient temperatures and humidities were recorded at the beginning and every five min during the mister cooling phase.

### Dressing and Weighing Procedures

To control for the effects of circadian rhythm on rectal temperature, all trials began at 7:30 am [81]. Upon arrival, subjects inserted a rectal probe and were weighed nude on an electronic scale, sensitive to the nearest 0.05 kg (Serta Systems Inc., SuperCount, Acton, MA). Skin thermistors and HR monitor were applied, and then subjects were dressed in station pants and T-shirt, followed by bunker pants, jacket, flash hood, running shoes, and an NBC over-boot (Figure 4). Following water administration, subjects donned SCBA tanks and their respirator facepiece, pulled over their flash hoods and put on helmet and gloves, to obtain full encapsulation. Subjects were then led into the climatic chamber where a final dressed weight was obtained and skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer, Pitts, PA). Subjects straddled the treadmill walking surface and a treadmill speed of 4.5$km \cdot h^{-1}$ with 0% elevation was established before beginning the first work phase.


***Figure 17.*** *Mister Cooling*

Upon completion of each work and rest phase, as well as upon completion of the trial, a dressed weight was obtained encompassing all gear. The subjects were removed from the climatic chamber and nude weight was recorded within 5 min of trial termination, after subjects undressed and towelled dry.

### Fluid Replacement and Sweat Measurements

During the familiarization exposure subjects were given 5 $mL \cdot kg^{-1}$ of cool water (~15°C) to drink, prior to entering the climatic chamber, at min 25 of each 30-min work / SCBA bottle change cycle, and at the beginning of each rest phase. If $T_{re}$ exceeded 39.0°C or if the subject felt that he or she could not continue for at least another 10 min, water was not administered for the remainder of the intermittent heat-stress trial. Sweat rate (SR) was calculated from the familiarization trial and this value was used to determine rates of fluid replacement that would maintain a state of euhydration during subsequent experimental trials. For all trials, nude and dressed masses were corrected for respiratory [83] and metabolic mass losses [84], as well as for fluid intake. The rate of sweat production (SR) incorporated the entire heat-stress trial.

## Physiologic Measurements

### Temperature Measurements

Mean values over 1-min periods for $T_{re}$, and a 7-point weighted mean skin temperature ( $\overline{T}_{sk}$ ) [82] were calculated, recorded, and printed by the computerized data-acquisition system. $T_{re}$ was measured using a flexible vinyl-covered rectal thermistor (YSI Precisions 4400 Series, Yellow Springs Instrument Co. Inc. Yellow Springs, OH), inserted approximately 15 cm beyond the anal sphincter. $\overline{T}_{sk}$ was obtained from 7 temperature thermistors (Mallinckrodt, Medical Inc, St. Louis, MO) taped on the head, abdomen, medial deltoid, hand, anterior thigh, shin and foot. Mean body temperature ( $\overline{T}_b$ ) and changes in body heat storage (ΔS, in kJ) were calculated using the following equations [42]:

$$\overline{T}_b = 0.33\,\overline{T}_{sk} + 0.67\,T_{re} \qquad (2)$$

and

$$\Delta S = mc\,\overline{T}_b \qquad (3)$$

where m is the mass of the subject (kg) and c is the specific heat of the human body ($3.48 kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$).

### Heart Rate and Blood Pressure Measurements

Heart rate was monitored using a transmitter (Polar Vantage XL), attached with an elasticized belt fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually every 5 min during both the work and recovery phases of the heat-stress trial. Blood pressure was taken prior to blood sampling and at the end of each rest phase for the heat-stress trials using a standard stethoscope and pressure cuff technique.

Mean arterial pressure (MAP) was approximated using the equation:

$$MAP \approx P_{Diastolic} + \frac{1}{3}(P_{Systolic} - P_{Diastolic}) \qquad (4)$$

where P represents pressure.

### Gas-Exchange Measurements

Details of the open-circuit spirometry used to determine expired min ventilation ( $\dot{V}_E$ ), $\dot{V}O_2$ and carbon dioxide production ( $\dot{V}CO_2$ ) have been presented previously [20]. Measurements were made during min 17-20, 20-23 and 47-50 of each 50-min work + simulated bottle change cycle and during min 12-15 of each rest phase. Values were averaged from a 2-min sampling period for each subject following a 1-min washout period. The current SCBA facepiece outtake valve was modified to incorporate the attachment of an adaptor that allowed expired gases to be collected during work (Figure 5).

### Blood Sampling and Measurements

A 5 mL blood sample was obtained by venipuncture, prior to the dressing procedures, to determine osmolality using the Advanced™ Micro-Osmometer (Model 3300, Advanced Instruments, Norwood, Massachusetts) (Figure 6).

### Statistical Analyses

A one-factor (cooling strategy) repeated measures ANOVA was used to compare the dependent measures of osmolality, fluid consumption, mass loss, TT, WT, and SR. An ANOVA with 2 repeated factors (cooling strategy and time of exposure) was performed on the various dependant measures sampled over time (ie., $\Delta T_{re}$, $\overline{T}_{sk}$, $\overline{T}_b$, $\dot{V}O_2$, Q, ΔS and HR) for the heat-stress trials. To correct for violations in the assumption of sphericity with the repeated factors, the Huynh-Feldt correction was applied to the F-ratio. When a significant F-ratio was obtained, post-hoc analyses utilized a Newman-Keuls procedure to isolate differences among the treatment means. All ANOVA's were performed using statistical software (SuperAnova V.1.11 (1991), Abacus Concepts, Inc). For all statistical analyses, an alpha level of 0.05 was used.

# Results

### Subjects

Subject anthropometric characteristics for age, height, mass, surface area and body fatness were 40.7 ± 0.82 y, 181.1 ± 1.8 cm, 86.9 ± 2.1 kg, 2.07 ± 0.03 $m^2$ and 17.5 ± 0.9%, respectively. $\dot{V}O_{2peak}$ and $HR_{peak}$ were 45.7 ± 1.4 $mL \cdot kg^{-1} \cdot min^{-1}$ and 190 ± 2.4 $b \cdot min^{-1}$, respectively.

### Osmolality

There were no significant differences in pre-osmolality values across the three cooling trials with mean values approximating 288 $mOsm \cdot kgH_2O^{-1}$, a value that is within the accepted range for a normal hydrated state [85].

### Gas Exchange

There were no significant differences in $\dot{V}O_2$ observed throughout the heat-stress trials. After 20 min of work, $\dot{V}O_2$ averaged 12.1 ± 0.2 $mL \cdot kg^{-1} \cdot min^{-1}$ and represented a workload of approximately 30% $\dot{V}O_{2peak}$.

### Blood Pressure

There were no significant differences observed between trials or overtime for systolic, diastolic or MAP. MAP ranged between 83 and 100 mmHg throughout the trials.

### Heart Rate

Figure 18 presents the HR response overtime for the heat-stress trials. As expected, there were no significant differences observed during the first 50 min of work (W1) since all trials followed the same initial protocol. During the first 20-min rest period (R1), HR was significantly higher for PC compared to M and FS, and remained higher for the duration of the trial. In addition, HR for FS was significantly lower compared to M during R1, as well as during the second work (W2) and rest (R2) periods. There were no significant differences observed during transition periods between FS and M.

### Rectal Temperature

The values for initial rectal temperature ($T_{re\ initial}$), final rectal temperature ($T_{re\ final}$), and delta rectal temperature ($\Delta T_{re} = T_{re\ final} - T_{re\ initial}$) are given in Table 7. There were no significant differences among the trials for these dependent measures. Although there were no significant differences among the trials for the rate of $T_{re}$ increase during individual work periods, the overall rate of $T_{re}$ increase throughout the heat-stress was significantly different among the trials (Table 7).

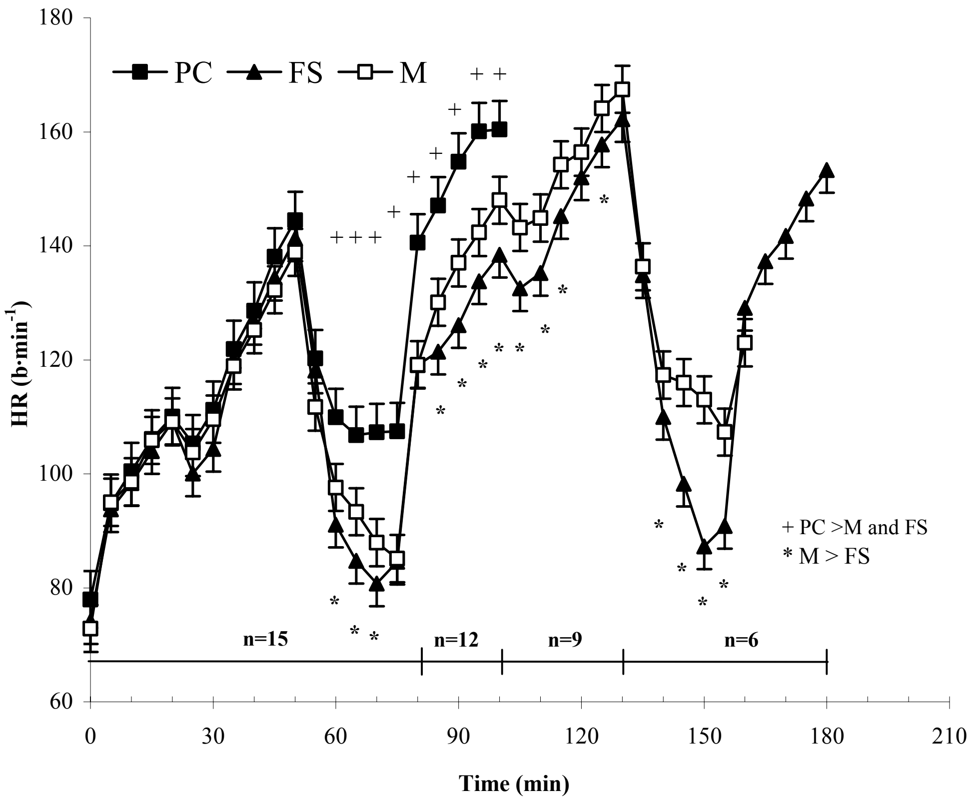


***Figure 18.*** *Heart Rate (HR) response during passive cooling (PC), mister (M), and forearm submersion (FS) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

***Table 7.*** *Initial, final, delta (final – initial) rectal temperature ($T_{re}$), and the rate of rectal temperature increase during the heat-stress trials at 35°C and 50 % relative humidity, while wearing full firefighting protective clothing and self-contained breathing apparatus for forearm submersion (FS), mister (M) and passive cooling (PC) conditions. Values are means (±SE) for n=15.*

| | ***FS*** | ***M*** | ***PC*** |
|---|---|---|---|
| **$T_{re\ initial}$ (°C)** | 36.71 (0.06) | 36.81 (0.07) | 36.83 (0.06) |
| **$T_{re\ final}$ (°C)** | 38.95 (0.10) | 39.16 (0.13) | 39.16 (0.07) |
| **$\Delta T_{re}$ (°C)** | 2.23 (0.11) | 2.35 (0.15) | 2.33 (0.09) |
| **Overall rate of $T_{re}$ increase (°C·$h^{-1}$)** | 0.79 (0.06)$^A$ | 1.01 (0.06)$^B$ | 1.30 (0.05) |

Significant differences: $^A$ F < M and PC; $^B$ M < PC

*$T_{re}$ response over time*

To normalise slight variations in $T_{re\ initial}$ data are shown as $\Delta T_{re}$ in Figure 19. No significant differences were observed during W1. At 60 min, $\Delta T_{re}$ for PC was significantly greater compared to FS and M. Also, M was signficantly greater than FS after min 70 of the heat-stress trials.

In the first rest period (R1) significant differences were observed in $\Delta T_{re}$ among all three cooling strategies and significant differences also were observed during R2, between FS and M. During R1, $\Delta T_{re}$ for PC continued to increase 0.21 ± 0.03°C at a rate of 0.62 ± 0.1°C·h$^{-1}$, whereas $\Delta T_{re}$ during R1 for M and FS decreased by 0.07 ± 0.05 and 0.35 ± 0.2°C at rates of 0.21 ± 0.2 and 1.05 ± 0.16°C·h$^{-1}$, respectively. Similarly, $\Delta T_{re}$ during R2 decreased 0.09 ± 0.1 and 0.50 ± 0.1°C at rates of 0.26 ± 0.3 and 1.50 ± 0.4°C·h$^{-1}$ for M and FS, respectively. There were no significant differences observed between R1 and R2 for either M or FS.

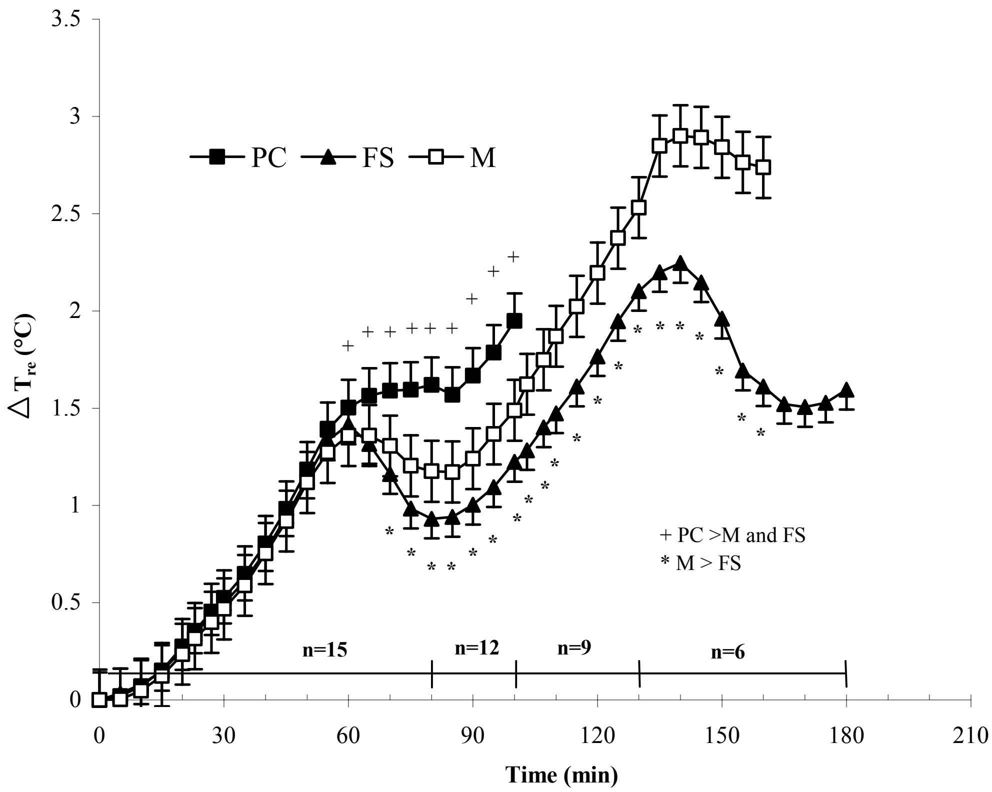


***Figure 19.** Delta rectal temperature ($\Delta T_{re}$) response during passive cooling (PC), mister (M), and forearm submersion (FS) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

### Mean Skin Temperature

The $\overline{T}_{sk}$ response for the cooling trials is depicted in Figure 20. After 55 min, $\overline{T}_{sk}$ was significantly greater for PC when compared to M, and after 60 min when compared to FS. In addition, M was significantly greater than FS from the beginning of E2 from 80 to 135 min. There were no other significant differences observed. Although, $\overline{T}_{sk}$ was not significantly different during the first 80 min when comparing FS and M, there were significant differences observed in hand temperature during submersion. Hand skin temperatures dropped to 20°C during the FS trial compared to only 32°C during the M trial.

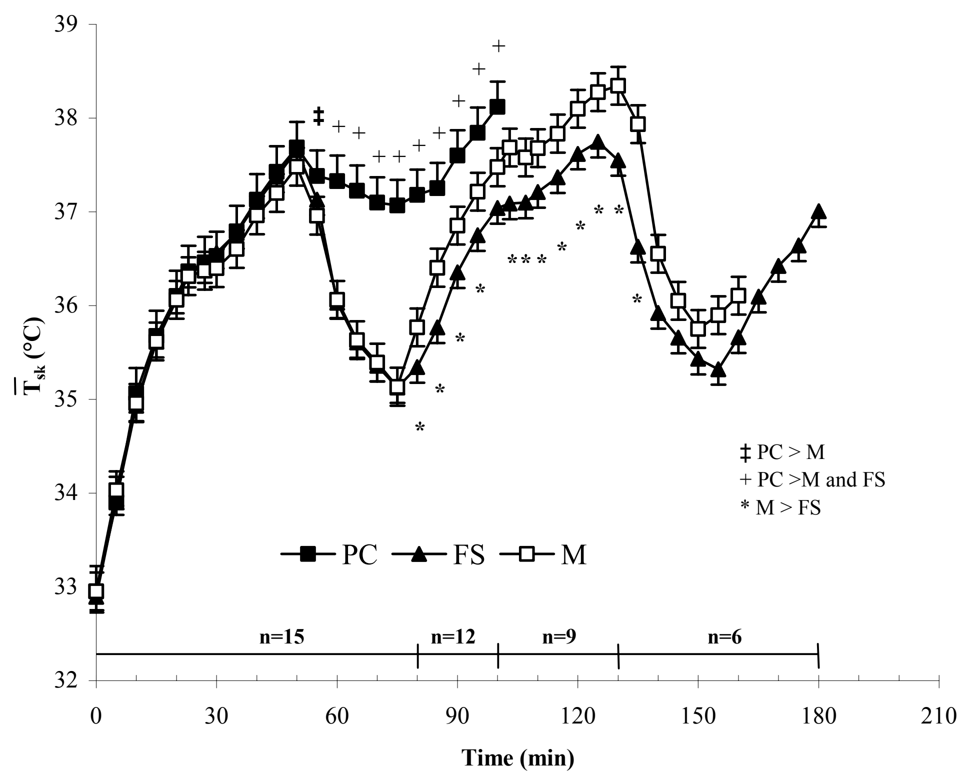


***Figure 20.*** *Mean skin temperature ( $\overline{T}_{sk}$ ) response during passive cooling (PC), mister (M), and forearm submersion (FS) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

### Mean Body Temperature and Heat Storage

Mean body temperature ( $\overline{T}_b$ ) decreased 0.90 ± 0.05°C and 0.65 ± 0.04°C during R1 for FS and M, respectively. In comparison, $\overline{T}_b$ for PC increased 0.04 ± 0.04°C during R1. During R2, $\overline{T}_b$ decreased 0.95 ± 0.10 and 0.73 ± 0.10 for FS and M, respectively. Heat storage (ΔS) decreased 270.5 ± 17.8 kJ and 195.0 ± 13.4 kJ during R1 and 277.1 ± 42.9 and 207.5 ± 35.0 kJ during R2 for FS and M, respectively. Comparatively, during R1, ΔS for PC increased 9.17 ± 11.6 kJ. All comparisons for $\overline{T}_b$ and ΔS were significantly different during R1 among the cooling trials.

### Tolerance Time

There were significant differences in the tolerance time (TT) and total work time (WT) observed across all three trials (Table 8). Comparing PC to M and FS showed significant increases in TT by 30% and 66%, respectively. Similarly, WT increased for M and FS by 25% and 62%, respectively, in comparsion to PC. Forearm submersion also significantly increased TT and WT approximately 30% compared to M, an increase equivalent to 30 min or approximately 1 bottle of air. Reasons for trial termination of the sessions are illustrated in Table 2 for the various cooling trials. Of the 45 experimental sessions, 47% (21 of 45) were terminated with subjects complaining of exhaustion, 10 of which occurred during the FS trial. A further 29% (13 of 45) were terminated because $T_{re}$ reached 39.5°C during the trial and HR and dizziness/nausea accounted for the remaining 24%.

### Environmental Conditions and Water Bath Temperatures

Ambient environmental conditions remained constant for PC and FS at 35°C and 50% R.H. (2.81 kPa) throughout the trials. Mister cooling decreased the local ambient temperature by 4.3 ± 0.6°C and increased humidity by 23.4 ± 3.6 % producing an ambient condition of 31.7°C and 73.4% R.H. (3.24 kPa) during rest phases. Water bath temperatures during FS trials increased 2.7°C during R1 and 3.3°C during R2. Heat transferred to the water during the 20 min submersion was 312.1 ± 13.0 W, and 392.5 ± 12.4 W for R1 and R2, respectively. There was a significantly greater heat transfer during min 0-10 (216.9 ± 10.3W and 259.8 ± 15.6W) compared to min 10-20 (95.2 ± 5.3W and 132.7 ± 8.9W) for R1 and R2, respectively. As well, R2 was significantly greater than R1.

### Sweat Rate, Body Mass Loss and Fluid Replacement

Sweat rate (SR), mass loss, and fluid replacement values are given in Table 9 for PC, M and FS. There were significant differences in SR and total fluid consumption for all comparisons within the heat-stress trials. Although a full fluid replacement schedule was attempted, there was still a decrease in body mass, but this was less than 0.8%.

***Table 8.*** *Tolerance time (TT), total work time (WT) expressed in min, and reasons for termination of the heat-stress trials conducted at 35°C and 50% relative humidity, with subjects wearing full firefighter protective ensemble and self-contained breathing apparatus for forearm submersion (FS), mister (M) and passive cooling (PC) conditions. Values represent the number of subjects during each trial that attained a rectal temperature ($T_{re}$) of 39.5°C, ended due to exhaustion (Exh), reached or exceeded a heart rate (HR) of 95% $HR_{peak}$ for 3 min, ended due to dizziness or nausea or attained the time limit of 290 min of work. Values are means (± SE) for n=15.*

| | ***FS*** | ***M*** | ***PC*** |
|---|---|---|---|
| **TT (min)** | 178.7 (13.00)$^{A}$ | 139.1 (8.28)$^{B}$ | 108.0 (3.59) |
| **WT (min)** | 124.7 (7.94)$^{A}$ | 95.1 (4.96)$^{B}$ | 78.0 (3.59) |
| ***Reasons for Trial Termination*** | | | |
| $T_{re}$ | 4 | 7 | 2 |
| **Exh** | 8 | 3 | 10 |
| **HR** | 2 | 2 | 3 |
| **Dizziness/Nausea** | 1 | 3 | 0 |
| **Time (290 min)** | 0 | 0 | 0 |

Significant differences: $^{A}$ F > M and PC; $^{B}$ M > PC

***Table 9.*** *Sweat rate (SR), total fluid intake, total and percent body mass change, and the percentage of water given that was consumed during the heat stress trials at 35°C and 50% relative humidity, while wearing full firefighting protective clothing and self-contained breathing apparatus for forearm submersion (FS), mister (M) and passive cooling (PC) conditions. Values are means (±SE) for n=15.*

| | ***FS*** | ***M*** | ***PC*** |
|---|---|---|---|
| **SR ($kg \cdot h^{-1}$)** $^{A}$ | 0.81 (0.08) | 0.93 (0.08) | 1.26 (0.07) |
| **Total fluid intake (kg)** $^{A}$ | 2.31 (0.19) | 1.94 (0.14) | 1.72 (0.12) |
| **Total mass Lost (kg)** | 0.35 (0.17) | 0.39 (0.10) | 0.62 (0.09) |
| **Body mass loss (%)** | 0.40 (0.19) | 0.45 (0.12) | 0.73 (0.11) |
| **Water consumption %** | 86.2 (4.66) | 83.8 (4.20) | 86.7 (5.45) |

Significant differences: $^{A}$ All comparisons significantly different

## Discussion

The purpose of the present study was to compare the effectiveness of forearm submersion, mister and passive cooling strategies during intermittent rest periods and to determine whether one modality was more effective than another in aiding heat transfer from the body while wearing FPC and SCBA. Although we could not simulate the radiant heat of direct fire exposure in our climatic chambers, we recognized that many firefighting activities do not involve direct exposure to a fire but still entail wearing FPC and SCBA, such as during overhaul, salvage and response to emergency calls which encorporate the risk of exposure to unknown agents. An environmental condition of 35°C and 50% R.H. was chosen to represent a very warm summer's day for the temperate climate region of Toronto.

In the present study, forearm submersion clearly was effective in reducing the heat strain associated with a given workload as well as extending total work time, although a thermal equilibruim was not attained. These results demonstrate the detrimental effects a cummulative oscillating heat storage can have during repeated bouts of work. The addition of active cooling allowed the reduction of the heat strain at a given time, but was not able to prevent the eventual exhaustion of participating subjects.

Hand and forearm submersion in cool water produces a vasoconstriction of the AVA's through centrally mediated temperature receptors in order to maintain thermal equilibrium. However, when the body is in a hyperthermic state, it has been shown that vasodilation of AVA's is not compromised at water temperatures ranging from 10-30°C [40, 42, 43]. Optimal water bath temperatures have be found to be between 10- 20°C, with the cooler water producing faster rates of body cooling at the onset, with a subsequent plateau observed after 20-30 min of submersion[40]. Since the increase in water bath temperature in the present study remained relatively constant, it is unlikely that the observed change in skin temperature were due to peripheral vasoconstriction. Furthermore, the fact that $T_{re}$ reductions were seen during the first 10 min of submersion not only supports the notion of peripheral vasodilation, but also the notion that cooled blood from the hands and forearm flows directly to the core via superficial veins as opposed to deep veins [42]. Countercurrent heat exchange between arteries and deep veins would warm the cooled blood returning to the core thereby slowing the rate of body cooling in response to the hand and forearm submersion.

Mean transfer of heat to the water bath was comparable to previous work using extremity submersion at 20°C [40, 41]. As well, a greater heat transfer to the water bath was observed during the first 10 min of the submersion compared to min 10-20, as has been previously reported [40, 41]. This observation can be attributed to an elevated heat transfer gradient at the beginning of the submersion. As $T_{re}$ - approached normal values, peripheral perfusion decreased due to vasoconstrictive responses of the AVA's. At the same time, the temperature of the water bath increased, decreasing the heat transfer gradient and subsequent heat transfer. In contrast, submersion in cold water during a normothermic state (37.0°C), would produce only a minimal change in $T_{re}$ due to the mediated vasoconstrictive response to maintain thermal equilibrium[45].

Effectiveness of the mister depends on the ability to exchange the humidity of the microenvironment with the ambient envirionment. In the current study, the mister affected heat transfer in several ways. First, the increased effective air velocity with the fan promoted greater evaporative and convective heat transfer. Second, the flash evaporation of the fine water mist led to a reduction in local temperature from 35°C to 30°C, which also promoted a greater convective heat transfer. However, the mister led to an increase in relative humidity by 20% and an increase in local environmental vapor pressure from 2.8 to 3.1 kPa, thus reducing the evaporative potential of the environment [8, 20].

It has been suggested that oscillating changes in $T_{re}$ may have an affect on fatigue [39]. Although $T_{re\ final}$ was not significantly different among the cooling trials, there did appear to be a tendency for individuals during the FS trial to have a lower $T_{re}$ at exhaustion, suggesting that subjects ended their trial due to factors other than reaching our ethical $T_{re}$ constraint. This idea is further illustrated by the subjects' reasons for trial termination, with a greater number of subjects ending due to HR and exhaustion during the FS trial compared to M (see Table 2). Furthermore, although M was able to extend tolerance and work times by approximately one bottle of air compared to PC, elevated rates of heat storage caused a greater number of subjects to reach critical rectal temperature levels and/or dizziness and nausea compared to FS. Comparing the M and FS trials at the end of W2, $T_{re}$ was 0.43°C higher in M compared to FS, and by the end of R2, the difference in $T_{re}$ was even greater, 39.4°C versus 38.5°C. Thus, although M helps to increase TT, there is a limited reduction of thermal strain, as was depicted by elevated $\overline{T}_{sk}$ , $T_{re}$ and HR values compared to FS overtime.

Potentially the mister rest period could be extended in order to further reduce $T_{re}$ to levels seen during FS. However, this would decrease work time and hinder productivity. Incorporating more than one mister in a large space could increase the cooling effects. However, in a closed space, utilizing more than one mister would be self-defeating due to additional increases in ambient vapor pressure. It is possible that in a closed space, the use of fans alone may be just as effective. Another possibility would be to use ice water in the mister container, in an attempt to increase cooling power. One way to increase the effectiveness of the submersion would be to use a combination of hands and feet[40], although this may not always be as practical a method in the field. To produce similar benefits to that of combined hand and foot submersion, the amount of time that the hands alone are submerged could be increased, keeping in mind that limb submersion is considered to be a self-limiting method [40]. Once the body reaches a normothermic state, peripheral vasoconstriction will prevent any further body heat loss during submersion. Thus, extending the length of a rest period may not achieve a substantial benefit for body cooling. In fact, it has been found that cooling power at 10°C and 20°C plateaues after 25-30 min as gradients decrease and rectal temperatures approach normal values [40]. Indeed, 10°C appears to be an optimal temperature for heat loss [30]; however, to increase the applicability of the present findings, a temperature (~18°C) was chosen, which would be indicative of the subjects' field environment. Hypothetically, the cooler water could be achieved by adding a block of ice to the water bath, causing a greater heat transfer gradient and thus resulting in a greater cooling of personnel, assuming that AVA perfusion was maintained.

In the past, the implementation of work and rest cycles have been found to help increase total work time, assuming that environmental conditions allow for cooling during rest periods [21]. At higher ambient conditions or when wearing protective clothing while remaining encapsulated, work and rest schedules may not allow for more total work to be accomplished. Furthermore, even removing restrictive clothing during rest, such as SCBA and upper body protective gear, may not be adequate to extend total work times at higher ambient conditions or metabolic rates. For example, in our previous work, firefighters following a continuous work protocol similar to the present study produced tolerance times of 67 min with a rate of $T_{re}$ increase of 1.75°C·h$^{-1}$ at 35°C and 50% R.H. Given that the $T_{re}$ cut-off was a conservative 39.0°C, and that 7 of 9 subjects reached $T_{re}$ cut-offs, subjects' tolerance time would have increased by 0.29 h or 17 min if they had been allowed to continue until $T_{re}$ values equalled 39.5°C. This would have created tolerance times of 84 min while performing continuous work at similar work rates and ambient environmental conditions. In contrast, in the present study working intermittently with passive cooling (removing upper body protective gear), produced an average tolerance time of 108 min of which 78 min represented actual work time. In this comparison, passive rest did extend the tolerance time, but actually reduced the amount of total work performed (78 versus 84 min). However, by incorporating an active cooling stategy during the designated rest periods, WT was increased by 25% and 60% during M and FS, respectively, when compared to PC.

When dealing with protective clothing ensembles in an occupational health and safety setting, the goal is to set limits such that individuals never reach their critical limits. From this view point, it is preferred that a firefighter succumbs and stops work due to physical exhaustion as opposed to heat exhaustion, similar to which has been observed during work at higher metabolic work rates [5, 34, 93]. Not only did forearm submersion extend TT and WT's by 60% compared to passive cooling and 30% compared to the mister trials, there was a significant reduction in the thermal strain associated with the given workload at a specific period of time. The implications of this finding is that even if the cooling is not used to extend total work time, cooling will significantly reduce the heat strain associated with any given task. Ultimately, this would help to reduce the occurrence of heat-related injury and possibly myocardial infarction in active firefighters.

# Conclusions

In extreme environmental conditions, active cooling may be the only viable option for reducing the heat strain associated with wearing FPC and SCBA for extended periods of time. The current findings suggest that active cooling has the ability to reduce both the cardiovascular and thermoregulatory strain, while significantly increasing TT and WT, where operationally necessary. In addition, there is a definite advantage during work in FPC and SCBA when utilizing forearm submersion compared to other methods of active or passive cooling in the heat.

# D. Fluid Replacement Stategies For Firefighters During Work in Warm Environments While Wearing Firefighting Protective Clothing.

## Abstract

This study examined different fluid replacement quantities during intermittent work while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA) in the heat (35°C, 50% R.H.). Twelve male Toronto firefighters participated in the heat-stress trials. Subjects walked at 4.5 $km \cdot h^{-1}$ with 0% elevation on an intermittent work (50 min) and rest (30 min) schedule. Work continued until rectal temperature ($T_{re}$) reached 39.5°C, or heart rate (HR) reached 95% of maximum or exhaustion. During the heat-stress trials subjects received one of four fluid replacement quantities, full hydration (F), two-thirds ($2/3^{rd}$), one-third ($1/3^{rd}$), and no hydration (NH). Tolerance time (min) was significantly greater during F (111.8 ± 3.5), $2/3^{rd}$ (112.9 ± 5.2) and $1/3^{rd}$ (104.2 ± 5.8) compared to NH (95.3 ± 3.8). In addition, work time (min) was significantly greater in F (82.6 ± 3.5), and $2/3^{rd}$ (82.9 ± 5.2) compared to NH (65.3 ± 3.8). Rates of $T_{re}$ increase and HR were significantly higher during NH compared to F, $2/3^{rd}$ and $1/3^{rd}$ after 27 min of the heat-stress trials. The current findings suggest that there is a definite advantage when incorporating even partial fluid replacement strategies while wearing FPC and SCBA in the heat.

**Keywords:** Uncompensable heat stress, exercise tolerance, rectal temperature, metabolic rate, protective clothing,

# Methods

## Subjects

Following approval by the DRDC Toronto's Human Ethics Review Committee, 12 subjects were selected from a pool of 40 active Toronto Firefighters to participate in the fluid replacement trials described below. Baseline testing was completed in August and the trials were conducted in the climatic chamber at DRDC Toronto between September and January to limit heat acclimation through casual exposure to hot environments. All subjects were medically screened and a full explanation of procedures, discomforts and risks were given prior to obtaining written informed consent. Subjects were selected such that the age, aerobic fitness and body fatness covered a wide spectrum of individuals who were representative of the Toronto Fire Service.

## Determination of $\dot{V}O_{2peak}$

Peak oxygen consumption ($\dot{V}O_{2peak}$) measurements have been described in detail previously[20, 98]. $\dot{V}O_{2peak}$ was defined as the highest observed 30-s value for oxygen consumption ($\dot{V}O_2$) together with a respiratory exchange ratio (RER) ≥ 1.15. Heart rate (HR) was monitored during the treadmill protocol using a transmitter/ telemetry unit (Polar Vantage XL, Finland). The highest value recorded at the end of the exercise test was defined as peak HR ($HR_{peak}$).
Body surface area ($A_D$) was calculated using the DuBois equation (1915) [77]. Body density was determined from underwater weighing (UWW) using body plethysmography to determine residual lung volume [78, 79]. Body fatness was calculated using the Siri equation [80].

## Clothing Ensembles

During work, subjects wore their own NFPA standard protective firefighting turnout gear (Garment Model – BPR5442TK, Morning Pride, Dayton, OH), gloves (Shelby Firewall), Nomex® flash hood (Majestic Fire Apparel), helmet (Firedome PX Series, Bullard, Kentucky), and self-contained breathing apparatus (SCBA) (MSA, Mine Safety Appliances Company, Pitts, Penn). Standard issue cotton station pants and a Toronto fire T-shirt were worn beneath the turnout gear, along with underwear, shorts, socks and running shoes. The Canadian Forces nuclear biological and chemical (NBC) impermeable protective over-boot was worn in place of the standard rubber boot in order to simulate the impermeable characteristics of the rubber boot. The total weight of the ensemble approximated 22 kg. During all trials, subjects breathed room air as opposed to SCBA; however, full SCBA was carried to simulate the weight of the bottle. The total thermal resistance of the firefighter protective clothing ensemble, determined with a heated articulating copper manikin, at a wind speed of 0.85 $m \cdot s^{-1}$, was 0.240 $m^2 \cdot °C \cdot W^{-1}$ (1.55 clo). The Woodcock vapour permeability coefficient, determined with a completely wetted manikin, was 0.27 (R.R. Gonzalez, personal communication).

### Experimental Design

All subjects performed a familiarisation exposure (35°C, 50% relative humidity, wind speed <0.1 $m \cdot s^{-1}$), at the designated workrate (4.5$km \cdot h^{-1}$, 0% incline) until attaining one or more of the specific end-point criteria (see below). The familiarisation trial was at least 10 days before their first experimental trial to limit the acute effects of acclimation. Each subject then performed, randomly assigned experimental sessions at 35°C and 50% R.H., incorporating one of four fluid replacement quantities, full hydration (F), two-thirds ($2/3^{rd}$), one-third ($1/3^{rd}$), and/or no hydration (NH), while wearing FPC and SCBA. The protocol timeline was broken into work and rest phases as shown in Figure 21.

*Work phase.* Each work cycle was divided into a work portion and a simulated SCBA bottle change, which have been previously described in detail (Part A) [34, 99](Figure 17). The work portion consisted of walking at 4.5 $km \cdot h^{-1}$ for 20 minutes while wearing the protective ensemble and SCBA. Following 20 minutes of work a 10 minute simulated bottle change occurred (see Figure 1). Following the 10 minute simulated bottle change subjects began another 20-minute work portion.

*Rest phase.* Following the second 20-minute work portion, a 30-minute rest phase began at 50 minutes. The first 5 minutes of the rest phase was allotted for disconnecting the data acquisition system, obtaining a dressed weight, and removing helmet, flash hood, gloves, jacket, tanks and SCBA face piece. Following 20 minutes of seated rest a second 5-minute transition period allowed subjects to reencapsulate, obtain a dressed weight, and reconnect to the data acquisition system before beginning the second work phase starting at 80 minutes.

The intermittent work and rest phases (50/30 min) were repeated until one or more of the following end-point criteria were reached: $T_{re}$ reaching 39.5°C, HR reaching or exceeding 95% of maximum for 3 minutes, dizziness or nausea precluding further work, subject exhaustion or discomfort, completing 4 cycles of work (290 minutes), or the investigator terminating the trial. End-point criteria for the rest phase were similar to the work phase except that the $T_{re}$ ceiling was raised to 40°C. If $T_{re}$ had not decreased below 39.5°C by the end of a rest phase, subsequent work was not performed. Tolerance time (TT) was defined, for all trials, as the elapsed time from the beginning of the work to the attainment of one or more of the end-point criteria that resulted in the termination of the trial. Total work time (WT) was defined as TT minus the time spent during rest.

### Dressing and Weighing Procedures

To control for the effects of circadian rhythm on rectal temperature, all trials began at 7:30 am [81]. Upon arrival, subjects inserted a rectal probe and were weighed nude on an electronic scale, sensitive to the nearest 0.05 kg (Serta Systems Inc., SuperCount, Acon, MA). Skin thermistors and HR monitor were applied, and then subjects were dressed in station pants and T-shirt,

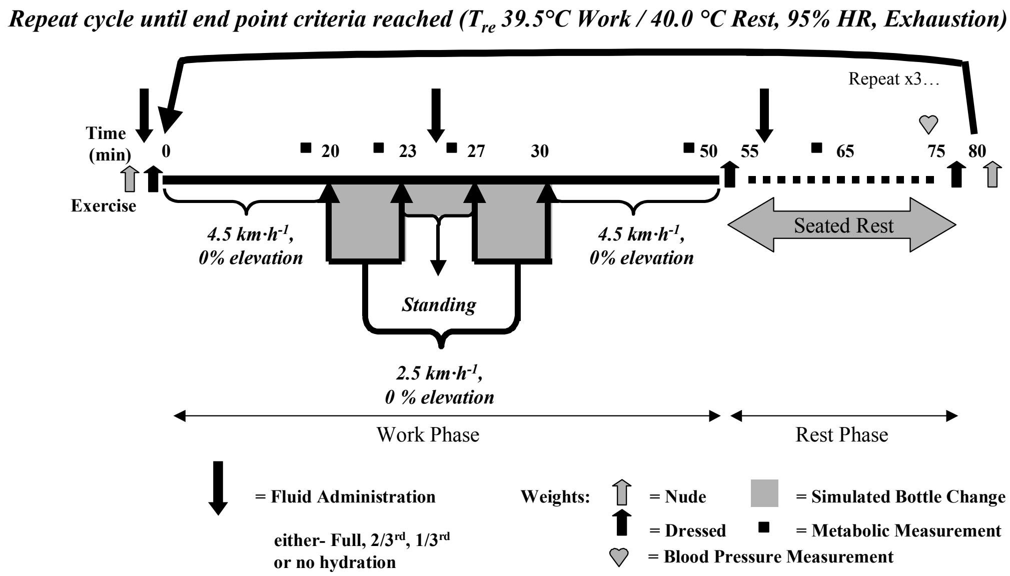


***Figure 21.*** *Protocol Timeline for full hydration (F), two-thirds (2/3rd), one-third (1/3rd), and no hydration (NH) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus.*

followed by bunker pants, jacket, flash hood, running shoes, and an NBC over-boot (Figure 4) . Following water administration, subjects donned SCBA tanks and their respirator facepiece, pulled over their flash hoods and put on helmet and gloves, to obtain full encapsulation. Subjects were then led into the climatic chamber where a final dressed weight was obtained and skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer, Pitts, PA). Subjects straddled the treadmill walking surface and a workrate of 4.5km·h$^{-1}$, 0% elevation was established before beginning the first work phase.

Upon completion of each work and rest phase, as well as upon completion of the trial, a dressed weight was obtained encompassing all gear. The subjects were removed from the climatic chamber and nude weight was recorded within 5 minutes of trial termination, after subjects undressed and towelled dry.

### Fluid Replacement and Sweat Measurements

During the familiarisation exposure subjects were given 5 mL·kg$^{-1}$ of cool water (~15°C) to drink, prior to entering the climatic chamber, at min 25 of each 30-min work/ bottle change cycle, and at the beginning of each rest phase. If $T_{re}$ exceeded 39.0°C or if the subject felt that they could not continue for at least another 15 minutes, water was not administered for the remainder of the intermittent heat-stress trial. Sweat rate (SR) was calculated from the familiarisation trial and this value was used to determine rates of fluid replacement that would maintain a state of hydration of 100%, 67%, 33% and 0% during subsequent experimental trials. Calculated sweat rates were converted to a rate per hour, divided by two and multiplied by the percentage for the trial, in order to determine fluid replacement volumes during each 30 minutes. For all trials, nude and dressed masses were corrected for respiratory [83] and metabolic mass losses [84], as well as for fluid intake. The rate of sweat production (SR) incorporated the entire heat-stress trial.

## Physiologic Measurements

### Temperature Measurements

Mean values over 1-min periods for $T_{re}$, and a 7-point weighted mean skin temperature ( $\overline{T}_{sk}$ ) [82] were calculated, recorded, and printed by the computerized data-acquisition system. $T_{re}$ was measured using a flexible vinyl-covered rectal thermistor (YSI Precisions 4400 Series, Yellow Springs Instrument Co. Inc. Yellow Springs, OH), inserted approximately 15 cm beyond the anal sphincter. $\overline{T}_{sk}$ was obtained from 7 temperature thermistors (Mallinckrodt, Medical Inc, St. Louis, MO) taped on the head, abdomen, medial deltoid, hand, anterior thigh, shin and foot.

### Heart Rate and Blood Pressure Measurements

Heart rate was monitored using a transmitter (Polar Vantage XL), attached with an elasticized belt fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually every 5 minutes during both the work and recovery phases of the heat-stress trial. Blood pressure was taken prior to blood sampling and at the end of each rest phase for the heat-stress trials using a standard stethoscope and pressure cuff technique. Mean arterial pressure (MAP) was approximated using the equation:

$$MAP \approx P_{Diastolic} + \frac{1}{3}(P_{Systolic} - P_{Diastolic}) \qquad (4)$$

where P represents pressure.

### Gas-Exchange Measurements

Details of the open-circuit spirometry used to determine expired minute ventilation ( $\dot{V}_E$ ), $\dot{V}O_2$ and carbon dioxide production ( $\dot{V}CO_2$ ) have been presented previously

[20]. Measurements were made during minutes 17-20, 20-23 and 47-50 of each 50-minute work + simulated SCBA bottle change cycle and during minutes 12-15 of each rest phase. Values were averaged from a 2-minute sampling period for each subject following a 1-minute washout period. The current SCBA face piece outtake valve was modified to incorporate the attachment of an adaptor that allowed expired gases to be collected during work (Figure 5).

### Blood Sampling and Measurements

A 5 mL blood sample was obtained by venipuncture, prior to the dressing procedures, to determine pre-osmolality using the Advanced™ Micro-Osmometer (Model 3300, Advanced Instruments, Norwood, Massachusertts) (Figure 6).

### Statistical Analyses

A one-factor (fluid replacement) repeated measures ANOVA was used to compare the dependant measures of osmolality, fluid consumption, mass loss, TT, WT, and SR. An ANOVA with 2 repeated factors (fluid replacement and time of exposure) was performed on the various dependant measures sampled over time (ie., $\Delta T_{re}$, $\overline{T}_{sk}$, $\dot{V}O_2$, and HR) for the heat-stress trials. To correct for violations in the assumption of sphericity with the repeated factors, the Huynh-Feldt correction was applied to the F-ratio. When a significant F-ratio was obtained, post-hoc analyses utilized a Newman-Keuls procedure to isolate differences among the treatment means. All ANOVA's were performed using statistical software (SuperAnova V.1.11 (1991), Abacus Concepts, Inc). For all statistical analyses, an alpha level of 0.05 was used.

## Results

### Subjects

Subject anthropometric characteristics for age, height, mass, surface area and body fatness were 40.7 ± 0.76 y, 181.1 ± 1.9 cm, 87.8 ± 2.5 kg, 2.08 ± 0.04 $m^2$ and 18.1 ± 1.0%, respectively. $\dot{V}O_{2peak}$ and $HR_{peak}$ were 45.2 ± 1.7 $mL \cdot kg^{-1} \cdot min^{-1}$ and 188 ± 2.2 $b \cdot min^{-1}$, respectively.

### Pre-Osmolality

There were no significant differences in pre-osmolality values across the four fluid replacement trials with mean values approximating 286 $mOsm \cdot kgH_2O^{-1}$, a value that is within the accepted range for a normal hydrated state [85].

### Gas Exchange

There were no significant differences in $\dot{V}O_2$ observed throughout the heat-stress trials. After 20 min of work, $\dot{V}O_2$ averaged 12.3 ± 0.4 $mL \cdot kg^{-1} \cdot min^{-1}$ and represented a workload of approximately 30% $\dot{V}O_{2peak}$.

### Blood Pressure

There were no significant differences observed between trials or over time for systolic, diastolic or MAP. MAP ranged between 89 and 94 mmHg throughout the trials.

### Heart Rate

Figure 22 presents the HR response overtime for the heat-stress trials. There were no significant differences observed during the first 30 minutes of work. HR was significantly greater during NH compared to $2/3^{rd}$ after 30 min, and at 40-45 min for F. HR for the $1/3^{rd}$ trial was significantly elevated compared to $2/3^{rd}$ at minutes 45-50 and minutes 65-75. There were no significant differences observed during the transition period prior to the second work phase between NH, F and $2/3^{rd}$.

### Rectal Temperature

The values for initial rectal temperature ($T_{re\ initial}$), final rectal temperature ($T_{re\ final}$) and delta rectal temperature ($\Delta T_{re} = T_{re\ final} - T_{re\ initial}$) are given in Table 10. There were no significant differences among the trials for these dependent measures. When final rectal temperature was compared during the completion of the last work period of each condition ($T_{re\ final\ (W)}$), there was a significantly higher $T_{re}$ observed during F compared to NH (Table 10). The overall rate of $T_{re}$ increase throughout the heat-stress was significantly greater for NH compared to $2/3^{rd}$. There were no other differences observed among the trials (Table 10).

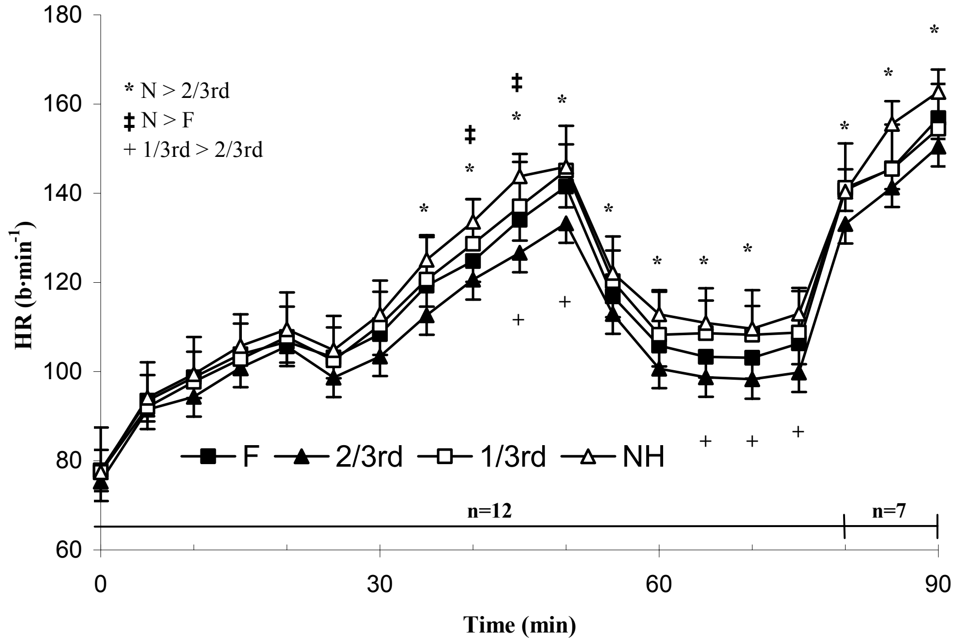


***Figure 22.*** *Heart Rate (HR) response during full hydration (F), two-thirds (2/3rd), one-third (1/3rd), and no hydration (NH) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

***Table 10.*** *Initial, final, delta (final – initial) rectal temperature ($T_{re}$),the rate of rectal temperature increase (↑) and final rectal temperature corrected for the final rest period ($T_{re\ final(w)}$) during the heat stress trials at 35°C and 50 % relative humidity, while wearing full firefighting protective clothing and self-contained breathing apparatus for full hydration (F), two-thirds (2/3rd), one-third (1/3rd), and no hydration (NH). conditions. Values are means (±SE) for n=12.*

| | F | 2/3rd | 1/3rd | NH |
|---|---|---|---|---|
| $T_{re\ initial}$ (°C) | 36.81 (0.07) | 36.78 (0.09) | 36.84 (0.07) | 36.85 (0.07) |
| $T_{re\ final}$ (°C) | 39.11 (0.07) | 39.04 (0.11) | 39.01 (0.11) | 38.98 (0.07) |
| $T_{re\ final\ (W)}$ (°C) | 39.11 (0.07)$^B$ | 38.99 (0.09) | 38.92 (0.10) | 38.81 (0.11) |
| $\Delta T_{re}$ (°C) | 2.31 (0.09) | 2.26 (0.11) | 2.17 (0.12) | 2.12 (0.09) |
| Rate of $T_{re}$ (↑) (°C·$h^{-1}$) | 1.25 (0.05) | 1.21 (0.05) | 1.26 (0.06) | 1.35 (0.06)$^A$ |

Significant differences: $^A$ NH < 2/3rd ; $^B$ F > NH

*$T_{re}$ response over time.* To normalise slight variations in $T_{re\ initial}$ data are shown as $\Delta T_{re}$ in Figure 23. No significant differences were observed before water admistration at 27 minutes. At 27 min, $\Delta T_{re}$ was significantly greater during the NH trial compared to F, 2/3rd and 1/3rd.

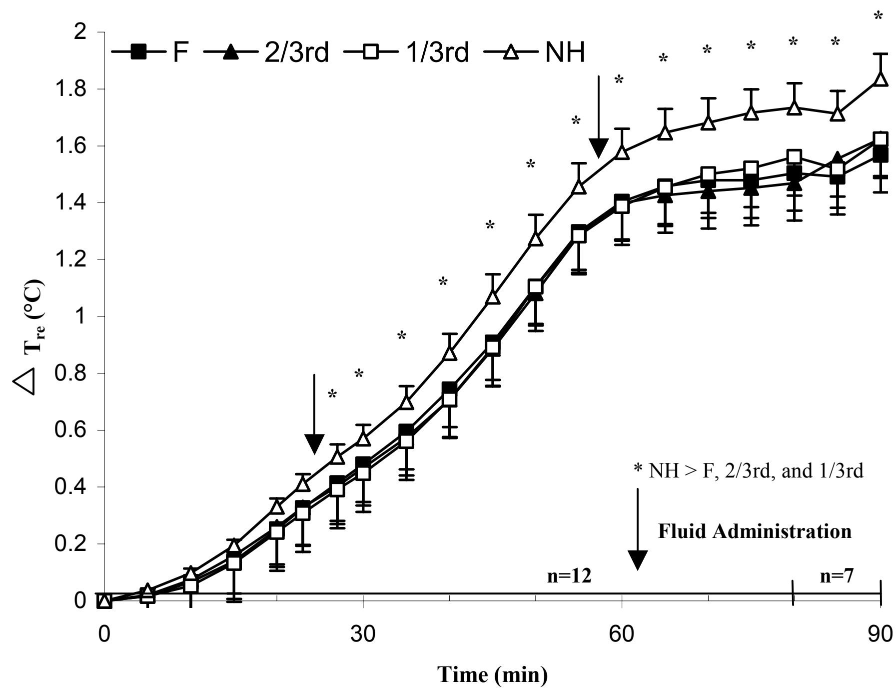


***Figure 23.*** *Delta rectal temperature ($\Delta T_{re}$) response during full hydration (F), two-thirds (2/3$^{rd}$), one-third (1/3$^{rd}$), and no hydration (NH) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

and remained throughout heat-stress trial. There were no other significant differences observed.

### Mean Skin Temperature

Mean skin temperature response is depicted in Figure 24. There were no significant differences observed in $\overline{T}_{sk}$ during the heat-stress trials.

### Tolerance Time

There were significant differences in the tolerance time (TT) and total work time (WT) observed during the heat-stress trials (Table 11). Tolerance time was significantly greater during F, 2/3$^{rd}$ and 1/3$^{rd}$ compared to NH. In addition, WT was significantly greater in F, and 2/3$^{rd}$ compared to NH. Reasons for trial termination of the sessions are illustrated in Table 2 for the various fluid replacement strategies. Of the 48 experimental sessions, 50% (24 of 48) were terminated with subjects complaining of exhaustion. Twenty-nine percent (14 of 48) were terminated due to reaching the HR cut-off. $T_{re}$ reached 39.5°C during 17% of the trials, and dizziness/nausea accounted for the remaining 4%.

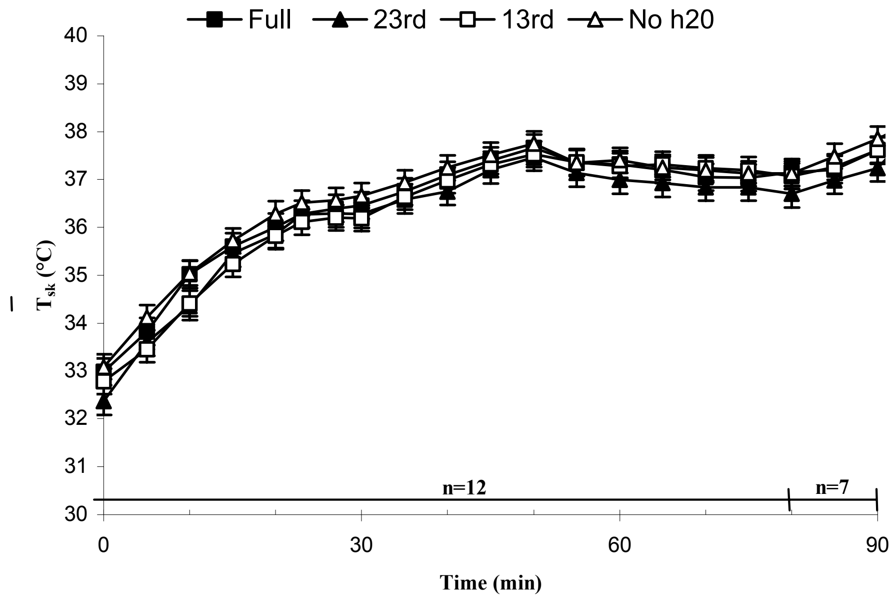


***Figure 24.*** *Mean skin temperature ( $\overline{T}_{sk}$ ) response during full hydration (F), two-thirds (2/3rd), one-third (1/3rd), and no hydration (NH) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).*

***Table 11.*** *Tolerance time (TT), total work time (WT) expressed in minutes, and reasons for termination of the heat-stress trials conducted at 35°C and 50% relative humidity, with subjects wearing full firefighter protective ensemble and self-contained breathing apparatus full hydration (F), two-thirds (2/3rd), one-third (1/3rd), and no hydration (NH). conditions. Values represent the number of subjects during each trial that attained a rectal temperature ($T_{re}$) of 39.5°C, ended due to exhaustion (Exh), reached or exceeded a heart rate (HR) of 95% $HR_{peak}$ for 3 min, ended due to dizziness or nausea or attained the time limit of 290 minutes of work. Values are means (± SE) for n=12.*

| | F | 2/3rd | 1/3rd | NH |
|---|---|---|---|---|
| **TT (min)** [A] | 111.8 (3.5) | 112.9 (5.2) | 104.2 (5.8) | 95.3 (3.8) |
| **WT (min)** [B] | 82.6(3.5) | 82.9 (5.2) | 74.2 (5.8) | 65.3 (3.8) |
| ***Reasons for Trial Termination*** | | | | |
| **$T_{re}$** | 2 | 4 | 2 | 0 |
| **Exh** | 7 | 3 | 6 | 8 |
| **HR** | 2 | 4 | 4 | 4 |
| **Dizziness/Nausea** | 1 | 1 | 1 | 0 |
| **Time (290 min)** | 0 | 0 | 0 | 0 |

Significant differences: [A] F, 2/3rd and 1/3rd > NH ; [B] F and 2/3rd > NH

## Sweat Rate, Body Mass Loss and Fluid Replacement

Sweat rate (SR), mass loss, and fluid replacement values are given in Table 12 for F, $2/3^{rd}$, $1/3^{rd}$ and NH trials. There were significant differences observed for fluid intake and replenishment percentages for all comparisons within the heat-stress trials. SR was significantly greater during F compared to $1/3^{rd}$ and NH. All comparisons for the total and percentage of body mass lost were signficantly different, except between $2/3^{rd}$ and $1/3^{rd}$. There were no other signficant differences.

***Table 12.*** *Sweat rate (SR), total fluid intake, total and percent body mass change, the percentage of fluid consumed and the % of fluid replenishment during the heat-stress trials at 35°C and 50% relative humidity, while wearing full firefighting protective clothing and self-contained breathing apparatus for full hydration (F), two-thirds ($2/3^{rd}$), one-third ($1/3^{rd}$), and no hydration (NH) conditions. Values are means (±SE) for n=12.*

| | F | $2/3^{rd}$ | $1/3^{rd}$ | NH |
|---|---|---|---|---|
| **SR ($kg \cdot h^{-1}$)** | 1.27 (0.07) $^{B}$ | 1.14 (0.09) | 1.01 (0.07) | 1.08 (0.08) |
| **Total fluid intake (kg) $^{A}$** | 1.78 (0.10) | 1.28 (0.10) | 0.62 (0.05) | 0 |
| **Total mass Lost (kg)** | 0.66 (0.11)$^{C}$ | 1.06 (0.18)$^{D}$ | 1.30 (0.13)$^{E}$ | 1.87 (0.15) |
| **Body mass loss (%)** | 0.76 (0.13)$^{C}$ | 1.24 (0.21)$^{D}$ | 1.52 (0.16)$^{E}$ | 2.16 (0.16) |
| **Fluid consumption %** | 90.20 (5.70) | 97.18 (3.54) | 95.20 (4.54) | Undefined |
| **% Fluid Replenishment $^{A}$** | 77.7 (0.05) | 62.5 (0.04) | 36.6 (0.02) | 0 |

Significant differences: $^{A}$ All comparisons were significant; $^{B}$ F > $1/3^{rd}$ and NH; $^{C}$ F < $2/3^{rd}$, $1/3^{rd}$ and NH; $^{D}$ $2/3^{rd}$ < NH; $^{E}$ $1/3^{rd}$ < NH.

## Discussion

The purpose of the present study was to compare the effectiveness of different levels of fluid replacement (F, 2/3rd, 1/3rd and NH) on intermittent work performance while wearing FPC and SCBA in the heat. Although we could not simulate the radiant heat of direct fire exposure in our climatic chambers, we recognized that many firefighting activities do not involve direct fire exposure but still encorporate wearing FPC and SCBA, such as during overhaul, salvage and response to emergency calls that encorporate the risk of exposure to unknown agents. An environmental condition of 35°C and 50% R.H. was chosen to represent a very warm summer's day for the temperate climate region of Toronto.

Previous findings suggest that optimum rates of rehydration should approximate the rate of sweat production in order to maintain total body water [67, 100-102]. However, it has been found that during cycle ergometer exercise (85W), 80% fluid replacement facilitated plasma volume restoration and decreased osmolarity despite the fact that fluid intake was less than total body-water loss [89]. Furthermore, different rates of fluid ingestion (0, 50% or 100%) have been found to produce a graded response on HR, $T_{re}$, and plasma electrolytes depending on the degree of dehydration [67]. Thus, it appears that even partial fluid replacement can be benefitial during exercise in the heat.

This study was the first to examine different fluid replacement levels while wearing FPC and SCBA in the heat. The present findings illustrate a definite physiological advantage when incorporating even partial fluid replacement. Tolerance and work times were significantly reduced and cardiovascular and thermoregulatory strain were significantly increased with fluid restriction. In addition, rate of core temperature increase and HR were significantly higher during NH compared to the fluid replacement trials.

Studies have shown a decreased central blood volume [103] and central venous pressure [103] with increased dehydration that reduce cardiac filling pressures [75] and stroke volume[53]. Consequently, HR increases [104] to maintain cardiac output and MAP [53, 58]. HR in the present study was significantly elevated in the NH trial following 35 minutes of work coinciding with the time for absorption of approximately 500 mL of fluid, similar to previous observations[65]. However, there were no significant differences in MAP observed in the present study. It is concievable that the increased HR was sufficient to maintain cardiac output and mean arterial pressures during the trial. When the independent and combined effects of hyperthermia and dehydration were examined it was found that both hyperthermia and dehydration lowered stroke volume by approximately 8% and increased HR significantly in order to prevent a decline in cardiac output and MAP[53]. It is also possible that since blood pressures were taken during the rest phase, the combined effect of dehydration and thermal strain were not as prevalent since cardiovascular strain was minimal at this point during the trial.

Ingesting a volume of cool water has the potential to slow the rate of increase in body temperature because of the additional heat storage capacity of the water [65, 105]. For example, ingesting 1 litre (or 1 kg) of 15ºC water can remove approximately 95 kJ of heat when core temperature is 38ºC (i.e., 4.18 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1} \cdot (38-15)$). This amount of heat loss would lower body temperature 0.3ºC for a 90 kg individual assuming 3.47 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$ as the average heat capacity of the body tissues. Thus, in theory, the different volumes of cool water that were consumed during the trials (see Table 12) should have slowed the rate of increase in body temperature to varying degrees. However, although $T_{re}$ was significantly reduced in the present study when cool water was ingested, the magnitude of this decrease was similar despite differing volumes of fluid that were ingested during the F, 2/3rd and 1/3rd trials (see Figure 23). Thus, we cannot account for the reduction in $T_{re}$ during the rehydration trials based solely on the heat-sink effect of the ingested water.

Increased sweat rates without an increase in sweat evaporation, as observed when wearing encapsulating clothing, can lead to an increase in the rate of dehydration and thermal strain [63, 66]. Sweat rate during F was higher than that recorded during the familiarization trial which was used to establish the rehydration schedules. As a result, the fluid provided during F actually corresponded to 85% of the fluid loss. In addition, subjects consumed only 90% of the fluid provided due to complaints of mild gastric distress and nausea. As a result, the rehydration schedule during F provided only 77% of the total fluid loss. As thermal strain and dehydration increase there is a decrease in the rate of gastric empting due to decreased stomach secretion and contraction [72] that may have contributed to the complaints of gastric distress from some subjects in the present study. Nevertheless, full fluid replacement was not achieved, despite a forced hydration strategy [70, 72]. Theoretically, subjects during the F trial needed to consume an additional 600 mL of water to achieve 100% fluid replacement. However, given the complaints of gastric distress it is unlikely that subjects would have been able to ingest this additional volume of water. It is possible that over time subjects could habituate to the consumption of large volumes of fluid [106], and, in theory, achieve further reductions in cardiovascular and thermal strain and increases in tolerance time that we could not demonstrate in the present study during F.

A practical approach to increasing the benefit of fluid administration would be to decrease the temperature of the water administered. A study examining three different temperatures of water (0.5°C, 19°C and 38°C) administered during the second hour of cycling at 51% $\dot{V}O_{2peak}$ found significant attenuation of $T_{re}$, and SR with 19°C and 0.5°C compared to 38°C [68]. However, an attenuation in FBF was also present when cold 0.5°C water was administered. Therefore, there may be an optimal temperature for the ingested fluid to allow the heat-sink effect to occur without compromising FBF.

Rectal temperature tolerated at exhaustion was not significantly different in the present study, although a trend of approximately 0.18°C difference was observed between F and NH. This is similar to previous findings[63]. Some subjects, specifically in the 1/3rd and NH trials, ended the trial as they completed a rest period (~75-80 min), and thus were not under the same cardiovascular strain recorded during a work period. In light of this descrepency, $T_{re}$ tolerated at exhaustion was also calulated using $T_{re}$ at the end of the last work performed. The subjects in question stated that they were approaching physical exhaustion at the end of this work period and would not have been able to continue exercise without the scheduled rest. When correcting for the final rest period, there was a significant decrease in the $T_{re}$ tolerated at the end of the final work period in NH compared to F (38.8°C vs. 39.1, respectively). These findings are consistent with those reported previously by McLellan and Cheung [65] who used a continous exercise and heat-stress protocol. It appears that increased circulatory instability produced by progressive dehydration at a given $T_{re}$ produced an earlier onset of exhaustion. This observation is similar to the response observed comparing trained and untrained individuals [87], where the untrained individuals experienced a greater cardiovascular strain at a given $T_{re}$ due to lower blood and stroke volumes [107]. In fact, fluid replacement during work in the heat has been deemed as important as hydration status prior to work [77]. In addition, no fluid replacement can negate advantages obtained from acclimation[33] and/ or aerobic fitness[51]placing a high fit or acclimated individual at higher risk of heat-related illness.

Since dehydration as low as 2% BW can have a detrimental effect on heat strain and tolerance during uncompensable heat-stress while working in FPC and SCBA, limiting the extent of this dehydration should be a long term goal of the active firefighter. Given that fatigue and heat-related illness correspond to a critical limiting $T_{re}$[108], fluid ingestion may be a viable way of attenuating the development of physiological strain through the reduction of $T_{re}$ and HR during a given work bout. As a result, proper amounts of fluid replacement could significantly decrease the risk of cardiovascular instability, syncope, myocardial infarction or even death during work in FPC and SCBA. Despite the advantages of fluid replacement and its documented benefits, fluid replacement cannot be seen as a substitute for active recovery methods [99]. Fluid replacement strategies need to be incorporated into an overall rehabilitation strategy which includes, work/rest cycles, active cooling, hydration and recovery.

Based on the present findings, we would recommend that firefighters consume a minimum 400mL (13 ounces) prior to donning their FPC, an additional 400mL (13 ounces) every air cylinder change and 500mL (16 ounces) during the final rehabiliation period. These recommendations are based on an 90 kg individual and would replenish about 70% of the fluid lost with the present set of environmental conditions and workrate. Reccommended fluid values will be proportionally higher or lower depending on individual body mass. Furthermore, these values should be increased as ambient temperatures or work intensity increase.

# Conclusions

A physiological advantage was observed in the present study when incorporating even partial fluid replacement while wearing FPC and SCBA in the heat. Tolerance and work times were significantly reduced and cardiovascular and thermoregulatory strain were significantly increased with fluid restriction. In addition, the rate of core temperature increase and HR were significantly higher during NH compared to the fluid replacement trials. These findings illustrate the neccessity for the incorporation of active fluid replacement strategies into daily firefighting procedures.

# E. Production of Slide Rule

During the fall of 2001, Dr. Richard Gonzalez from the United States Army Research Institute of Environmental Medicine (USARIEM) was approached about the possibility of conducting thermal manikin testing of the new clothing ensemble purchased by the Toronto Fire Service. In light of the September 2001 terrorist attacks in New York City, Dr. Gonzalez and USARIEM offerred their support at no charge to DRDC Toronto and the Workplace Safety Insurance Board of Ontario. The manikin determinations of the thermal and evaporative resistance coefficients were essential to allow the use of the USARIEM heat strain model for the prediction of continuous work times in different environmental conditions. A summary of these coefficients for the various combinations of protective clothing used in the present study is presented in Table 13.

***Table 13.*** *Manikin determinations of the thermal (CLO) and evaporative ($I_m$) resistance coefficients for the new Toronto Firefighting Protective Clothing.*

| Condition | CLO | CLO Gamma | Im/CLO | Im/CLO gamma |
|---|---|---|---|---|
| Fully Encapsulated - over t-shirt and long pants. **O m/s walk** | **1.7015** | **-0.082** | **0.1739** | **0.2283** |
| Fully Encapsulated - over t-shirt and long pants. **0.27 m/s walk** | **1.6029** | **-0.0737** | **0.1743** | **0.2326** |
| Fully Encapsulated - over t-shirt and long pants. **0.85 m/s walk** | **1.5527** | **-0.0429** | **0.179** | **0.0541** |
| No helmet, respirator, hood or gloves. T-shirt and long pants. **0 m/s walk** | **1.2432** | **-0.1694** | **0.3729** | **0.4228** |
| No helmet, respirator, hood, gloves or protective overcoat. T-shirt and long pants. **0 m/s walk** | **0.8689** | **-0.1894** | **0.5995** | **0.3308** |

The next stage in the development of the slide rule involved using the USARIEM heat strain model to predict core temperature changes for the set of environmental conditions and workrates described in Part A of the present study. These predicitions were then compared to the actual mean data that were recorded during the laboratory testing described in Part A. Examples of these comparisons are shown belown in Figures 25-28 for 35°C and 50% relative humidity.

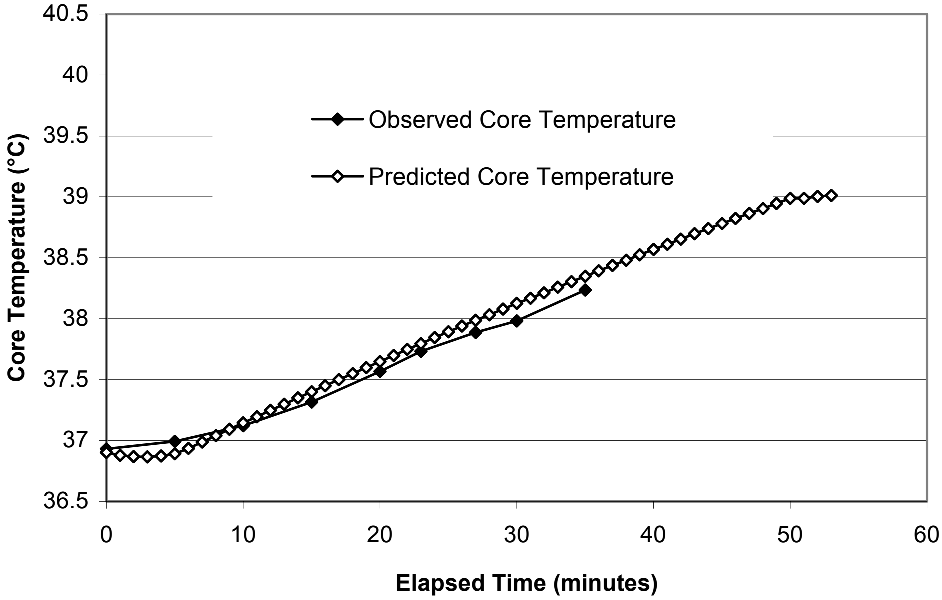


***Figure 25.*** *USARIEM heat strain model predicted core temperature versus observed core temperature during Heavy work wearing firefighting protective clothing and self-contained breathing apparatus at 35°C and 50% relative humidity.*

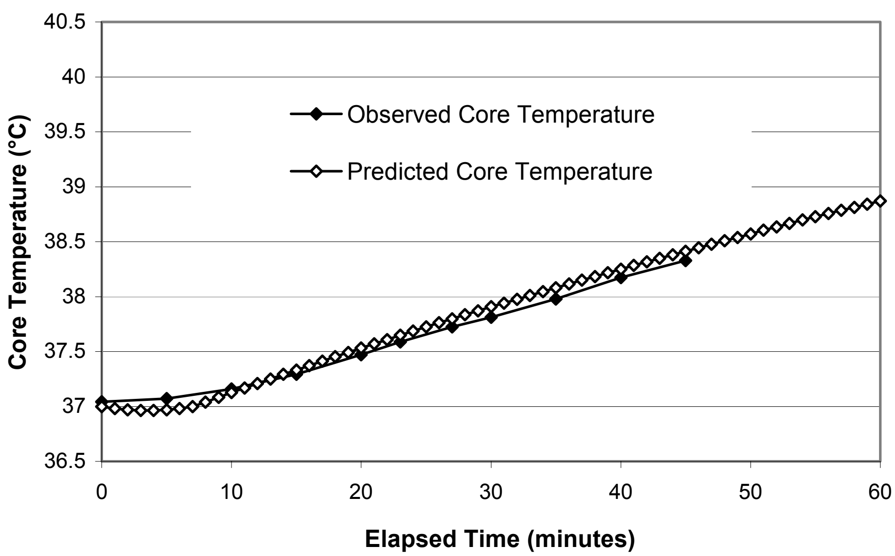


***Figure 26.*** *USARIEM heat strain model predicted core temperature versus observed core temperature during Moderate work wearing firefighting protective clothing and self-contained breathing apparatus at 35°C and 50% relative humidity.*

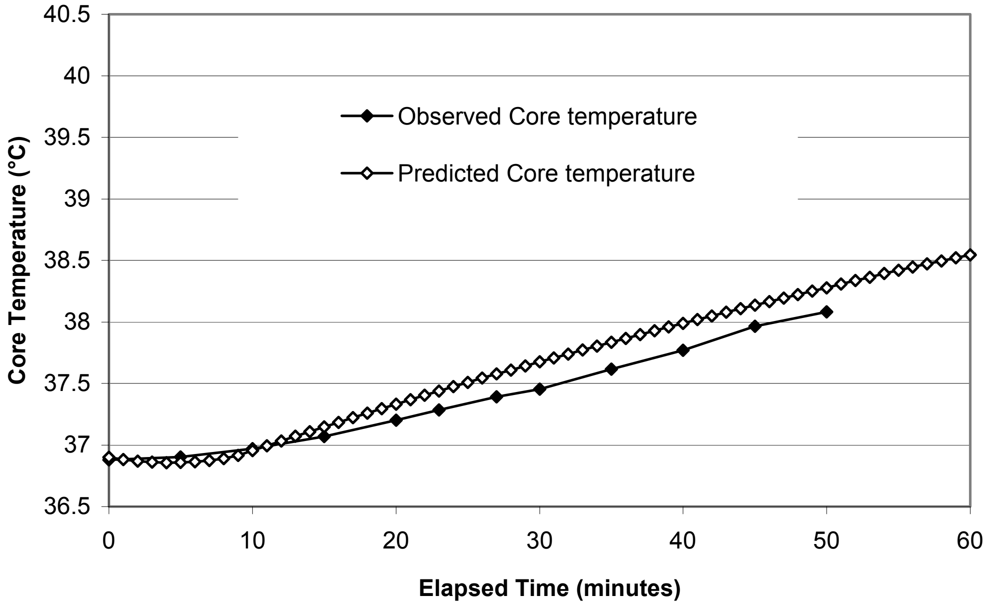


***Figure 27.*** *USARIEM heat strain model predicted core temperature versus observed core temperature during Light work wearing firefighting protective clothing and self-contained breathing apparatus at 35°C and 50% relative humidity.*

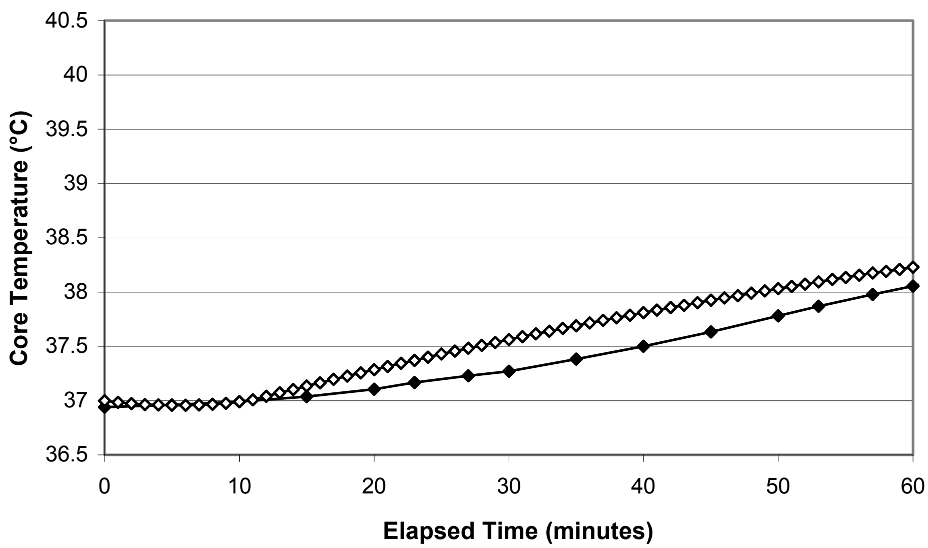


***Figure 28.*** *USARIEM heat strain model predicted core temperature versus observed core temperature during Very Light work wearing firefighting protective clothing and self-contained breathing apparatus at 35°C and 50% relative humidity.*

With only one exception (Heavy 30°C), the core temperature predictions from the USARIEM heat strain model agreed closely with the actual mean data responses. As a result, we felt confident in using the USARIEM heat strain model to predict the thermal strain associated with wearing the firefighting protective clothing in other sets of environmental conditions.

The slide rule, as shown below in Figure 29 and 30, was developed with 3 sets of tables that predict the continuous work times associated with an increase in $T_{re}$ to 38.0ºC, 38.5ºC and 39.0ºC. The latter rise in core temperature is considered by the US Army to be associated with the risk of a 5% incidence of heat casualties and it is the core temperature that is used by the Canadian Director of Nuclear, Biological and Chemical (NBC) Defence to predict work times in NBC protective clothing. This set of prediction tables for the Toronto Fire Service was defined as their "maximal operational limit". A set of predictions for a rise in $T_{re}$ to 38.0ºC was also included since provincial ministerial guidelines have adopted the American Conference of Government Industrial Hygenists (ACGIH) recommendations for the management of heat stress in the workplace. However, it is uncertain at this time whether the Toronto Fire Service would be governed by these ministerial guidelines under conditions of emergency rescue and response. Nevertheless, we have defined this set of prediction tables as "no risk of heat illness". A third set of prediction tables have been developed for a $T_{re}$ increase to 38.5ºC. This set of predictions have been defined as "normal operations, low risk of heat stress" and give the Toronto Fire Service greater flexibility than the restrictions imposed by ministerial guidelines for planning emergency response operations.

## COMMANDERS GUIDE FOR CONTINUOUS WORK TIMES FOR FIREFIGHTERS

**Work Intensity**

Very Light = **VL**
Light = **L**
Moderate = **M**
Heavy = **H**

**Humidity**

Dry (? 20%)
Moderate (21-40%)
Humid (40-64%)
Very Humid (? 65% )

**Heat Stress** — **Green/Yellow/Red** — **Yellow = Normal Operations**

**Humidity** — **(D, M, Hu, VHu)**

| Temp (°C) | VL | L | M | H |
|---|---|---|---|---|
| ?15 | NL | NL | 150 | 120 |
| 16-20 | NL | 180 | 130 | 100 |
| 21-25 | 190 | 150 | 110 | 80 |
| 26-30 | 140 | 110 | 85 | 40 |
| 31-35 | 120 | 100 | 72 | 35 |
| 36-40 | 100 | 80 | 50 | 30 |
| ?41 | 50 | 40 | 30 | 15 |

**NL** = No Limit (5 or more hours ~ 300 min)

*****- Work times do not include direct exposure to the radiant heat of a live fire.

**Instructions for Use**

1. Select desired **work intensity** and **heat stress colour** (see inside of insert for definition).
2. Adjust slide rule until appropriate combination of **humidity, heat stress colour and work intensity** appear.
3. For specific temperature range **continuous** work times are provided that include **ten minute rest periods** for rehydration and change of air cylinders.
4. Upon obtaining a **continuous limit** refer to **rehab guidelines** on back.

**Examples of work intensity for Emergency and Training Operations (include but are not limited to)**

**Heavy** – Victim carry, advancing with charged hose line, roof ventilation and stair climb with equipment.
**Moderate** – Primary search, overhaul, aerial and ground ladder set-up and vehicle extrication.
**Light** – Pump operations, light sweeping.
**Very Light** – Incident command staff.

This Project was funded by a research grant provided by the Workplace Safety and Insurance Board (Ontario) 

DEFENCE DÉFENSE DRDC Toronto

## GUIDE FOR FLUID REPLACEMENT, REHABILITATION AND PERSONNEL MANAGEMENT

**Signs and Symptoms of Heat Illness**

**Heat Exhaustion-**Excessive fluid loss leading to fatigue, weakness, pale clammy skin, circulatory collapse, low blood pressure, nausea, headache, dizziness and possible fainting. Refer to EMS for assessment.

Treatment-**Stop activity, lie individual down, remove clothing, replenish fluids and provide active cooling.**

**Heat Stroke-**Body temp in excess of 40°C, disorientation and unconsciousness.

Treatment-**Remove clothing and cool body immediately by immersing in water, wrapping in wet cool clothing or wetting skin with cool water. Refer to EMS for evacuation to medical facility, while continuing to cool during transfer.**

**Fluid Replacement (for an 80 kg individual) – note -**values will be proportionally higher or lower depending on individual body mass
Prior to donning PPE (if possible) and during every cylinder change, consume a minimum:

200 mL (7 ounces) of water for ambient temperatures of 25°C or below
300 mL (10 ounces) of water for ambient temperatures of 25°C to 30°C
400 mL (13 ounces) of water for ambient tempeatures of 30°C and above

Regardless of environmental condition, 500 mL (16 ounces) of water should be consumed during the final rehabilitation period.

**Rehabilitation Strategy – Forearm Submersion (water temp~10°C-20°C)**
Remove SCBA cylinder, helmet/hood, facepiece, gloves and jacket and open pants.
Submerge forearms in cool water with hands open and fingers extended for 20 min.
During submersion, fluids should be administered in order to maximize the duration of hand submersion and cooling capacity.

**Personnel Management -** Following the first rehab session, personnel returning to work need an additional cooling session following each subsequent cylinder of air.
Before returning to Heavy or Moderate work an intervening assignment of light work and cooling should be completed.
Continuous rotation of personnel between lighter and heavier work is strongly recommended.

***Figure 29.*** *Sliderule produced. The Yellow rectangle represent the windows, where the insert will move showing tolerance times for the desired heat stress and humidity levels.*

**Green - No risk of heat illness**
**(time for core temperature to increase to 38.0°C)**

| Green | | | | Green | | | | Green | | | | Green | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dry | | | | Moderate | | | | Humid | | | | Very Humid | | | |
| VL | L | M | H | VL | L | M | H | VL | L | M | H | VL | L | M | H |
| 107 | 69 | 52 | 39 | 104 | 68 | 51 | 38 | 101 | 67 | 50 | 37 | 98 | 63 | 50 | 37 |
| 90 | 62 | 48 | 36 | 86 | 60 | 47 | 35 | 83 | 59 | 46 | 35 | 81 | 67 | 45 | 34 |
| 77 | 56 | 44 | 34 | 74 | 54 | 43 | 33 | 71 | 52 | 42 | 32 | 67 | 51 | 41 | 31 |
| 67 | 51 | 41 | 32 | 63 | 49 | 40 | 30 | 60 | 47 | 39 | 29 | 58 | 45 | 37 | 28 |
| 60 | 46 | 38 | 29 | 55 | 44 | 37 | 28 | 51 | 42 | 35 | 26 | 48 | 40 | 33 | 25 |
| 52 | 42 | 35 | 27 | 48 | 39 | 33 | 25 | 45 | 37 | 31 | 22 | 42 | 35 | 29 | 20 |
| 46 | 38 | 32 | 24 | 43 | 35 | 30 | 21 | 39 | 33 | 27 | 18 | 36 | 30 | 24 | 15 |

**Yellow – Normal Operations, Low risk of heat illness**
**(time for core temperature to increase to 38.5°C)**

| Yellow | | | | Yellow | | | | Yellow | | | | Yellow | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dry | | | | Moderate | | | | Humid | | | | Very Humid | | | |
| VL | L | M | H | VL | L | M | H | VL | L | M | H | VL | L | M | H |
| NL | 134 | 85 | 58 | NL | 130 | 83 | 56 | NL | 125 | 82 | 56 | NL | 117 | 80 | 56 |
| NL | 110 | 75 | 53 | 234 | 106 | 75 | 52 | 204 | 101 | 73 | 51 | 186 | 98 | 71 | 50 |
| 161 | 93 | 69 | 50 | 144 | 87 | 66 | 48 | 133 | 84 | 64 | 47 | 122 | 81 | 62 | 46 |
| 120 | 80 | 62 | 46 | 109 | 76 | 60 | 44 | 100 | 71 | 57 | 42 | 92 | 68 | 54 | 40 |
| 97 | 70 | 56 | 42 | 87 | 65 | 53 | 40 | 80 | 61 | 50 | 37 | 72 | 57 | 48 | 35 |
| 80 | 62 | 51 | 38 | 72 | 57 | 49 | 35 | 65 | 53 | 44 | 31 | 60 | 49 | 41 | 27 |
| 69 | 55 | 46 | 33 | 61 | 50 | 42 | 28 | 55 | 45 | 38 | 24 | 50 | 41 | 33 | 20 |

**Red- Maximum operational limit**
**(time for core temperature to increase to 39.0°C)**

| Red | | | | Red | | | | Red | | | | Red | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dry | | | | Moderate | | | | Humid | | | | Very Humid | | | |
| VL | L | M | H | VL | L | M | H | VL | L | M | H | VL | L | M | H |
| NL | NL | 141 | 82 | NL | NL | 139 | 81 | NL | NL | 134 | 79 | NL | 255 | 130 | 78 |
| NL | 233 | 117 | 75 | NL | 205 | 113 | 73 | NL | 196 | 110 | 71 | NL | 173 | 106 | 69 |
| NL | 162 | 102 | 68 | NL | 144 | 97 | 66 | NL | 136 | 93 | 64 | NL | 126 | 88 | 62 |
| NL | 125 | 88 | 62 | 233 | 113 | 83 | 59 | 183 | 106 | 81 | 56 | 155 | 98 | 75 | 53 |
| 169 | 103 | 78 | 56 | 141 | 93 | 73 | 52 | 121 | 85 | 68 | 49 | 107 | 79 | 64 | 45 |
| 125 | 86 | 69 | 50 | 105 | 78 | 64 | 45 | 92 | 71 | 58 | 40 | 82 | 65 | 53 | 35 |
| 98 | 75 | 61 | 43 | 84 | 67 | 55 | 36 | 74 | 59 | 49 | 30 | 65 | 53 | 42 | 25 |

***Figure 30.*** *Slide rule insert containing predicted tolerance times for firefighters wearing protective clothing and SCBA at various ambient temperatures and humidities. Heat stress is labelled in three colours (green, yellow, and red) representing no risk ($T_{re}$ –38.0°C), normal operations ($T_{re}$ –38.5°C) and maximum operational limit ($T_{re}$ – 39.0°C), respectively.*

# Recommendations

## A. Physical Work Limits

When working with protective clothing in an occupational setting, a major issue of contention is the length of time that an individual can work before sucumbing to heat exhaustion. In fact, the main goal should be to set work limits in such a way that the individual approaches but never reaches this state.

In cooler ambient conditions, implementing work and rest cycles could increase total work time while slowing the rise in $T_{re}$ [25]. Furthermore, if operational requirements permit Commanders to rotate duties, this may be another effective method to reduce the average workrate and thereby extend work time.

However, at higher ambient temperatures passive recovery is not recommended as a means to reduce $T_{re}$ below pre-recovery levels. Furthermore, during passive recovery in hot environments, HR **should not** be used as an indicator for the extent of heat strain being experienced by the firefighter.

At higher environmental temperatures, other strategies must be incorporated into the rehabilitation period in order to reduce the cardiovascular and thermal strain.

## B. Pants versus Shorts

Replacing the duty uniform pants that are worn under the bunker pants with shorts will reduce the cardiovascular and thermal strain during exercise that lasts in excess of 60 minutes. Together with the previous work conducted in support of the New York City Fire Department[24, 25] we recommend the implementation of this practice for the Toronto Fire Service and other fire departments considering this option.

## C. Active Cooling

**Rehabilitation strategy**

Not only did forearm submersion extend TT and WT's by 60% compared to passive cooling and 30% compared to the mister trials, but there was also a significant reduction in the thermal strain associated with ta given workload at a specific period of time. The implications of these finding are that even if the cooling is not used to extend total work time, cooling will significantly reduce the heat strain associated with any given task. Ultimately, this would help to reduce the occurrence of heat-related injury and possibly myocardial infarction in active firefighters.

**Forearm Submersion Procedure**

Firefighters should remove their SCBA cylinder, helmet/hood, facepiece, gloves and jacket and open their pants. They then should

submerge their forearms in cool water with their hands open and fingers extended for 20 min.
During submersion, fluids should be administered in order to maximize the duration of hand submersion and cooling capacity.
Extending the length of a rest period beyond 20 min may not achieve a substantial benefit for body cooling, due to plateaus in cooling after 25-30 min [41].

## D. Hydration Strategies

Fluid replacement recommendations for a 90 kg individual (mean=87.8kg) based on 70% fluid replacenment are given below. Note that values will be proportionally higher or lower depending on individual body mass.

Prior to donning PPE (if possible) and during **every cylinder change**, consume a minimum of,

200 mL (7 ounces) of water for ambient temperatures of 25°C or below,
300 mL (10 ounces) of water for ambient temperatures of 25°C to 30°C,
400 mL (13 ounces) of water for ambient tempeatures of 30°C and above,

Regardless of environmental condition, 500 mL (16 ounces) of water should be consumed during the final rehabilitation period.

## E. Personnel Management (Slide Rule)

Following the first rehab session, personnel returning to work need an additional cooling session following each subsequent cylinder of air.
Before returning to Heavy or Moderate work an intervening assignment of light work and cooling should be completed.
Continuous rotation of personnel between lighter and heavier work is strongly recommended.

**Please refer to the slide rule for further information on safe predicted limits at various combinations of environmental temperatures and relative humidities.**

# Dissemination of Knowledge

## Conference Attendance/ Abstract Presentation

### CSEP annual conference, October 19, 2002, St. Johns, Newfoundland.

Physical Work Limits for Toronto Firefighters in Warm Environments
Glen A. Selkirk and Tom M. McLellan. DRDC Toronto, Ontario.

This study describes the relationship of exercise time (ET) and metabolic rate for 3 environmental temperatures (25°C, 30°C and 35°C) and 50% R.H. while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA). Firefighters (33 male and 4 female) were matched and divided into 4 groups defined as Heavy, (H, n=9), Moderate, (M, n=9), Light, (L, n=10), and Very Light, (VL, n=9). Subjects walked on a treadmill until core temperature reached 39°C, heart rate reached 95% of maximum or until exhaustion. ET (min) increased from 41 to 47 to 56 for H, 54 to 65 to 92 for M, 67 to 77 to 134 for L, and 87 to 121 to 196 for VL, for 35°C, 30°C, and 25°C, respectively. M, L, and VL had significant increases in ET when comparing 25°C to 30°C, whereas only VL had a significant increase when 30°C and 35°C were compared. The % change in ET was significantly greater for L (74%) and VL (65%) compared to H (20%) and M (39%) for 30°C vs. 25°C. For 35°C vs. 30°C there were no differences in % change between the groups (~23%). Thus, for low metabolic rates, the 0.5 kPa change in vapour pressure from 30°C to 25°C had a greater relative impact on ET compared to the 0.7 kPa change in vapour pressure from 30°C to 35°C. These findings show the differential impact of environmental conditions at various metabolic rates on ET while wearing FPC and SCBA.

Research was funded by WSIB for the Toronto Fire Services.

### American College of Sports Medicine, Annual Conference, May 29, 2003, San Francisco, California

THE EFFECT OF REPLACING PANTS WITH SHORTS ON THE HEAT STRESS OF WEARING FIREFIGHTING PROTECTIVE CLOTHING

T.M. McLellan and G.A. Selkirk, Defence R&D Canada, Toronto, Canada (Sponsor: I. Jacobs, FACSM)
Firefighting protective clothing reduces heat transfer from the body and therefore heat stress is increased during exercise compared with the wearing of the station uniform. One option under consideration by several Fire Services to reduce this heat stress is to remove the station uniform pants (P) worn under the protective bunker clothing and replace them with shorts (S). **PURPOSE:** It was the purpose of this study to examine whether replacing P with S would indeed reduce the heat stress during exercise in warm environments. **METHODS:** Twenty-four Toronto Firefighters were allocated to one of four groups that performed heavy (H, 4.8 km/h, 5% grade), moderate (M, 4.5 km/h, 2.5% grade), light (L, 4.5 km/h) or very light (VL, 2.5 km/h) exercise while wearing their full protective ensemble and self-contained breathing apparatus. Subjects performed a familiarization trial followed by an experimental trial at 35ºC and 50% relative humidity. **RESULTS:** Replacing P with S had no impact on the rectal temperature ($T_{re}$) or heart rate response during heavy or moderate exercise where tolerance times were less than 1 hour (40.8 ± 5.8 and 53.5 ± 9.2 min for H and M, respectively while wearing P, and 43.5 ± 5.3 and 54.2 ± 8.4 min, respectively while wearing S). In contrast, as tolerance times were extended during lighter exercise $T_{re}$ was reduced by as much as 0.4ºC after 80 min of exercise while wearing S. Tolerance times were

significantly increased from 65.8 ± 9.6 and 83.5 ± 11.6 min during L and VL, respectively while wearing P to 73.3 ± 8.4 and 97.0 ± 12.5 min, respectively while wearing S. **CONCLUSIONS:** It was concluded that replacing P with S under the firefighting protective bunker clothing would reduce the heat stress associated with wearing the protective ensemble and extend exposure times approximately 10-15% during light exercise. However, during heavier exercise where exposure times were less than 1 hour replacing P with S was of little benefit.

Supported by the Province of Ontario Workplace Safety Insurance Board.

A COMPARISON BETWEEN A PHYSIOLOGICAL AND PERCEPTUAL STRAIN INDEX FOR INDICATING HEAT STRESS OF FIREFIGHTERS

G.A. Selkirk and T.M. McLellan, Defence R&D Canada, Toronto, Canada (Sponsor: I. Jacobs, FACSM)

Recent findings have shown that a perceptual strain index (PeSI) using measures of thermal comfort (TC) and ratings of perceived exertion (RPE) was similar to the physiological strain index (PhSI) calculated from measures of rectal temperature ($T_{re}$) and heart rate (HR) during exercise in the heat (Tikuisis et al. MSSE 34: 1454-1461, 2002). **PURPOSE:** It was the purpose of this study to examine whether PeSI was similar to PhSI for firefighters wearing protective clothing in warm environments. **METHODS:** Thirty-seven Toronto Firefighters were allocated to one of four groups that performed heavy (H, 4.8 km/h, 5% grade), moderate (M, 4.5 km/h, 2.5% grade), light (L, 4.5 km/h) or very light (VL, 2.5 km/h) exercise while wearing their full protective ensemble and self-contained breathing apparatus. Subjects performed a familiarization trial followed by experimental trials at 25ºC, 30ºC and 35ºC with 50% relative humidity. Measures of TC, RPE, $T_{re}$ and HR were recorded after 20 min of exercise and every 30 min thereafter until exhaustion. **RESULTS:** After 20 min of exercise PeSI (2.15 ± 0.81) was significantly lower than PhSI (3.05 ± 0.60) regardless of the environmental conditions or metabolic rate. As the duration of exercise increased to 50 min with light exercise the underestimation of PhSI with PeSI was maintained. At exhaustion, PeSI (6.18 ± 1.32) was significantly lower than PhSI (6.89 ± 0.60) but this difference was evident only at 25ºC (5.78 ± 1.62 and 6.80 ± 0.77 for PeSI and PhSI, respectively) and 30ºC (5.94 ± 1.59 and 6.96 ± 0.72 for PeSI and PhSI, respectively). At 35ºC there was no difference between PeSI (6.80 ± 1.52) and PhSI (6.91± 0.67). **CONCLUSIONS:** It was concluded that PeSI underestimates PhSI for these firefighters working at various intensities and environmental conditions but the underestimation was less prevalent in the warmest climate.

Supported by the Province of Ontario Workplace Safety Insurance Board.

## CSEP annual conference, October 3, 2003, Niagara-on-the-Lake, Ontario.

### Active Versus Passive Cooling During Work in Warm Environments Wearing Firefighting Protective Clothing.

G.A. Selkirk[1], T. M. McLellan[1,2], and J. Wong[2]. [1]DRDC Toronto, Ontario. [2]FPEH, Exercise Science, University of Toronto, Toronto, Ontario.

This study examined active versus passive cooling during intermittent work while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA) in the heat (35°C, 50% R.H.). During the heat-stress trials, 15 firefighters walked at 4.5 $km \cdot h^{-1}$ with 0% elevation on an intermittent work (50 min) and rest (30 min) schedule until specific end-pt criteria were attained. One of three cooling strategies, forearm submersion (FS), mister (M), and passive cooling (PC) were employed during the rest phases. Tolerance time (TT) and total work time (WT) (min) were significantly increased during FS (178.7 ± 13.0 and 124.7 ± 7.94, respectively) and M (139.1 ± 8.28 and 95.1 ± 4.96, respectively) compared with PC (108.0 ± 3.59 and 78.0 ± 3.59). In addition, TT and WT were significantly greater in FS compared to M. During the first rest phase, $T_{re}$ dropped significantly lower

during FS (~0.4°C) compared to M (~0.08°C) while PC increased (~0.2°C). By the end of the second rest period $T_{re}$ was 0.9°C lower in FS compared to M. The current findings show a definite advantage when utilizing forearm submersion compared to other methods of active or passive cooling while wearing FPC and SCBA in the heat.

Research was funded by WSIB for the Toronto Fire Services.

### Fluid Replacement Strategies For Firefighters During Work in Warm Environments While Wearing Firefighting Protective Clothing.

G.A. Selkirk[1], T.M. McLellan[1,2] and J. Wong[2]. [1]DRDC Toronto, Ontario. [2]FPEH, Exercise Science, University of Toronto, Toronto, Ontario.

This study examined different fluid replacement quantities during intermittent work while wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA) in the heat (35°C, 50% R.H.). Twelve male Toronto firefighters participated in the heat-stress trials. Subjects walked at 4.5 $km \cdot h^{-1}$ with 0% elevation on an intermittent work (50 min) and rest (30 min) schedule. Work continued until rectal temperature ($T_{re}$) reached 39.5°C, or heart rate (HR) reached 95% of maximum or exhaustion. During the heat-stress trials subjects received one of four fluid replacement quantities, full hydration (F), two-thirds ($2/3^{rd}$), one-third ($1/3^{rd}$), and/or no hydration (NH). Tolerance time (TT) and total work time (WT) (min) were significantly decreased during NH (95.3 ± 3.8 and 65.3 ± 3.8, respectively) and $1/3^{rd}$ (104.2 ± 5.8 and 74.2 ± 5.8, respectively) compared with $2/3^{rd}$ (112.9 ± 5.2 and 82.9 ± 5.2, respectively) and F (111.8 ± 3.5 and 82.6 ± 3.5, respectively). Furthermore, TT and WT were significantly greater in $1/3^{rd}$ compared to NH. The current findings suggest that there is a definite advantage when incorporating even partial fluid replacement strategies while wearing FPC and SCBA in the heat.

Research was funded by WSIB for the Toronto Fire Services.

## Journal Publications/ Submissions

Article 1:

**Physical Work Limits for Toronto Firefighters in Warm Environments.**

**G.A. Selkirk and T.M. McLellan**

Operational Medicine Section- Defence R&D Canada – Toronto, 1133 Sheppard Avenue West., P.O. Box 2000, Toronto, Ontario, Canada, M3M 3B9.

**Accepted - American Industrial Hygiene Assosiation Journal**

Article 2:

**Heat stress while wearing pants or shorts under firefighting protective clothing**

T.M. McLellan and G.A. Selkirk

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**Accepted - Ergonomics**

Article 3:

**Active Versus Passive Cooling During Work in Warm Environments While Wearing Firefighting Protective Clothing.**

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**Submitted - American Industrial Hygiene Association Journal**

Article 4:

**Fluid Replacement Strategies For Firefighters During Work in Warm Environments While Wearing Firefighting Protective Clothing.**

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**to be submitted - American Industrial Hygiene Assosiation Journal**

## Presentations

Heat stress of wearing firefighting protective clothing: defining the problem and creating solutions. Presented to Toronto Fire Service Chief and Deputy Chiefs, February 2003.

Heat stress of wearing firefighting protective clothing: defining the problem and creating solutions. Presented to the Workplace Safety Insurance Board of Ontario, February 2003.

Approaches for firefighter rehabilitation. Invited plenary speaker at the Eighteen Biennial Symposium on the Occupational Health and Hazards of the Fire Service. This symposium was hosted by the International Association of Fire Fighters and the John P. Redmond foundation. San Francisco, October, 2003.

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# List of symbols/abbreviations/acronyms/initialisms

| | |
|---|---|
| 1/3rd | One third hydration |
| 2/3rd | Two thirds hydration |
| $\dot{V}O_2$ | Rate of oxygen consumption |
| $\dot{V}CO_2$ | Rate of carbon dioxide production |
| $\dot{V}O_{2peak}$ | Peak rate of oxygen consumption |
| $O_2$ | Oxygen |
| $CO_2$ | Carbon dioxide |
| $\dot{V}_E$ | Expired minute ventilation |
| $\overline{T}_{sk}$ | Mean skin temperature |
| $\overline{T}_B$ | Mean body temperature |
| $\Delta T_{re}$ | Change in rectal temperature |
| $\Delta$ S | Change in body heat storage |
| $A_D$ | Surface area |
| $A_D$:mass | Surface area-to-mass ratio |
| ANOVA | Analysis of Variance |
| Avg $\dot{V}O_2$ | Average oxygen consumption |
| BF | Body fatness |
| BMI | Body mass index |
| BM | Body mass |
| DRDC | Defence, Research and Development Canada |

| | |
|---|---|
| ECG | Electrocardiograph |
| $E_{max}$ | Maximum evaporative cooling capacity |
| $E_{req}$ | Required evaporative cooling |
| ET | Exercise time |
| $ET_{25}$ | Exercise time prediction for 25°C |
| $ET_{30}$ | Exercise time prediction for 30°C |
| $ET_{35}$ | Exercise time prediction for 35°C |
| $ET_{35,\ 38.5}$ | Exercise time prediction for rectal temperature of 38.5°C at 35°C |
| $ET_{38.5}$ | Exercise time prediction for rectal temperature of 38.5°C |
| $ET_{38.5\text{-}1SD}$ | Exercise time prediction for rectal temperature of 38.5°C minus 1 standard deviation in amplitude |
| $ET_{38.5\text{-}2SD}$ | Exercise time prediction for rectal temperature of 38.5°C minus 2 standard deviations in amplitude |
| F | Full hydration |
| FS | Forearm Submersion |
| FPC | Firefighting protective clothing |
| H | Heavy |
| $H_2O$ | Water |
| HR | Heart rate |
| $HR_{peak}$ | Highest observed heart rate during exercise |
| $i_m$ | Woodcock water vapour permeability coefficient |
| L | Light |
| MAP | Mean arterial pressure |
| M | Mister |
| M | Moderate |

| | |
|---|---|
| NFPA | National Fire Protection Association |
| NH | No hydration |
| NBC | Nuclear, biological and chemical |
| P | Pants |
| PC | Passive Cooling |
| PFT | Pulmonary Function Test |
| Q | Amount of heat transferred |
| R.H. | Relative humidity |
| RER | Respiratiory exchange ratio |
| RPE | Rating of perceived exertion |
| RTC | Rating of thermal comfort |
| SBC | Simulated bottle change |
| SCBA | Self-contained breathing apparatus |
| S | Shorts |
| SR | Sweat Rate |
| $T_{re}$ | Rectal temperature |
| $T_{re\ final}$ | Final rectal temperature |
| $T_{re\ initial}$ | Initial rectal temperature |
| UHS | Uncompensable heat-stress |
| UWW | Under water weighing |
| VL | Very Light |
| WSIB | Workplace Safety Insurance Board |

# Appendices

## Appendix A – Phase I - Volunteer Consent/ Invasive Consent Forms

**Volunteer Consent Form**

**Protocol Number:** L-294
**Project Title:** Physical Work Limits for Toronto Firefighters in Warm Environments
**Principal Investigator:** Dr. T.M. McLellan

1. I ________________________ of ____________________________________

(name) (address and phone no.)

hereby volunteer to participate as a test subject in the DCIEM experiment "Physical Work Limits for Toronto Firefighters in Warm Environments" (Protocol L-294). I have had the opportunity to read the information package and have had the opportunity to discuss the attached protocol with the investigator and a physician. All of my questions concerning this study have been fully answered to my satisfaction. However, I may obtain additional information about the research project and have any questions about this study answered by contacting Dr. Tom McLellan at 416-635-2151.

2. I am aware that my maximal aerobic power will be determined on a treadmill by progressively increasing the speed and elevation until I can no longer continue. During this test, my heart rate and expired air will be monitored.

3. I understand that there will be four weekly sessions (a familiarisation session and 3 experimental trials) that will involve wearing my firefighting protective ensemble and self-contained breathing apparatus, and walking on a treadmill at temperatures of 25ºC, 30ºC and 35ºC with 50% relative humidity. The speed and grade of the treadmill will vary from 3 $km \cdot h^{-1}$ with no grade to 5 $km \cdot h^{-1}$ with a 10% grade depending on which of four groups I am allocated to. The walking will continue for a maximum of 4 hours or until a) my rectal temperature (measured with a rectal thermistor) increases to 39.5°C, b) heart rate (measured with a telemetry unit) has increased to 95% of my maximal value and remained there for three minutes, c) adverse symptoms including (but not limited to) dizziness or nausea preclude further exercise, d) I decide to voluntarily end the exposure, or e) the investigator, technician or the physician decides to end the trial. Following this exercise period, I will remain seated in the environmental chamber for a further 30 minutes or until my rectal temperature reaches 40ºC. My respirator, overcoat and breathing apparatus will be removed during this rest period. During these trials, my skin temperature will be measured with heat flow transducers, skin and clothing vapour pressures will be determined with humidity sensors and my ventilation will be collected at different time intervals to measure my metabolic rate. I am aware that prior to each of these 4 sessions, 5 ml of blood will be taken. I understand that over the duration of the study, which will last at least 4 weeks, 20 ml of blood may be drawn. I have been made aware of and understand the discomfort involved with these procedures and the associated risks. I am aware that I must sign a separate invasive medical procedure consent form for this procedure. I understand that I will be asked to drink 500 ml of a cool carbohydrate and electrolyte solution prior to each trial and during the rest period after exercise while I am still in the chamber. I also understand that my rectal temperature will continue being monitored for up to 45 minutes following the experiment and that I agree to drink water and Gatorade® during this recovery period. I agree not to engage in hard physical exercise or to consume alcohol or anti-inflammatories such as aspirin, Tylenol or Advil for 24 hour before or caffeine for 12 h before each test.

4. I have been told that the principal risks of this experiment involve hyperthermia, dizziness and/or dehydration and the complex of symptoms or conditions associated with these physiological states. I understand and accept these risks. I have also been given examples of minor (skin irritation) and remote (heart attack, bowel perforation) risks associated with this study and consider these risks acceptable.

5. I hereby consent to the medical screening assessment outlined in the protocol and agree to provide responses to questions that are to the best of my knowledge truthful and complete. Furthermore, I agree to advise the investigators of any health status changes since my initial assessment (including but not limited to viral illnesses, new prescription or 'over-the-counter' medications, and new risk of pregnancy). I have

**THIS CONSENT FORM CONTINUES ON THE REVERSE SIDE OF THIS PAGE**

been advised that the medical information I reveal and the experimental data concerning me will be treated as confidential and not revealed to anyone other than the investigators without my consent except as data unidentified as to source. In the highly unlikely event that I become incapacitated during my participation, I understand that every necessary medical treatment will be instituted even though I am unable to give my consent at that time. I will go with the Investigator(s) to seek immediate medical attention if either the Investigator(s) or I consider that it is required. Every effort will be made to contact a family member or the designated person indicated below should that be necessary. I am aware that a physician will be on-call in DCIEM during any exposures in the environmental chamber. I am also aware and agree that I must not donate blood within 30 days of any part of this experiment.

6. For female subjects: I have been informed that this experiment could be potentially harmful to a fetus. Therefore, I consent to pregnancy screening by a physician, and should the physician conclude that a blood test to determine my pregnancy status is required, then I consent to the administration of this test. I understand that this result and all discussion pertaining to this matter will be treated as confidential between physician and subject. If I have any concern regarding a possible pregnancy, I will consult a DCIEM physician before undertaking or resuming any phase of the experiment. Furthermore, I will take appropriate precautions to prevent pregnancy for the duration of the entire experiment.

7. I understand that I am free to refuse to participate and may withdraw my consent without prejudice or hard feelings at any time. Should I withdraw my consent, my participation as a subject will cease immediately, unless the Investigator(s) determine that such action would be dangerous or impossible (in which case my participation will cease as soon as it is safe to do so). I also understand that the Investigator(s), their designate, or the physician(s) responsible for the research project may terminate my participation at any time, regardless of my wishes.

8. I have been informed that the research findings resulting from my participation in this research project may be used for commercialization purposes. I understand that for my participation in this research project, I am entitled to a remuneration in the form of a stress allowance in the amount of $33.00 for the $\dot{V}O_{2\,max}$ test and $56.28 for each of the 4 heat exposures for a total amount of $258.12 if I complete the entire research project. I also understand that I am entitled to partial remuneration if I do not complete all of the sessions.

9. I have informed the principal investigator that I am currently a subject in the following DCIEM experiments (include protocol number and principal investigator) ___________________________ and I am participating in the following research studies outside of DCIEM (provide the name of the institution) ___________________________.

Volunteer's Signature: ___________________________________ Date: _____________________

Witness Name: ___________________________ Witness Signature: ______________________

Date ______________

Certified fit to participate in this experiment as outlined in the research protocol with the limitations appended below.

Family Member or Designated Person (Name, Address, Phone number & Relationship)
______________________________________________________________________________

DCIEM Physician's Name: ________________________ Physician's Signature: ________________________

Date: _______________

Principal Investigator: ___________________ Signature: ____________________ Date: ______________

## INVASIVE PROCEDURES CONSENT FORM

**Protocol Number:** L-294
**Project Title:** Physical Work Limits for Toronto Firefighters in Warm Environments
**Principal Investigator:** Dr. T.M. McLellan

1. *Rectal Probe:* A small plastic tube is inserted through the anus into the rectum and is left indwelling for the experiment. Insertion of the probe may result in mild discomfort, but since the Subject inserts the probe themselves, this is minimal. Although there is a possible risk of perforation of the bowel during insertion (perhaps causing severe abdominal inflammation necessitating emergency surgery), the investigator and his associates are unaware of this ever having occurred. Initially, the disinfected probe is given to the subject in a clean package and the subject will reuse their own probe, having sole responsibility for disinfecting the probe using standard techniques **immediatley following a session**. Therefore, although there is a possible risk of transmission of infectious disease (such as HIV or hepatitis), this risk is extremely negligible.

2. *Venipuncture:* A small needle is used to pierce the skin overlying the antecubital (around the elbow area of the forearm) vein. This venipuncture is used to obtain a blood sample prior to exercise as detailed in the information package. Either a physician or a properly qualified and physician-authorised technician performs the venipuncture and blood sampling. The blood sampled in any one experiment will be replaced by the next day. Occasionally, fainting due to nervous reflexes may occur during the procedure. Other complications may include infection of the wound site and leaking of blood into the surrounding tissue (bruising).

I ____________________________ hereby consent to the procedures above. These procedures and their complications have been explained to me to my satisfaction by the Investigator, and I have had the opportunity to ask questions both of the Investigator and of a physician.

Volunteer's Signature: ______________________________________ Date: __________

Witness Name: ________________________________ Signature: ____________________________
Date: ___________

# Appendix B – Phase II - Volunteer Consent/ Invasive Consent Forms

**Volunteer Consent Form**

**Protocol Number:** Revised L-295, Amendment #1
**Project Title:** Influence of Hydration and Active Cooling During Rest on Work Tolerance for Toronto Firefighters
**Principal Investigator:** Dr. T.M. McLellan

1. I ________________________ of ______________________________________________________
(name) (address and phone no.)
hereby volunteer to participate as a test subject in the DRDC Toronto experiment "Influence of Hydration and Active Cooling During Rest on Work Tolerance for Toronto Firefighters" (Revised Protocol L-295, Amendment #1). I have had the opportunity to read the information package and have had the opportunity to discuss the attached protocol with the investigator and a DRDC Toronto physician or Medical Officer. All of my questions concerning this study have been fully answered to my satisfaction. However, I may obtain additional information about the research project and have any questions about this study answered by contacting Dr. Tom McLellan (416) 635-2151 or Glen Selkirk (416) 635-2000 x 3011.

2. I am aware that my maximal aerobic power will be determined on a treadmill by progressively increasing the speed and elevation until I can no longer continue. During this test, my heart rate and expired air will be monitored. My body composition will also be determined using skinfold thickness measurements.

3. I understand that there will be seven weekly sessions (a familiarisation session and 6 experimental trials) that will involve wearing my firefighting protective ensemble and self-contained breathing apparatus, and walking on a treadmill at 4.5 $km \cdot h^{-1}$ and 35ºC with 50% relative humidity. After 20 minutes, I will walk on the treadmill at 2.5 $km \cdot h^{-1}$ for 3 minutes, have 4 minutes of standing rest and then another 3 minutes of walking at 2.5 $km \cdot h^{-1}$ to simulate a bottle change. I will then walk again for 20 minutes at 4.5 $km \cdot h^{-1}$. After this exercise session, I will complete a 20 minute seated rest recovery in the same environment. During this rest period, my respirator, overcoat, SCBA, helmet and flash hood will be removed. This exercise-rest cycle will continue until a) my core temperature (measured with a rectal thermistor) increases to 39.5°C, b) heart rate (measured with a telemetry unit) has increased to 95% of my maximal value and remained there for three minutes, c) adverse symptoms including (but not limited to) dizziness or nausea preclude further exercise, d) I ask to stop, or e) I complete a maximum of 4 cycles. For the familiarisation session, I will be asked to drink $5mL \cdot kg^{-1}$ of bodyweight of water before I enter the chamber and every 30 minutes thereafter. For 4 of the experimental trials, I will receive either no fluid or 1/3, 2/3 or all of the fluid that I lose through sweating during the familiarisation session. Two additional experimental sessions will involve full fluid replacement and either fan-cooling with a mister or forearm immersion during the 20-min recovery period. For all trials, my skin temperature will be measured with thermistors, and skin and clothing vapour pressures will be determined with humidity sensors. My ventilation will be collected at different time intervals to measure my metabolic rate. My blood pressure will also be measured at the end of the 20 minute seated recovery phase. I am aware that prior to each of these 4 sessions, 5 ml of blood will be taken. I understand that over the duration of the study, which will last at least 7 weeks, 35 ml of blood may be drawn. I have been made aware of and understand the discomfort involved with these procedures and the associated risks. I am aware that I must sign a separate invasive medical procedure consent form for this procedure. I also understand that my core temperature will continue being monitored for up to 45 minutes following the experiment and that I agree to drink water and

Gatorade® during this recovery period. I agree not to engage in hard physical exercise or to consume alcohol or anti-inflammatories such as aspirin, Tylenol or Advil for 24 hour before or caffeine for 12 h before each test.

4. I have been told that the principal risks of this experiment involve hyperthermia, dizziness and/or dehydration and the complex of symptoms or conditions associated with these physiological states. I understand and accept these risks. I have also been given examples of minor (skin irritation) and remote (heart attack, bowel perforation) risks associated with this study and consider these risks acceptable as well. Also, I acknowledge that my participation in this study, or indeed any research, may involve risks that are currently unforeseen by DRDC Toronto.
For Canadian Forces (CF) members only: I understand that I am considered to be on duty for disciplinary, administrative and Pension Act purposes during my participation in this experiment and I understand that in the unlikely event that my participation in this study results in a medical condition rendering me unfit for service, I may be released from the CF and my military benefits apply. This duty status has no effect on my right to withdraw from the experiment at any time I wish and I understand that no action will be taken against me for exercising this right.

5. I have been advised that the following medical support will apply during the experiment:
A physician will be required to perform the medical screenings before the experimental sessions begin. The presence of a physician in the environmental climatic facility will not be required during the actual experiment. All experiments will be conducted during regular working hours. Dr. McLellan or Glen Selkirk will inform the "covering" physician in advance of the experimental schedule, and will ensure that a physician is in the building before commencing and throughout the duration of these tests.

6. I hereby consent to the medical screening assessment outlined in the protocol and agree to provide responses to questions that are to the best of my knowledge truthful and complete. Furthermore, I agree to advise the investigators of any health status changes since my initial assessment (including but not limited to viral illnesses, new prescription or 'over-the-counter' medications, and new risk of pregnancy). I have been advised that the medical information I reveal and the experimental data concerning me will be treated
as confidential ('Protected B' IAW CF Security Requirements), and not revealed to anyone other than the DRDC Toronto investigators without my consent except as data unidentified as to source. Moreover, should it be required, I agree to allow the experimental data to be reviewed by an internal or external audit committee with the understanding that any summary information resulting from such a review will not identify me personally. I am aware of the requirement to sign a separate consent form for invasive medical procedures. In the highly unlikely event that I become incapacitated during my participation, I understand that every necessary medical treatment will be instituted even though I am unable to give my consent at that time. I will go with the Investigator(s) to seek immediate medical attention if either the Investigator(s) or I consider that it is required. Every effort will be made to contact a family member or the designated person indicated below should that be necessary. I am aware that a physician will be on-call in DRDC Toronto during any exposures in the environmental chamber. I am also aware and agree that I must not donate blood within 30 days of any part of this experiment.

6. For female subjects: I have been informed that this experiment could be potentially harmful to a fetus. Therefore, I consent to pregnancy screening by a physician, and should the physician conclude that a blood test to determine my pregnancy status is required, then I consent to the administration of this test. I understand that this result and all discussion pertaining to this matter will be treated as confidential between physician and subject. If I have any concern regarding a possible pregnancy, I will consult a DRDC Toronto physician before undertaking or resuming any phase of the experiment. Furthermore, I will take appropriate precautions to prevent pregnancy for the duration of the entire experiment.

7. I understand that I am free to refuse to participate and may withdraw my consent without prejudice or hard feelings at any time. Should I withdraw my consent, my participation as a subject will cease

immediately, unless the Investigator(s) determine that such action would be dangerous or impossible (in which case my participation will cease as soon as it is safe to do so). I also understand that the Investigator(s), their designate, or the physician(s) responsible for the research project may terminate my participation at any time, regardless of my wishes.

8. I have been informed that the research findings resulting from my participation in this project may be used for commercialization purposes. I understand that for my participation in this research project, I am entitled to a remuneration in the form of a stress allowance in the amount of $33.00 for the $\dot{V}O_{2\,max}$ test and $56.28 for each of the 7 heat exposures for a total amount of $426.96 if I complete the entire research project. I also understand that I am entitled to partial remuneration if I do not complete all of the sessions.

9. I have informed the principal investigator that I am currently a subject in the following DCIEM experiments (include protocol number and principal investigator) ___________________________ and I am participating in the following research studies at institutions other than DRDC Toronto (provide the name of the institution ___________________________.
I understand that by signing this consent form I have not waived any legal rights I may have as a result of any harm to me occasioned by my participation in this research project beyond all risks I have assumed.

Volunteer's Signature: ___________________________________ Date: _____________________

Witness Name: ___________________________ Witness Signature: ______________________
Date ______________

Certified fit to participate in this experiment as outlined in the research protocol with the limitations appended below.

Family Member or Designated Person (Name, Address, Phone number & Relationship)
_____________________________________________________________________________

DRDC Toronto Physician's Name: ________________________
Physician's Signature: _______________________ Date: _______________

Section Head/ Commanding Officer's Signature (see notes below)_____________________
CO's Unit: ________________________

Principal Investigator: ___________________ Signature: ____________________ Date: ______________

Notes:
For Military personnel on permanent strength of CFEME: Approval in principle by Commanding Officer is given in Memorandum 3700-1 (CO CFEME), 18 Aug 94; however, members must still obtain their Section Head's signature designating approval to participate in this particular research project.
For other military personnel: All other military personnel must obtain their Commanding Oficer's signature designating approval to participate in this research project.

For civilian personnel at DRDC Toronto: Signature of Section Head is required designating that volunteer subject is considered to be at work and that approval has been given to partiipate in this research project.

FOR SUBJECT ENQUIRY IF REQUIRED:
Should I have any questions or concern regarding this project **before, during, or after** participation, I understand that I am encouraged to contact Defence R&D Canada- Toronto (DRDC Toronto), P.O. Box 2000, 1133 Sheppard Avenue, Toronto, Ontario, M3M 3B9. This contact can be made by surface mail at this address or in person, by phone or e-mail, to any oth the DRDC Toronto numbers and addresses listed below:

Principle Investigator or Principal DRDC Toronto Investigator: Dr. Tom McLellan (416)636-2151, Tom.McLellan@drdc-rddc.gc.ca
Chair DRDC Toronto Human Research Ethics Committee (HREC): Dr. Jack Landolt (416) 635-2120, Jack.Landolt@drdc-rddc.gc.ca
DRDC Toronto Medical Advisor: Cdr. Cyd Courchesne (416) 635-2024, Cyd.Courchesne@drdc-rddc.gc.ca

I understand that I will be given a copy of this consent form (and the invasive consent form) so that I may contact any of the above-mentioned individuals at some time in the future should that be required.

## INVASIVE PROCEDURES CONSENT FORM

**Protocol Number:** Revised L-295, Amendment #1
**Project Title:** Influence of Hydration and Active Cooling During Rest on Work Tolerance for Toronto Firefighters
**Principal Investigator:** Dr. T.M. McLellan

1. *Rectal Probe:* The rectal probe contains a sensor within a small plastic tube that is used to measure core temperature. A small plastic tube is inserted through the anus into the rectum and is left indwelling for the experiment. Insertion of the probe may result in mild discomfort, but since the Subject inserts the probe by themselves, this is minimal. Although there is a theoretical risk of perforation of the bowel during insertion (perhaps causing severe abdominal inflammation necessitating emergency surgery), the investigator and his associates are unaware of this ever having occurred. Initially, the disinfected probe is given to the subject in a sterile, unopended package with his/her name on it. The subject then removes the probe from the package and inserts it according to instructions form the Investigator. At the conclusion of each experimental session, the subject has the sole responsibility of removing the probe and disinfecting it **immediately following a session** using standard techniques (including placement of the probe in fresh disinfectant for a minimum of thirty minutes), for reuse in subsequent sessions by the same individual. Although there is a theoretical risk of transmission of infectious disease (such as HIV or hepatitis), this is negligible provided that the subject exercises good laboratory practices in the handling of the used probe, eg., in not misplaing itin another subject's storage slot.

2. *Venipuncture:* A small needle is used to pierce the skin overlying the antecubital (around the elbow area of the forearm) vein. This venipuncture is used to obtain a blood sample prior to exercise as detailed in the information package. Either a physician or a properly qualified and physician-authorised technician performs the venipuncture and blood sampling. The blood sampled in any one experiment will be replaced by the next day. Occasionally, fainting due to nervous reflexes may occur during the procedure. Other complications may include infection of the wound site and leaking of blood into the surrounding tissue (bruising).

SUBJECT'S DECLARATION:

I ____________________________ hereby consent to the procedures above. These procedures and their complications have been explained to me to my satisfaction by the Investigator, and I have had the opportunity to ask questions both of the Investigator and of a physician.

Volunteer's Signature: ____________________________________ Date: __________

Witness Name: ________________________________ Signature: _________________________
Date _____________

Principal Investigator: _____________________________ Signature: _________________________
Date: ____________

I understand that I shall be given a copy of this consent form.