

THERMOREGULATORY RESPONSES OF FIRE  
FIGHTERS TO WORK AND RECOVERY IN HEAT

by

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B.Sc.(Kinesiology), Simon Fraser University, 1990

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

in the School of Kinesiology

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FIGHTERS TO WORK AND RECOVERY IN HEAT.

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## ABSTRACT

The present work considers the physiological responses of a fire fighter to work in a hot humid environment, by discussing work rate, ambient conditions, protective clothing, heart rate, oxygen uptake, and temperature regulation. A fire fighter is subject to severe physiological stress during fire suppression activity, due to the combined effect of dangerous temperature extremes and strenuous work in heavy impermeable clothing.

A preliminary experimental study examined the additional physiological strain which protective clothing and a breathing apparatus produces in a fire fighter. Five professional fire fighters (mean age  $33.2 \pm 5.8$  years) completed two sub-maximal step tests in an environmental chamber at  $40\text{ }^{\circ}\text{C}$  and  $70\%$  relative humidity, while wearing shorts (S) or protective clothing and a breathing apparatus (P). The data showed that protective clothing and a breathing apparatus significantly increase the physiological strain placed on a fire fighter. When wearing protective clothing subjects could not thermoregulate effectively and produced a mean rise in core temperature of  $1.17\text{ }^{\circ}\text{C}$  during exercise and recovery. This rise in core temperature was significantly ( $p \leq 0.05$ ) more than the  $0.05\text{ }^{\circ}\text{C}$  rise which occurred during work and recovery in shorts.

A second study examined whether a more efficient cooling technique, interjected between work periods, can decrease the degree of heat stress during repetitive fire fighting activity. Twelve professional fire fighters (mean age  $31.8 \pm 6.7$  years) completed two work/recovery trials in an environmental chamber at  $40\text{ }^{\circ}\text{C}$  and at  $70\%$  relative humidity. One trial was an optimal recovery (OR) trial and the other was a normal recovery (NR) trial. In both conditions a subject wore full protective clothing and a breathing apparatus during the work. In the OR trial subjects removed their protective coat and sat in front of a fan during both recovery periods. In the NR trial subjects merely unbuckled their coat and were not cooled by a fan during either recovery period. During the OR trial the group mean physiological responses were significantly lower ( $p \leq 0.05$ ). Core temperature increased by  $1.5\text{ }^{\circ}\text{C}$  in the NR trial but only by  $0.8\text{ }^{\circ}\text{C}$  during the OR trial. The results suggest that a more efficient cooling practice has the potential to reduce physiological strain and decrease the chance of heat exhaustion during repetitive fire fighting activity. The results also suggest that while a short exposure to heavy work in a hot environment will not endanger a healthy fire fighter, long term exposure will lead to a dangerous accumulation of heat stress and fatigue irrespective of physical prowess.

## DEDICATION

I would like to dedicate this thesis  
to all of the fire fighters who have  
lost their lives in the line of duty.

## QUOTATION

If you had known when you were younger what you know now, you would have made different mistakes.

Anonymous

## ACKNOWLEDGMENTS

There are a number of people who I would like to thank, who have helped make this thesis possible. I would first like to thank Dr. Eric Banister for his insight, encouragement and support of this project. I would also like to thank Dr. Jim Morrison for his input into the design of this project and his helpful advice. I would also like to acknowledge Dr. Tom Richardson who ensured the safety of the subjects throughout the experiments. I would also like to thank Dr. Mike Walsh who developed the software used in the data collection and also gave some helpful advice in the preparation of the thesis.

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## PREFACE

The author chose the subject matter of this thesis by combining his two areas of interest. As a professional fire fighter with a science background in kinesiology, the author felt that he was in a unique position to combine his two areas of experience. With use of the resources at Simon Fraser University, the author felt that he could perform some scientifically sound experiments which could yield valuable insight into the physiological responses of a fire fighter to work and recovery in heat. Very few studies have tried to determine the thermoregulatory responses of a fire fighter, and it was the authors intention to contribute to this area of research from a practical perspective.

A preliminary study was conducted to determine the effect of protective clothing on the thermoregulatory responses of a fire fighter. An important finding of this study was the large increase in core temperature experienced by a fire fighter during a recovery period. From the results of this preliminary study an extended study was designed. The purpose of the extended study was to gain a better understanding of the amount of physiological stress that protective clothing produces during work and recovery, and investigate the effect of providing better cooling to a fire fighter during a short recovery period. The goal of the extended study was to provide recommendations on how to improve the effectiveness of recovery periods and reduce the environmental stress placed on fire fighters.

## **Chapter 1: REVIEW OF RELATED LITERATURE**

### **Physiological responses of fire fighters working in hot environments: a review**

#### **Introduction**

Fire fighters perform a variety of tasks within a wide range of ambient temperatures. The tasks vary in duration and in the amount of physical effort required to complete them. The thermoregulatory and cardiovascular demands of fire fighting can be extreme due to the high level of physical and environmental stress encountered. The severe physiological stress is caused by the combined effect of environmental heat and the high energy cost of fire fighting work in heavy protective clothing. An additional physiological stress is placed on fire fighters by the impermeable nature of their clothing which prevents the evaporation of sweat and increases their heart rate, oxygen consumption, skin and core temperature. Heavy protective clothing also increases both the work rate and thermoregulatory stress of the fire fighter. Research has shown that a fire fighter reaches a near maximal heart rate, for prolonged periods during heavy work in a hot, polluted environment (Romet and Frim 1987, Sothman *et al.* 1992, White *et al.* 1989). Fire fighters also face considerable psychological stress induced by long periods of inactivity punctuated by highly stressful alarms and stressful situations such as victim rescue or an interior fire attack.

#### **Working in the fire fighters environment**

The physical environment which a fire fighter contends with is one of potentially dangerous temperature extremes which typically range between 38 °C and 66 °C, but may exceed more than 200 °C (Davis and Dotson 1987, Romet and Frim 1987, Venghte 1989). The heat exposure a fire fighter faces during a fire fighting task varies in severity, is often of short duration, and is irregular in intensity. The work rate of a fire fighter is stressful because of the heavy work

they have to perform, wearing heavy, restrictive, impermeable, protective clothing.

Gathering research data on the physiological response to fire fighting in emergency situations is very difficult since most portable measuring devices are not practical in such dangerous situations. The energy cost of performing simulated fire fighting activities has been measured and is classified as heavy work (Romet and Frim 1987). The energy cost of selected fire fighting has been estimated to range between 11.0 to 12.7 kcal·min<sup>-1</sup> (Gavhed and Holmer 1989). The more demanding tasks of fire fighting produce a heart rate in excess of 150 beats·min<sup>-1</sup>, and a rapid increase in core temperature of 1.3 °C (Romet and Frim 1987). A fire fighter's protective clothing (turnout gear) and self contained breathing apparatus (SCBA) weigh up to 30 kg. During fire fighting activity the weight of protective clothing is compounded by a fire fighter carrying an additional load, such as ladders (33 kg), hoses (25 kg), and ventilation equipment (25 kg) (Duncan *et al.* 1979).

Protective clothing and equipment can cause an increase in the energy expenditure of a fire fighter, 20 % or more (Bishop *et al.* 1994, Duncan *et al.* 1979, Faff and Tutak 1989). Davis *et al.* (1982) estimated that the energy cost of moderate work while wearing protective clothing and SCBA is raised 33 % above that required to perform the same work without protective clothing and SCBA. The increase in energy expenditure is mainly attributed to heat stress produced by the humid microclimate generated inside the clothing, and not the weight of the clothing and SCBA (Duncan *et al.* 1979, Faff and Tutak 1989, White *et al.* 1989). The heat stress inside a fire fighter's protective clothing typically causes a reduction in plasma volume of between 8 to 15 %, and a reduction of up to 20% has been reported in a fire fighter during the first 20 minutes of fighting a structure fire (Davis and Dotson 1987). The decrease in plasma volume results in an accelerated fatigue rate and other possible heat related disorders (Davis and Dotson 1987).

Sothman *et al.* (1991) found that a fire fighter self-selects a work intensity which is  $73 \pm 10$  % of their  $\dot{V}O_2\text{max}$  when engaged in

simulated fire fighting activity. Their study also determined that there was an inverse relationship between task execution time and the relative intensity of work selected by the fire fighter (Sothman *et al.* 1991). Thus the fire fighter who works at a lower intensity is able to work longer before reaching a state of fatigue. The relative intensity of work, self-selected by the fire fighter, should be considered as an important physiological determinant of work behaviour.

A major finding in a study by White *et al.* (1989) was the severe heat stress generated when a fire fighter performed work in protective clothing and SCBA, or a chemical suit and SCBA, compared with wearing light work clothing. The study found that a young, trained and healthy firefighter reached a near maximal stress level after 72 minutes in a chemical suit, and after only 25 minutes when wearing protective clothing while performing low intensity work in a neutral environment. During high intensity work, the time to fatigue was approximately 12 minutes with the chemical suit and 3 minutes in full protective clothing.

### **Temperature regulation**

Humans tolerate only a relatively small change in internal or core temperature. The body protects itself against overheating through thermoregulation. The thermostat for thermoregulation is located in the hypothalamus (Clark and Edholm 1985). This coordinating center controls regulatory adjustment in response to feedback from thermal receptors in the skin as well as to a change in the temperature of blood perfusing the hypothalamic region (Alpaugh 1988). The body loses excess heat through conduction, convection, radiation, and evaporation. During heavy exercise, or work in a hot environment, evaporation becomes the body's primary method of dissipating heat (Parsons 1993). In a warm, humid environment, the effectiveness of evaporative heat loss is dramatically reduced. A person then becomes especially susceptible to a dangerous state of dehydration and a spiraling, dangerous, increase in core temperature.

A fire fighter accumulates thermal stress from the radiant heat of a fire, and from metabolic heat production resulting from physical work. The human body is only about 25 % mechanically efficient during work. The remaining 75 % of metabolically generated energy is released as heat (Alpaugh 1988, Pascoe *et al.* 1994a) A fire fighter's heat tolerance is based on the accompanying level of physiological disruption produced by their work in the heat. A high heat tolerance is characterized by a small increase in core temperature and heart rate, and is accompanied by an increased muscle blood flow and a high sweating rate at a given exercise intensity (Gavhed and Holmer 1989). A greater heat tolerance may be achieved by repetitive heat exposure (acclimatization) and may be further increased by physical training (Aoyagi *et al.* 1994, Febbraio *et al.* 1994, Gavhed and Holmer 1989, Nadel *et al.* 1974, Nielsen 1994, Verdaguer-Cordina *et al.* 1995). Several studies have shown that physical training results in a smaller core temperature increase at a given exercise intensity (Aoyagi *et al.* 1994, Febbraio *et al.* 1994, Gavhed and Holmer 1989, Nadel *et al.* 1974).

Heat stress is defined as the aggregate heat load accumulating in the body from environmental and physical work sources. Environmental factors modifying heat stress include air temperature, radiation, convection and conduction (Alpaugh 1988). Various measured heat stress indices are calculated from ambient temperature, radiant heat, and relative humidity and characterize the potential heat threat of an environment to an exercising subject (Alpaugh 1988, Parsons 1993, Verdaguer-Cordina *et al.* 1995). Clothing also affects the amount of heat stress.

Heat strain is defined as the extent of the physiological response required to accommodate heat stress (Alpaugh 1988). The severity of the strain depends on both the extent of heat stress as well as the age, physical fitness level, degree of acclimatization, and hydrated state of the individual (Alpaugh 1988, Parsons 1993). When heat strain becomes excessive the individual feels discomfort and persistent unaccommodated strain will degrade into a heat disorder. The major forms of heat disorder are cramps, heat

exhaustion, and heat stroke. Heat stroke is a serious condition resulting from sweat suppression and a artificially increased body heat content (Alpaugh 1988, Parsons 1993). The symptoms of heat stroke are a hot dry skin, confusion and convulsions. Heat stroke is a medical emergency and is fatal if not treated.

## **Forms of heat transfer**

### **Conduction**

The direct transfer of heat from the body to a liquid or solid is termed conduction. Conduction of heat occurs between 2 surfaces in contact with each other. Only 3% of the body's heat loss at room temperature occurs through conduction (Venghte 1989). The rate depends on the temperature gradient between the skin and a surrounding surface, as well as the conductive property of the surface (Clark and Edholm 1985). The key to heat dissipation by conduction is the development of a thermal gradient between a warm body to a cooler surrounding medium (Verdaguer-Cordina *et al.* 1995).

Heat conduction in any evaluation of a fire fighter's homeostasis is usually underestimated. Conduction is significantly increased if clothing becomes wet or compressed (Venghte 1989). Water provides a conductive bond between separate surfaces increasing heat conduction by displacing insulating air from between and within the layers of clothing. If water is not present compression of clothing layers will bring conducting surfaces closer and increase conduction. A good example of the heat transfer caused by compression of protective gear, is the blistering of a fire fighter's knees from crawling on a hot surface (Venghte 1989).

### **Convection**

Convection is the exchange of heat between a body and any surrounding flowing medium (usually air or water). Convective heat flow depends on the extent of the body surface area exposed to the surrounding medium, the rate of flow of the surrounding medium, and the difference in temperature between the skin surface and the

flowing medium in contact with it (Kerslake 1972, Pascoe *et al.* 1994a). At room temperature 12% of the body's heat loss is through convection (Venghte 1989). If air or water movement is slow, the rate of heat loss due to convection will also be slow .

Heat transfer to or from the body by convection depends on the movement and density of water and air around a fire fighter. Convection affects the transfer of heat to the clothing and the transfer of heat within and between the layers of clothing and the body by venting (Venghte 1989). Any space between the layers of clothing is filled with air, and therefore air convection currents are possible. Research has shown that during activity, body movement increases the circulation of air trapped in clothing and thus increases convective heat transfer (Nielson *et al.* 1985). Consideration of convective airflow within layers of clothing in determining thermal transfer, is one of the most overlooked factors in the design, or selection, of fire fighting protective clothing (Venghte 1989).

### **Radiation**

Thermal radiation is electromagnetic radiant energy emitted by a source, due to the temperature of the source (Pascoe *et al.* 1994a). The body loses and gains heat by radiation to its surroundings by transmitting electromagnetic heat waves through the air. Radiation accounts for 60 % of the body's total heat loss at room temperature while at rest (Venghte 1989). If the environment is warmer than body temperature, more heat will be radiated to the body than from it and vice-versa. Radiation depends directly on the temperature gradient between two surfaces, their distance from each other and the reflectivity of their respective surfaces (Venghte 1989). Thermal radiation is the most significant method of heat transfer in fire fighting. A fire fighter is the potential recipient of a large net heat transfer from the fire.

## **Evaporation**

Heat loss by evaporation occurs when heat is transferred to the environment, as water is vaporized from the respiratory passages and skin surface. At rest and at room temperature 25 % of the body's heat loss is through evaporation (Venghte 1989). However during work or exercise in a high environmental temperature the body relies heavily on evaporative heat loss to prevent overheating (Clark and Edholm 1985, Rowell 1986). When the environment temperature is greater than skin temperature, the body gains heat through conduction and radiation. If the body is unable to lose this heat gain through evaporation the body's temperature may rise dangerously. Skin blood flow is elevated in a hot environment to increase general heat loss from the body surface through sweat evaporation (Kerslake 1972). Skin blood flow increases linearly with core temperature after a certain threshold temperature is reached (Gavhed and Holmer 1989). When sweat reaches the outer surface of the skin it evaporates, abstracting energy from the body, and effectively cooling the body surface. Evaporative heat loss is reduced by a high ambient humidity, lack of air movement and clothing. If the humidity is high, sweat will not evaporate and heat loss will be greatly limited. If there is no air movement around the body, the air becomes saturated with water vapor and the rate of evaporation is lowered. Clothing traps moisture before it evaporates. This increases the temperature of the clothing, which will dissipate heat principally to the micro-environment inside the clothing (Pascoe *et al.* 1994)

Exercise in hot, humid environments poses a great challenge to temperature regulation because a large sweat loss in high humidity contributes little to evaporative cooling. A large sweat loss places an undue demand on the body's fluid reserve and creates a relative state of dehydration (Parsons 1993). If sweating is excessive and fluid is not continually replaced, plasma volume falls and core temperature may rise to a lethal level (Venghte 1989). An acute fluid loss in excess of 4 to 5 % body mass significantly impedes heat dissipation, compromises cardiovascular function and work capacity. If the cooling effect of sweat evaporation is prevented or



overwhelmed, skin temperature rises and pain is experienced as the skin temperature reaches 48 °C (Venghte 1989). Impervious clothing protects the skin from such a thermal load, but renders the skin almost completely ineffective for temperature regulation.

The evaporation of sweat is very effective in reducing the thermal load. Some 640 calories of heat are removed from the body, for each gram of sweat evaporated (Venghte 1989). Evaporative efficiency is the proportion of secreted sweat which actually evaporates (Nunneley 1989). Evaporative cooling during work is determined from the weight loss of a subject, weighed nude before and after work, if no dripping takes place. With heavy exercise, the maximum sweating rate ranges from 1200 to 1800 grams per hour (Venghte 1989). Sweating is not uniform throughout the body surface; 50 % occurs on the trunk, 25 % on the lower limbs, and 25 % on the head and arms (Clark and Edholm 1985). The sweating mechanism can become fatigued, but it usually requires several hours of exposure to high temperature before this problem arises (Venghte 1989). Evaporation of sweat from the skin and respiratory passages is the only way a fire fighter can dissipate body heat when environmental temperature exceeds skin temperature. This loss of heat through evaporation is why a fire fighter can withstand an air temperature in excess of 200 °C for a short period of time. Skoldstrom (1987) found that although at 45 °C a fire fighter in full protective clothing had a high sweat rate, evaporation was low and evaporative heat loss insignificant as sweat was retained in the clothing and not evaporated.

It is very difficult to determine the extent of evaporative cooling during a fire fighting work period. No current method for determining evaporation rate can account for the complex water loss process of a fire fighter working in protective clothing, where secreted sweat may either evaporate at the skin or wick into the clothing where it may evaporate, drip or remain trapped (Nunneley 1989). Only sweat which evaporates at the skin provides effective cooling. Evaporation from clothing provides a reduced cooling effect because the site of the phase change is removed from the skin

(Nunneley 1989). The impermeable barrier of protective clothing, prevents effective evaporation of sweat and produces heat strain in a fire fighter even under moderate ambient conditions.

The evaporative process may be defined by physical equations relating skin wettedness and a permeation efficiency factor for clothing (Pascoe *et al.* 1994a). Heat storage occurs when the required evaporative rate is greater than the maximum evaporative rate. The body usually only produces sufficient sweat to meet the required evaporative rate under normal conditions.

### **Heat storage**

Normal human body core temperature is 37°C, but it may vary by 1.5 °C during a day (Kerlake 1972, Pascoe *et al.* 1994a). In order for the body to maintain a thermal equilibrium, heat generated within the body, and heat transferred into the body from the environment, must be balanced by an outward heat transfer. When heat generation and input is greater than heat output the body's core temperature rises. The variables involved in temperature regulation are represented by the heat balance equation. There are a number of heat balance equations but they all involve the same underlying principles. The basic heat balance equation is:

$$M - W = E + R + C + K + S$$

During heat balance ( $S = 0$ ) thus:

$$M - W - E - R - C - K = 0$$

The body's metabolic rate (M) provides energy that allows the body to do mechanical work (W) and the remainder is released as heat (M - W) (Parsons 1993). Heat transfer may be through evaporation (E), radiation (R), convection (C), or conduction (K). A rate of heat storage (S) is determined by the combined rates of total heat loss and total heat gain. When there is a net heat gain, heat storage will be positive and body core temperature will rise. When there is a net

heat loss, heat storage will be negative and body core temperature will decrease. If the body is in heat balance, core temperature will not change and the rate of heat storage (S) will be zero (Parsons 1993).

To determine the amount of thermal stress experienced by an individual one of several heat stress indices (HSI) may be used (Parsons 1993, Pascoe *et al.* 1994b). The use of such indices is not very applicable when protective clothing is worn (Parsons 1993, Pascoe *et al.* 1994b). The WBGT is a common practical heat stress index which accounts for 4 primary weather variables contributing to climatic heat stress. These weather variables are temperature, radiant energy, wind and humidity (Verdaguer-Cordina *et al.* 1995). The WBGT is a good global index for quantifying thermal stress as a temperature, but it gives no indication of the specific applicable internal and body surface temperatures used in calculating the separate forms of thermal heat transfer and overall heat storage. For example the WBGT does not consider a clothing insulation effect (Parsons 1993). In the case of a fire fighter working inside a burning building, it would be impossible to calculate a WBGT for the wide variation in temperature encountered. For an outside environment WBGT is calculated from:

$$\text{WBGT} = [0.7 \times \text{WBT}] + [0.2 \times \text{TG}] + [0.1 \times \text{DBT}]$$

Where WBT is the natural wet bulb temperature, TG is the internal temperature of a 150mm diameter black globe and DBT is the air or dry bulb temperature (Parsons 1995).

Other heat stress indices are not well correlated with heat strain (body heat storage), but some provide a better evaluation of the immediate environment surrounding the body than does the WBGT (Alpaugh 1988). There have been many different heat stress indices developed in order to establish safe working limits in a variety of situations. Some heat stress indices are based on a calculation involving the heat balance equation while other indices are simply based on a measured temperature, which simulate the

response of the human body (Parsons 1995). There are other heat stress indices which have established equations from the physiological response of subjects (e.g. sweat loss) to various conditions. A commonly used heat stress index is the ISO 7933 (International Organization for Standardization) which uses an analytical method of assessment of hot environments based on a calculation of the required sweat rate index required to maintain heat balance under the current ambient conditions (Parsons 1995).

An attempt has been made to develop a heat stress model which will predict the physiological response to different combinations of work rate, clothing and environmental conditions (Lotens 1995, Morgan *et al.* 1995). The use of such models indicates their validity is limited by their failure to simulate the complex effects of clothing on heat balance (Nunneley 1989). Computer models are particularly limited by their inability to represent such complex interactions as: the rate at which the weight and stiffness of protective clothing increases the metabolic cost of a task; the effect of profuse sweating which wets clothing and alters its heat transfer characteristics; the effect of body movement which alters the air exchange rate through clothing; and the effect of an individual's aerobic fitness and heat acclimation level which affect temperature regulation (Nunneley 1989). The accuracy of computer models seem to be greatly reduced as more complicating variables are introduced into the model. Currently there are no models which may be used to calculate the heat stress encountered during fire fighting activity accurately.

A heat storage calculation, or the calculation of heat stress indices and construction of a heat stress model are not very applicable to a fire fighter working in a hot environment (Parsons 1993, Pascoe *et al.* 1994b). Protective clothing provides a high level of thermal insulation, low or no moisture permeability and poor ventilation. Accompanying the inadequate heat exchange between protective clothing and the environment, there is a decrease in the rate of evaporative heat loss (Pascoe *et al.* 1994b). Since the work of a fire fighter is extremely variable, it is very difficult to calculate an

applicable mean metabolic rate or the quantity of mechanical work performed during different fire fighting tasks. Fire fighters are exposed to a wide range of environmental temperature which cannot be controlled. All of these factors suggest that the best way to determine the heat stress experienced by a fire fighter is through extensive systematic investigation of the individual thermal response to a wide range of fire fighting conditions.

## **Clothing**

### **General**

Heat is transferred through clothing by conduction and evaporation, and is transferred from clothing to the environment by conduction, radiation and evaporation (Pascoe *et al.* 1994a, Holmer 1995). If clothing is not permeable, condensation will occur within the clothing layers. In a hot environment condensation most likely occurs just beneath the outermost, impermeable clothing layer (Pascoe *et al.* 1994a, Holmer 1995). When this occurs a heat build up increases local temperature, which slows down conductive cooling. The microclimate within different layers of protective clothing directly affects heat exchange at the skin surface and thus will directly affect the physiological and psychological response of an individual (Holmer 1995).

The physiological stress caused by strenuous work in protective clothing is a very serious, currently debated issue. Some researchers and fire officials feel that protective clothing should provide less thermal protection in order to improve temperature regulation (Fornell 1992, Stitleburg 1993). Due to other technological advances in areas such as sprinkler systems, fire fighters spend more time performing tasks other than fire fighting, such as in auto extrication, which have little fire risk but a high work stress. Thus there is a growing concern to reduce the thermal protection of fire fighting clothing in order to improve temperature regulation encountered when performing other strenuous operations. Fire fighting fatality statistics support this view. For example in 1993, 7.8 % of all fire fighting deaths in the United States resulted from burns

(Washburn *et al.* 1994). In the same year 50.6 % of fire fighting deaths were attributed to a heart attack, of these 95 % were due to stress or overexertion (Washburn *et al.* 1994). These figures suggest that more lives could be saved by improving the cooling capability of protective clothing even to the extent of decreasing its heat resistance property.

### **Materials**

A fire fighter's protective clothing consists of rubber boots, gloves, helmet, Nomex<sup>®</sup> hood, turnout coat and turnout pants. Protective clothing is designed to provide protection against radiant heat and chemical agents, as well as prevent local burning of the skin. The turnout coat and pants consist of a thermal liner, a moisture barrier, and an outer shell (Fornell 1992). The thermal liner provides insulation from high external heat, and a second line of defense against flame contact (Fornell 1992). Batt liners are the most common insulating material used in thermal liners but are very heavy (Pascoe *et al.* 1994b). New batt liners which enhance vapour transfer between the body and liner are being developed. Such innovation may reduce the weight of the turnout coat and reduce the heat load on a fire fighter (Fornell 1992). The purpose of the moisture barrier is to prevent liquids from passing through the coat. The moisture barrier can be either impermeable (neoprene coating) or permeable (Gore-Tex<sup>®</sup>, Tetratex<sup>®</sup>, Teflon<sup>®</sup> coating) (Fornell 1992, Pascoe *et al.* 1994b, White and Houdous 1988). Impermeable liners will not allow liquid to pass in either direction. Permeable liners will allow evaporated sweat to pass through the barrier to the outside, but will prevent external moisture from passing through to the fire fighter (Fornell 1992). Permeable fabrics, such as Gore-Tex<sup>®</sup>, have pores of sufficient size to allow water vapour molecules to pass through, but not large enough for water droplets to penetrate (White and Houdous 1988). The outer shell provides protection from flame and is often made from Nomex<sup>®</sup> or PBI<sup>®</sup> blended with Kevlar<sup>®</sup> (Pascoe *et al.* 1994b).

## **Standards**

In 1975, legislation was introduced to develop protective clothing for fire fighters which would provide greater protection against burns. This 1975 legislation evolved into the NFPA 1971, *Standard on Protective Clothing for Structural Fire Fighting* (Fornell, 1992). NFPA 1971 specified limits for material flammability and insulation protection. The legislation has since been updated 3 times in 1981, 1986, 1991. In 1987, the NFPA implemented further standards for protective clothing referred to as "NFPA 1500". These standards recommend that a fire fighter wears a "bunker" coat, bunker pants, low boots and a Nomex® hood to protect the head and neck region. The bunker pants and low boot configuration provides greater protection to the legs than the previously used hip boot. The NFPA 1500 standard represents years of work by government agencies and professional fire fighters. The multiple fabric layers of this protective clothing provides excellent thermal protection to the fire fighter, but is bulky, heavy, inflexible and impermeable (Bone *et al.* 1994, Huck 1991, Venghte 1989).

Current standards require that a turnout coat or pant protect the wearer against second degree burns when a heat flux of 84 kW/m<sup>2</sup> (2cal/cm<sup>2</sup>) is applied to the outside surface for a minimum of 17.5 seconds (Kransy *et al.* 1988). Protection against physical and chemical agents unfortunately ensures that protective clothing is highly impermeable to water vapour, and thus significantly and negatively affects temperature regulation in the body (Holmer, 1995). A fire fighter's helmet also reduces heat dissipation, since the head and face accounts for 30 to 40 % of the body's ability to remove heat (Pascoe *et al.* 1994). Thus wearing an impermeable helmet and Nomex® hood will greatly reduce heat dissipation.

## **Ease of Movement**

Protective clothing fabric layers tend to be made of materials that are relatively rough-surfaced, causing frictional force between the layers that contribute to loss of mobility or increased energy expenditure when the wearer moves (Huck, 1991). As a result, a fire

fighter's mobility may be restricted by the very clothing meant to protect him, and may contribute to certain types of injury (Huck, 1991). Protective clothing also increases the metabolic cost of performing a task by adding weight and restricting movement (Nunneley 1989). The binding or hobbling effect of protective clothing can significantly increase the metabolic cost of work (Nunneley 1989). Clothing also adds extra movement required tasks in order to compensate for loss of manual dexterity and a restricted visual field (Nunneley 1989). The added movement increases heat exchange through clothing by ventilating the microclimate with ambient air. The magnitude of pumping depends on the specific body movement as well as clothing design and fit (Nunneley 1989). Research has shown that body position affects the insulative effect of clothing. Neilson *et al.* (1985) found that clothing insulation, maximal in the standing position, was reduced by 8 to 18 % in the seated position and reduced by 30 to 50% during bicycling and walking.

### **Proper Fit**

It is very important to ensure that a fire fighter's protective clothing fits properly. Protective clothing which is too tight decreases convective heat loss and may increase work rate by causing joint restriction. Protective clothing that is too large simply adds extra weight and may also increase work rate and the risk of injury.

### **Permeability**

Heavy protective clothing produces a high relative humidity close to the skin and retards the vaporization of moisture from the skin surface, this significantly inhibits or even prevents completely any evaporative cooling (Bone *et al.* 1994, Huck 1991, Pascoe *et al.* 1994a, Venghte 1989). Ventilation holes, which are frequently inserted in protective clothing, are virtually ineffective for removing hot, moisture laden air produced by the high sweat rate of the fire fighter (Huck 1991). Very little humid air within the clothing can escape, by means of convection, through the small ventilation holes. Also when the exterior air temperature rises above the body



temperature within the clothing, any air exchange will bring in hot air which accelerates the build up of heat inside the protective clothing (Venghte 1989). Recently the World's No. 2 maker of fire fighting clothing was fined \$967,000 US in order to compensate 36 fire fighters who were scalded by moisture that had accumulated inside their clothing.

An interesting study by White and Houdous (1988) compared the physiological effect of performing moderate and high intensity work while wearing fire fighter turnout gear which had either an impermeable neoprene barrier liner, or a permeable Gore-Tex<sup>®</sup> liner. They found a significant, though minimal, difference in skin temperature between the neoprene and Gore-Tex<sup>®</sup> barrier during continuous work in a warm environment. However, they found no significant difference between the two liners in tolerance time, heart rate, sweat rate or the subjective rating of the wearer on the preferred material. White and Houdous (1988) concluded from these results that the physiological benefit normally attributed to vapor permeable material (Gore-Tex<sup>®</sup>) is minimized when a permeable liner is used in conjunction with fire fighter turnout gear during sustained moderate to heavy work in a warm environment.

### **Weight**

The weight of the protective clothing and breathing apparatus increases physical work load of the fire fighter and causes an increase in physiological stress (Duncan *et al.* 1979, Skoldstrom 1987). The weight of a fire fighter's protective clothing and breathing apparatus (up to 30 kg), coupled with the impermeable property of the clothing, produce a high physiological strain in the wearer during a period of intense work in the heat.

A significantly higher heart rate and core temperature is shown when a subject wears full turn-out gear compared with wearing light clothing (Duncan *et al.* 1979, Skolstrom 1987, Smith *et al.* 1995). White *et al.* (1989) found that the most stressful clothing-SCBA ensemble was a full compliment of protective clothing and breathing apparatus. The next most stressful ensemble was a

chemical suit with SCBA, followed by light clothing and SCBA, with the least stressful being light clothing. Several studies have shown that the energy cost of work by fire fighters is greatly increased when they wear protective clothing and a breathing apparatus (Bishop *et al.* 1994, Duncan *et al.* 1979, Faff and Tutak 1989). The increase in energy expenditure is attributed more to the heat stress stemming from clothing material, than from the combined weight of the clothing and SCBA (Duncan *et al.* 1979, Faff and Tutak 1989, White *et al.* 1989). White *et al.* (1989) and Smith *et al.* (1995) found that a subject reported a significantly higher rating of perceived exertion (RPE) when working in protective clothing compared with light clothing.

A study reported in Fire Engineering (Anonymous 1991) found that substituting 6 ounces per square yard (osy) weight fabric for 7.5 osy weight fabric in the protective clothing shell reduced heat stress and provided more flexibility and comfort for the user. Five fire fighters completed 2 bouts of nine relevant fire training tasks in the 2 different weight shells. The protective clothing with the 6 osy fabric improved evaporative cooling by 25 to 30 % and improved subjective comfort and mobility ratings by 40 % compared with the 7.5 osy fabric shell (Anonymous 1991).

### **Underwear**

An area which has received little research attention is the effect of several different types of accompanying clothing which may be worn under protective clothing. Underwear made of a light fabric which wicks away moisture (e.g. polypropylene), improves thermal comfort and decreases heat strain. Bakkevig and Nielsen (1995) concluded that underwear design clearly has an influence on evaporation rate in a multi-layered ensemble during work at high intensity.

## **Heart rate**

### **General**

As a fire fighter works in a hot environment, the circulatory demand of the combined effect of heat stress and muscular work increases their heart rate to a very high level (Gavhed and Holmer 1989, Romet and Frim 1987). Heart rate is elevated during fire fighting activity in order to supply oxygen to the working muscle (Brooks and Fahey 1985). Heart rate is also increased in order to lower mean body temperature by increasing blood flow to the peripheral vasculature (Skoldstrom 1987). After prolonged exposure to heat, dehydration will produce a compensatory rise in heart rate (Saltin and Hermansen 1966).

It has been reported that a near maximal heart rate may be attained during fire fighting activity (Haapaniemi *et al.* 1995, Lusa *et al.* 1993, Romet and Frim 1987, Sothman *et al.* 1992, Whiteet *al.* 1989). The high heart rate is caused by environmental stress, work stress, psychological stress and the high motivation of the fire fighter (Duncan *et al.* 1979, Faff and Tutak 1989). As indicated previously the heart rate of a fire fighter is significantly higher during work in protective clothing compared with light clothing (Davis and Santa Maria 1975, Duncan *et al.* 1979, Skoldstrom 1987, Smith *et al.* 1995). The extent to which work stress, environmental stress and anxiety contribute to the high heart rate has not been established (Duncan *et al.* 1979). However, it has been established that the mental effect on heart rate is depressed at a high exercise intensity (Gavhed and Holmer 1989).

### **Heart Rate and Activity**

Barnard and Duncan (1975) evaluated the heart rate of 35 fire fighters responding to 189 alarms, and found that 15 to 30 seconds after an alarm sounded a mean increase in heart rate of  $47 \text{ b}\cdot\text{min}^{-1}$  (range  $12$  to  $117 \text{ b}\cdot\text{min}^{-1}$ ) occurred. En route to the fire scene, approximately 1 minute after the alarm, the mean heart rate still showed an increase of  $30 \text{ b}\cdot\text{min}^{-1}$  (range  $1$  to  $80 \text{ b}\cdot\text{min}^{-1}$ ) above the recorded resting heart rate. Barnard and Duncan (1975) concluded

that the heart rate response observed indicated that a fire fighter experiences an initially high state of anxiety before reaching a fire. Kuorinka and Korhonen (1981) found that the elevated heart rate after an alarm was due to combined physical and mental stress and a relative proportion cannot be attributed to either. No secondary, anticipatory heart rate increase has been noted during the approach to a fire (Kuorinka and Korhonen 1981).

Romet and Frim (1987) found that a heart rate increase was related to both the stress of the physical environment and the work of various fire fighting activities. They found the most demanding fire fighting task to be a building search and victim rescue, which increased mean heart rate to  $153 \text{ b}\cdot\text{min}^{-1}$  (Romet and Frim 1987). Sothman *et al.* (1992) found that during an actual fire suppression emergency, a fire fighter worked at  $157 \pm 8 \text{ b}\cdot\text{min}^{-1}$  for  $15 \pm 7$  minutes. This was  $88 \pm 6 \%$  of the their previously determined maximum heart rate (Sothman *et al.* 1992). Lusa *et al.* (1993) found that during  $17 \pm 4$  minutes of work in a simulated shipboard fire, 35 subjects had an average heart rate of  $150 \pm 13 \text{ b}\cdot\text{min}^{-1}$ , and a peak heart rate of  $180 \pm 13 \text{ b}\cdot\text{min}^{-1}$ .

Haapaniemi *et al.* (1995) monitored 11 fire fighters during a real fire fighting situation and found that their heart rate ranged from 73 to 98 % of maximum. Five of the 11 fire fighters exceeded 85 % of their maximum heart rate for a period up to 22 minutes (mean = 6.9 min). Maximum heart rate values of 180 to  $190 \text{ b}\cdot\text{min}^{-1}$  are usually expected for young fit individuals. The maximum rate decreases as an individual becomes older so that by the age of 50 a maximum heart rate of 165 to  $170 \text{ b}\cdot\text{min}^{-1}$  is common (Brooks and Fahey 1985).

### **Heart Rate and Clothing**

While the added weight and heat retention qualities of the fire fighter's protective clothing increases the energy demand and heart rate of the individual, a high environmental temperature seems to contribute more to the high heart rate (Duncan *et al.* 1979, Skoldstrom 1987). Skoldstrom (1987) found that, at the same work

rate, a fire fighter's heart rate was  $25 \text{ b}\cdot\text{min}^{-1}$  higher at  $15 \text{ }^{\circ}\text{C}$  when they wore protective equipment than when they wore light clothing. At  $45 \text{ }^{\circ}\text{C}$  the difference was  $73 \text{ b}\cdot\text{min}^{-1}$ . Romet and Frim (1987) also concluded that heart rate increased slightly in response to physical work and was increased further by environmental heat stress. Thus in actual fire fighting situations, the observed high heart rate may be dependent more on environmental temperature than the physical work, or the weight of protective clothing.

A study by Manning and Griggs (1983) found that there was no significant difference in exertion level between subjects wearing protective clothing with either a heavy SCBA, a light SCBA, or no SCBA. They concluded that regardless of the weight of the SCBA, a fire fighter exerted themselves to between 85% and 100% of their maximum heart rate, and adjusted their work output to maintain that near maximal level (Manning and Griggs 1983).

## **Oxygen uptake**

### **Oxygen Demand of Fire Fighting**

Fire fighters show a group mean maximum oxygen uptake ( $\dot{V}\text{O}_2\text{max}$ ) in a range from  $39$  to  $49 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$  (Davis *et al.* 1982, Faff and Tutak 1989). O'Connell *et al.* (1986) concluded that an oxygen uptake value of  $2.7 \text{ l}\cdot\text{min}^{-1}$  and  $39 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$  was the minimum measure needed for a fire fighter to perform a fire suppression task satisfactorily. The most demanding fire fighting operation has been estimated to require a mean oxygen uptake ( $\dot{V}\text{O}_2$ ) value of  $41 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$  (Gledhill and Jamnik 1992, Faff and Tutak 1989). Lemon and Hermiston (1977b) found that even when external stress such as heat and emotion were eliminated, fire fighting consists of heavy physical work which demands 60 to 80% of an individual's maximal oxygen uptake to accomplish. Lusa *et al.* (1993) found that during a simulated shipboard fire subjects worked at an average oxygen consumption of  $2.4 \pm 0.5 \text{ l}\cdot\text{min}^{-1}$  for  $17 \pm 4$  minutes. A maximal aerobic power of at least  $2.8$  to  $3.0 \text{ l}\cdot\text{min}^{-1}$  is considered necessary to guarantee an adequate safety margin for work in such conditions (Kilbom 1980).

### **Effect of Clothing**

Work in protective clothing adds significantly to the oxygen cost of fire fighting (Davis and Santa Maria 1975, Duncan *et al.* 1979, Skoldstrom 1987, Smith *et al.* 1995). Smith *et al.* (1995) reported a slight increase in oxygen consumption during a steady-state walking task when subjects wore full protective clothing. They attributed this gradual increase in oxygen consumption to the progressive heat stress caused by the protective clothing.

### **Oxygen Uptake and Heart Rate**

The accurate assessment of oxygen consumption provides important information in determining the energy expenditure of physically demanding tasks. Measuring heart rate to predict  $\dot{V}O_2$  has been used for a long time in exercise and occupational settings (Astrand and Rodhal 1977, Saltin and Hermansen 1966). This approach is based upon the linear relationship between the increase in oxygen uptake and heart rate, during sub maximal exercise performed on a treadmill or ergometer (Sothman *et al.* 1991).

Several factors alter the relationship between heart rate and oxygen uptake during activity. These include, a hot environment, isometric versus isotonic muscle contraction and upper body versus lower body work (Duncan *et al.* 1979, Sothman *et al.* 1991). Fire fighting is an occupation where all of these factors may be present. Sothman *et al.* (1991) created a fire fighting setting that incorporated heat stress (54 °C), isometric muscle work, and reliance on upper body work while wearing an SCBA. The work confirmed previous studies which found that oxygen uptake was approximately 20 % less than that which would have been predicted from the heart rate obtained from conventional cycle ergometry or treadmill testing (Sothman *et al.* 1991). The above estimates of  $\dot{V}O_2$  are very similar to that observed by Lusa *et al.* (1993) during 17 minutes of work in a simulated ship fire. Lusa *et al.* (1993) found that fire fighters worked at  $79 \pm 6$  % of their maximal heart rate but only  $60 \pm 12$  % of their maximal oxygen consumption. The discontinuity between heart rate and  $\dot{V}O_2$  is unexplained.

An increased ambient temperature seems to have little effect on the oxygen uptake of a fire fighter but will increase heart rate (Duncan *et al.* 1979, Skoldstrom 1987). In a hot environment, the heart rate response is shifted to a higher level relative to the oxygen uptake demand of the task (Gavhed and Holmer 1989). Thus for work in a hot environment it is not valid to conclude that the oxygen uptake accompanying fire fighting work will be similar to that found in other exercise tasks at corresponding heart rates (Duncan *et al.* 1979). The difference is probably due to the enhanced heart rate needed to maintain cardiac output in face of diversion of some of the blood flow to the periphery in order to aid in temperature regulation.

### **Core temperature**

Core temperature normally increases during exercise, and the magnitude of the rise is determined by the relative stress of the work rate (Rowell 1986). This well-regulated temperature adjustment probably creates a favorable environment for physiologic and metabolic function. When environmental temperature is between 4 and 30 °C body core temperature is independent of the air temperature (Clark and Edholm 1985). Under such conditions, core temperature will rise in direct proportion to the relative exercise intensity (Rowell 1986).

Physical work in a hot environment causes the body's core temperature to rise from its normal range between 36 to 38°C (Kerlake 1972). The rise in core temperature causes the skin and peripheral blood vessels to dilate, thus bringing more blood to the cooler tissues near the surface of the body (Venghte 1989). As work rate increases, and if sweating stops or the sweat is not effectively evaporated, the body's core temperature rises to a dangerous level between 39 °C to 40 °C, at which point exhaustion or heat stroke is increasingly encountered (Alpaugh 1988, Parsons 1993, Sawka 1992). Sawka *et al.* (1992) found that heat exhaustion was rarely associated with a core temperature less than 38 °C, but exhaustion always occurred prior to a temperature of 40 °C being reached.

Saltin and Hermansen (1966) determined that for steady state exercise in the heat, rectal temperature ( $T_{re}$ ) is a satisfactory method of measuring core temperature. Lind (1963) determined that rectal temperature is directly related to metabolic rate, below a critical air temperature. When ambient temperature is above this critical temperature,  $T_{re}$  is also dependent on air temperature and may continue to rise to a dangerous level (Duncan *et al.* 1979, Lind 1963). Several authors have concluded that while working in heat, rectal temperature should not rise above 39 °C or heat stroke may occur (Alpaugh 1988, Faff and Tutak 1989, Parsons 1993). Heart rate rises rapidly during work in a hot environment, while rectal temperature shows a delayed response. Duncan *et al.* (1979) showed that the rectal temperature of a fire fighter reaches a high enough level to indicate a very definite thermal stress. Studies have shown when a person wears protective clothing in the heat, there is an after-rise in rectal temperature following the cessation of work, while heart rate declines (Duncan *et al.* 1979, Faff and Tutak 1989, Smith *et al.* 1995, White *et al.* 1991, Webb 1986).

Rectal temperature in a fire fighter increases more when they wear protective clothing than when they wear light clothing (Duncan *et al.* 1979, Skolstrom 1987, Smith *et al.* 1995, White *et al.* 1989). Montain *et al.* (1994) found that subjects who wore full protective clothing had lower physiological tolerance to work in heat, since core temperature at exhaustion was lower in more fully rather than in partially, clothed subjects. Romet and Frim (1987) found that increase in  $T_{re}$  is related to both the physical and environmental stress which occur during fire fighting.

### **Skin temperature**

Skin temperature results from the complex interaction of the external environment, clothing, conduction, convection, evaporation, metabolic work rate and an individual's state of hydration (Clark and Edholm 1985). Skin temperature may vary considerably at different sites on the body according to the presence of clothing and to the difference in air convection over various parts of the body (Parsons



1993). Several studies have shown that skin temperature increases significantly more when a fire fighter wears protective clothing than when they wear light clothing (Duncan *et al.* 1979, Skoldstrom 1987, White *et al.* 1989). If exercise is prolonged in a hot environment, skin temperature tends to rise as sweating slows due to dehydration, and increased convection of heated blood to the skin (Venghte 1989). Sweating usually begins when skin temperature rises above 33 to 35 °C (Venghte 1989).

### **Fire fighter cooling devices**

Recently introduced personal cooling devices seem to reduce heat stress. Both the military and industry have investigated the use of air, ice, freon<sup>®</sup> and liquid cooled suits (Pascoe *et al.* 1994a, Speckman *et al.* 1988, White *et al.* 1991). These suits are expensive to manufacture and have met with mixed success. White *et al.* (1991) found that ice water and freon<sup>®</sup> cooling garments, worn under encapsulating chemical suits, significantly reduced heart rate, skin temperature, core temperature and dehydration. Bennett *et al.* (1995) investigated the effect of a cool vest under fire fighting protective clothing and concluded that the device reduced heat strain during exercise, facilitated recovery and minimized heat strain during subsequent exercise.

Speckman *et al.* (1988) analyzed seven studies which used liquid and air cooled undergarments, and concluded that both types of cooling are effective. An air cooled vest provides a greater increase in cooling efficiency at a lower air flow rate, which improves heat transfer by increasing the transit time of air across the skin. Other studies investigating individual cooling methods have found that torso cooling is more effective than head and neck cooling (Epstein *et al.* 1986). Air cooling is inferior to water cooling because of the low heat capacity of air and mechanical limitations. Cooling the torso by water- or air-cooled vests has a similar effect but is not as effective as an ice bag vest. Cooling the torso with a fan is least effective (Epstein *et al.* 1986).

## **Recovery periods**

A recovery period has been found to be a vital component of safe working practice for a fire fighter. Although there are no regulated industry standards, the current practice of taking a recovery break is based on the subjective feelings of the fire fighter, who takes a break when he thinks he needs one, or a break is timed with the depletion of an SCBA air bottle. Another common practice proposes a recovery period every 20 to 30 minutes. Determination of an appropriate recovery period is difficult, since each fire fighter performs a different task under different conditions. There also may not be the time, or desire, to take a rest break due to the severity of the fire fighting activity.

An important issue which has received very little attention is the physiological consequence of intermittent work compared with continuous work in a hot environment. One of the few studies to compare intermittent with continuous work in the heat was completed by Kraning and Gonzalez (1991). In the study intermittent work consisted of walking, jogging and rest, while continuous work was at a time weighted average of intermittent work. The investigators found that after 60 minutes rectal temperature was 38.5 °C during continuous work and 38.9 °C for intermittent work. They concluded that when heat stress was not compensated, intermittent work induced more physiological strain than continuous work (Kraning and Gonzalez 1991).

White *et al.* (1991) investigated the physiological and subjective response of 9 subjects who walked on a treadmill (23 % of  $\dot{V}O_2\text{max}$ ) while wearing two types of protective ensembles, in 3 different thermal environments. They concluded that even at a low work intensity, an individual wearing protective clothing in the heat needs a progressively shorter work period and a more frequent and longer rest period.

As noted earlier it is very important for a fire fighter to replace water loss during a recovery period. A water loss of more than 2 % of an individual's body weight decreases their work performance. A water loss of 6 to 10 % of body weight produces heat exhaustion and

possibly heat stroke (Windisch 1990). Thus it is imperative that a fire fighter always remains well hydrated and has ample access to a clean water supply during recovery (Windisch 1990, Xander 1987).

Overall the potential danger of performing heavy work in a hot environment requires that a maximal permissible limit be put on the work period before a recovery period is implemented. If recovery time is not practical, then frequent rotation of individuals between stressful and less demanding tasks can reduce heat stress. A recovery period should also account for individual variability in the heat, as the personal fitness level, state of acclimatization, and level of hydration may affect performance. Recovery time, where possible, should be at least equal in duration to working time and should be in a cool environment.

### **Acclimatization**

Repeated exposure to a hot environment will lead to acclimatization and an increased ability to tolerate heat stress (Gavhed and Holmer 1989, Nielsen 1994, Parsons 1993). The cardiovascular system adapts to repeated exercise in the heat by increasing plasma volume which increases stroke volume and cardiac output (Rowell 1986). Prolonged exposure to heat will also enlarge sweat glands and improve their ability to produce sweat (Parsons 1993). An increased blood flow and sweating rate induced by acclimatization produces a slower rise in core temperature (Nielsen 1994). Research indicates that there are individual and group variations in acclimatization. Fit people acclimatize more rapidly to heat stress than the less fit. Acclimation training is essential to a fire fighter if they are to work efficiently in a hot environment. Acclimation is induced by periodic intermittent exposure to an exercise stress lasting from 30 minutes to an hour in a hot environment.

Repeated heat stress induces a thermoregulatory adjustment which results in improved exercise capacity and less discomfort during a subsequent heat exposure (Clark and Edholm 1985, Febbraio *et al.* 1994, Nadel *et al.* 1974). The ability to acclimatize to moderate heat stress does not deteriorate appreciably with age (Faff

and Tutak 1989). Under hot humid conditions an older fire fighter seems to show better adaptation than a younger person to exercise stress (Faff and Tutak 1989). Gavhed and Holmer (1989) found that the volunteer fire fighter is less tolerant to exercise under heat stress than the more trained and acclimatized professional fire fighter. The difference remains even after age, body size and physical work capacity are taken into consideration.

Clark and Edholm (1985) investigated the acclimatization of 18 subjects who spent 4 hours a day for 5 days in a hot environmental room. The sweat rate increased from 0.8 to 1.55 l/m<sup>2</sup> on the first day to range between 1.5 to 3.4 l/m<sup>2</sup> on the fifth day of acclimatization. Subject variability in sweat rate remained the same during the five days, with the lowest sweat producing subject remaining lowest throughout the experiment. Seven days of heat acclimation with training usually increases sweat rate and reduces the rectal temperature and exercise heart rate under the same conditions of heat stress (Febbraio *et al.* 1994). However, when wearing protective clothing while working in the heat, endurance training and heat acclimation is less effective in improving tolerance (Aoyagi *et al.* 1994). When wearing protective clothing, any increased sweat rate induced by training and acclimation will decrease blood volume and increase discomfort without augmenting body cooling (Aoyagi *et al.* 1994). Thus the advantage of heat stress training for a fire fighter remains equivocal.

### **Fitness**

It is clear that a high level of physical fitness is required for a fire fighter to tolerate the physiological demand of working in a hot environment. A high level of fitness will not only allow a fire fighter to complete a required task with less physiological strain but it will also leave a large reserve for a situation which requires extra effort. The metabolic cost of carrying a weight is not constant from one fire fighter to the next. The physiological effect of carrying a fixed load, such as an SCBA, varies with the size and physical conditioning of the individual (Nunneley 1989). A fire fighter should train regularly in a

warm environment in order to improve their physical fitness and ability to tolerate heat. A regular training program will also increase the relative intensity at which a fire fighter selects to work. The high physical demands of some fire fighting activities, suggest that the more physically fit individual would be able to complete the more difficult task better.

Fire fighting demands a high degree of strength in the individual (Davis and Santa Maria 1975, Gledhill and Jamnik 1992, Lemon and Hermiston 1977). Davis *et al.* (1982) found there was a significant relationship between fitness attributes (strength and aerobic fitness) and effectiveness in performing fire fighting tasks. The fit individual tolerates a higher blood lactate concentration, a higher oxygen debt and extracts more oxygen for transport per litre of air ventilated (Davis and Dotson 1987). Therefore the fit individual can work at a higher aerobic intensity and will require less oxygen for a given work rate. An efficient use of air is very important to a fire fighter since many tasks are performed wearing a breathing apparatus which has a limited supply of air.

### **Summary**

A short term exposure to heavy work in a hot environment will not endanger a healthy fire fighter. However long term exposure, as is associated with a large structure fire, may lead to an accumulation of heat stress such that it endangers the fire fighter. Exhaustion in fire fighters is usually caused by the combined effects of heavy work and environmental thermal stress during an extended period of time. Response to heat stress is dependent on a number of individual characteristics, which makes it virtually impossible to predict the heat strain which a fire fighter will experience in a given situation. The ability of a fire fighter to work well in a hot environment is a function of their individual physical working capacity as well as their heat tolerance.

A fire fighter's protective clothing and breathing apparatus adds significantly to their physiological stress during work in a hot environment. Heavy protective clothing significantly inhibits

evaporative cooling by producing high relative humidity close to the skin. The impermeable property of a fire fighter's clothing prevents the evaporation of sweat, and thus increases heart rate, breathing frequency, skin temperature and core temperature. By improving permeability of turnout gear, while retaining its heat protection properties, improved clothing would create less stress in the fire fighter during work, and a longer total working period could be tolerated. The weight of protective clothing and breathing apparatus increases the physical work rate of the fire fighter and adds an additional physiological stress. An important aim should be a reduction in the weight of a fire fighter's clothing and breathing apparatus, which will lower heart rate and core temperature, lower physiological strain and prolong work periods before exhaustion. Protective clothing is essential in order to protect the fire fighter, however, its adverse effect outlined above must be recognized and mitigated. Currently there are only minimal guidelines issued to a fire fighter regarding the effective use of protective clothing and breathing apparatus. Considering the vast number of fire fighters, it is apparent that further research is needed in the design and effect of protective clothing.

During a fire fighting situation the prediction of energy expenditure and oxygen uptake from heart rate is not accurate. In a hot environment the heart rate is higher, than in a cool environment at the same work rate. However oxygen uptake remains similar in both conditions. Therefore the linear relationship between heart rate and oxygen uptake cannot be used to predict energy expenditure in a hot environment.

The amount of physiological heat stress on a fire fighter is mainly dependent on the maximal oxygen uptake and heat tolerance of the individual (Davis *et al.* 1982, Gavhed and Holmer 1989). Thus physical training sessions and simulated fire fighting should be ongoing components of a fire fighter's training in order to increase their tolerance to heat stress and improve their cardiovascular fitness level. A fire fighter must also be able to recognize the signs of heat stress and know when to rest and cool down.

It is evident from this review that more information is needed to understand the complex relationship between a fire fighter, their protective clothing and the environment in which they work. There have been relatively few studies on the physiological response of a fire fighter to work in a hot environment. Existing studies have been conducted using simulated fire fighting tasks or treadmill and cycle ergometer tests in environmentally controlled rooms. These studies have determined the general direction of the physiological effect which occurs while working in the heat, but they have failed to quantify the effect an actual fire fighting situation produces. It is apparent that more studies are required to understand the physiological stress of working in a hot environment, in order to provide recommendations that could reduce the environmental stress placed on a fire fighter. Few studies have attempted to evaluate a firefighter's emotional state during different experimental conditions, and the effect that psychological stress may have on their ability to work in a hot environment.

## **Recommendations**

- Protective clothing imposes increased cardiovascular and thermoregulatory demands on a fire fighter which can lead to a serious injury. Further research is needed to determine if the added thermal protection of modern fire fighter clothing outweighs the added physiological strain produced in the fire fighter on the fire ground.
- The heat stress factor associated with fire fighting helmets should be recognized, and they should be removed during recovery.
- More research is needed in the areas of light permeable clothing, proper clothing fit, underwear composition, personal cooling devices and optimal work/rest periods for fire fighting tasks.
- A fire fighter needs to maintain a high level of muscular strength and aerobic fitness. Increased fitness levels will result in increased performance and fewer injuries.
- Fire fighters need to understand their physiological limitation, and how to adjust their physical effort to their physiological resource.
- A Cooling vest, inside protective clothing, has the potential to reduce the heat stress encountered by a fire fighter.
- Efficient work/rest periods can be used in conjunction with a cooling vest to enable a fire fighter to perform optimally, while wearing protective clothing in a hot humid environment.



## Chapter 2

### **The effect protective clothing has on the thermoregulatory responses of a fire fighter during work in hot humid conditions**

#### **Introduction**

The physiological demands of fire fighting can be extreme due to the high level of physical and environmental stress encountered. The severe physiological stress is caused by the combined effect of environmental heat and the high energy cost of fire fighting work in heavy protective clothing. A fire fighter's protective clothing has been reported to increase energy expenditure significantly during work (Duncan *et al.* 1979, Faff and Tutak 1989). The increase in energy expenditure is mainly attributable to the heat stress generated by the clothing. The impermeable nature of a fire fighter's clothing prevents the evaporation of sweat, and thus increases heart rate, oxygen consumption, skin temperature, and core temperature. The weight of protective clothing and breathing apparatus also increases the physical work load of the fire fighter and causes an additional increase in heart rate, oxygen consumption, and core temperature. Some studies have confirmed that a fire fighter reaches near maximum heart rate (HR), for a prolonged period of time, as heavy work is performed in a hot polluted environment (Romet and Frim 1987, Sothman *et al.* 1992, White *et al.* 1989).

The technological developments in the fire service has been focused on the improvement of protective clothing, rather than reducing the heat stress experienced by the fire fighter. Fire ground death statistics suggest that more research should be focused on reducing the heat stress experienced by fire fighters. In 1993, 7.8 % of all fire fighting deaths in the United States resulted from burns, while 50.6 % of the deaths were attributed to heart attacks (Washburn *et al.* 1994). According to the National Fire Protection Association (NFPA) 95 % of the 1993 fire fighter deaths from heart attack were due to stress or overexertion. These statistics suggest

that more lives could be saved by improving the cooling capability of protective clothing.

Previous laboratory studies have used treadmill running or cycle ergometry to evaluate heat stress in fire fighters. These exercises do not seem to simulate the movement of a fire fighter properly during typical fire fighting tasks. Fire fighters typically climb stairs or ladders, walk, or clamber over obstacles during the execution of fire fighting tasks. Only a single study (O'Connell *et al.* 1986) has simulated the typical climbing fire fighting movement during an assessment of the safety, job relatedness and objectivity of a stair-treadmill ergometer for measuring a fire fighter's fitness.

Since the intent of the present series of studies was to use stepping as the exercise stimulus during work in the heat by a fire fighter, it was important to examine the probable dimension of the physiological response to various stepping intensities. The present study was also designed to compare the response of a fire fighter stepping at different intensities in full protective clothing and breathing apparatus (SCBA) in hot humid conditions, with a criterion light weight clothing and no load ensemble.

### **Hypotheses**

The null hypotheses adopted in a preliminary examination of the physiological response of a fire fighter to work and recovery in heat are:

1. There is not a significant ( $p \leq 0.05$ ) group mean difference in core temperature rise due to incremental stepping work in hot humid conditions between an experimental condition where subjects wore full protective clothing and SCBA, and a control condition where the same subjects wore only shorts and running shoes while completing the same exercise task.
2. There is no difference in the ability of subjects to complete 4 different 3 minute stepping periods, which increase by 5 steps/min from 30 steps/min to 45 steps/min, under the same hot humid conditions as described above, wearing either full protective clothing and SCBA or shorts and running shoes.

## **Methodology**

### **Subjects**

Five professional fire fighters volunteered for the study. They were all healthy, physically active and non-smokers. Physical characteristics of the subjects (mean  $\pm$  SD) were: age  $33.2 \pm 5.8$  yrs, weight  $80.8 \pm 5.9$  kg and height  $178.8 \pm 5.1$  cm. The subjects averaged  $7.0 \pm 5.8$  years of fire fighting experience. The protocol for the experiments received ethical approval from the Ethics Committee at Simon Fraser University. The subjects had a physical examination prior to the experiment to ensure they were capable of completing the tests. Before each experiment a subject read a description of the purpose and potential hazards of the experiment, and signed an informed consent document.

### **Experimental design**

Each subject completed two sub-maximal step tests at least 1/2 hour apart. The first was an incremental 4 stage, 3 minute per stage stepping task with a 30 second rest between each stage. In each stage the step rate was slightly faster than the previous stage and thus required progressively more work from the subject. Following the step test a subject sat down and was monitored during a 10 minute cool down period. During the first step test a subject wore shorts (S) and running shoes. For the second step test a subject wore a full complement of protective clothing (P), including a self contained breathing apparatus (SCBA). In the second step test a subject attempted the same 4 stage, three minute per stage task with a 30 second rest between each stage and a 10 minute recovery period following the exercise. The subject was instructed to stop exercising at any time they felt fatigued or over heated.

### **Task**

The work was performed in an environmental chamber on a two step test box with a 22.9 cm (9") per step. The subject made two 22.9 cm steps up, followed by two steps down, for a two step count. The first stage required a subject to step for 3 minutes at a rate of 30 steps

per minute, the second stage was at 35 steps per minute, the third at 40 steps per minute, and the fourth stage at a rate of 45 steps per minute. There was a 30 second rest period between each stage and a subject sat down for a 10 minute recovery period in the chamber following each complete task. The step test is one already used in the Canadian Standardized Test of Fitness, and is regarded as a very safe sub-maximal test of cardiovascular fitness. The experiments were conducted in an environmental chamber at a dry bulb temperature of  $40 \pm 1$  °C and a relative humidity of  $70 \pm 5\%$ , in order to simulate a warm working environment. The air speed inside the room was less than 2 m/s.

### **Clothing**

The protective clothing consisted of 'turnout' pants and coat, helmet, rubber boots, gloves, and a Nomex<sup>®</sup> hood. Under the protective clothing a subject wore a t-shirt and shorts. The breathing apparatus was a Scott 4.5 model which weighed 18 kg. The combined weight of the protective equipment and breathing apparatus was  $27 \pm 2$  kg.

### **Dependent measures**

Physiological measures recorded during the experiment were: heart rate, oxygen consumption, skin temperature and core temperature (rectal). Heart rate (HR) was continuously monitored and recorded with a Polar Vantage heart rate monitor. ECG electrodes were also placed on the subject and a three-lead ECG was sampled and recorded by a computer every 5 seconds. Oxygen consumption ( $\dot{V}O_2$ ) was determined by recording mixed expired  $O_2$  and  $CO_2$  fractions and expired gas volume was measured every 5 seconds. The steps were positioned next to the calibrated oxygen consumption instrumentation (Applied Electrochemistry Inc. Oxygen Analyzer S-3A and Carbon Dioxide Gas Analyzer CD-3A). Skin temperature ( $T_{sk}$ ) was measured, and recorded every 10 seconds, with 4 thermistors (YSI model 700) taped to the skin of the chest, upper arm, thigh, and calf with surgical tape. A mean skin temperature ( $T_{sk}$ ) was calculated using Equation 1 (Ramanathan 1964). Rectal temperature ( $T_{re}$ ) was

measured, and recorded every 5 seconds, with a flexible vinyl-covered thermistor probe (YSI model 401) inserted 10 to 15 cm in the rectum. Before each experimental session the subjects were equipped with the thermistors, electrodes, polar heart rate belt, and the mouth piece used for measuring oxygen consumption. Water loss during the two conditions was determined by weighing the subject nude and dry, before and after each trial.

$$T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{calf}) \quad (1)$$

### **Data analysis**

Physiological responses were analyzed by a two-factor, repeated measures analysis of variance (ANOVA) to determine whether the group means from the two trials were distinct. Descriptive statistics were computed for heart rate, oxygen uptake, skin temperature, and rectal temperature. Statistical analysis was performed on each physiological response at the 10 minute mark of work, and at the end of recovery. The 10 minute mark represented the end of the third stage of the step test for both clothing trials. The difference between a variable in the protective clothing and shorts trial was considered to be statistically significant at a level of  $p \leq 0.05$ . All variables are reported as the group mean  $\pm$  SD (n=5).

## **Results**

### **Physiological responses**

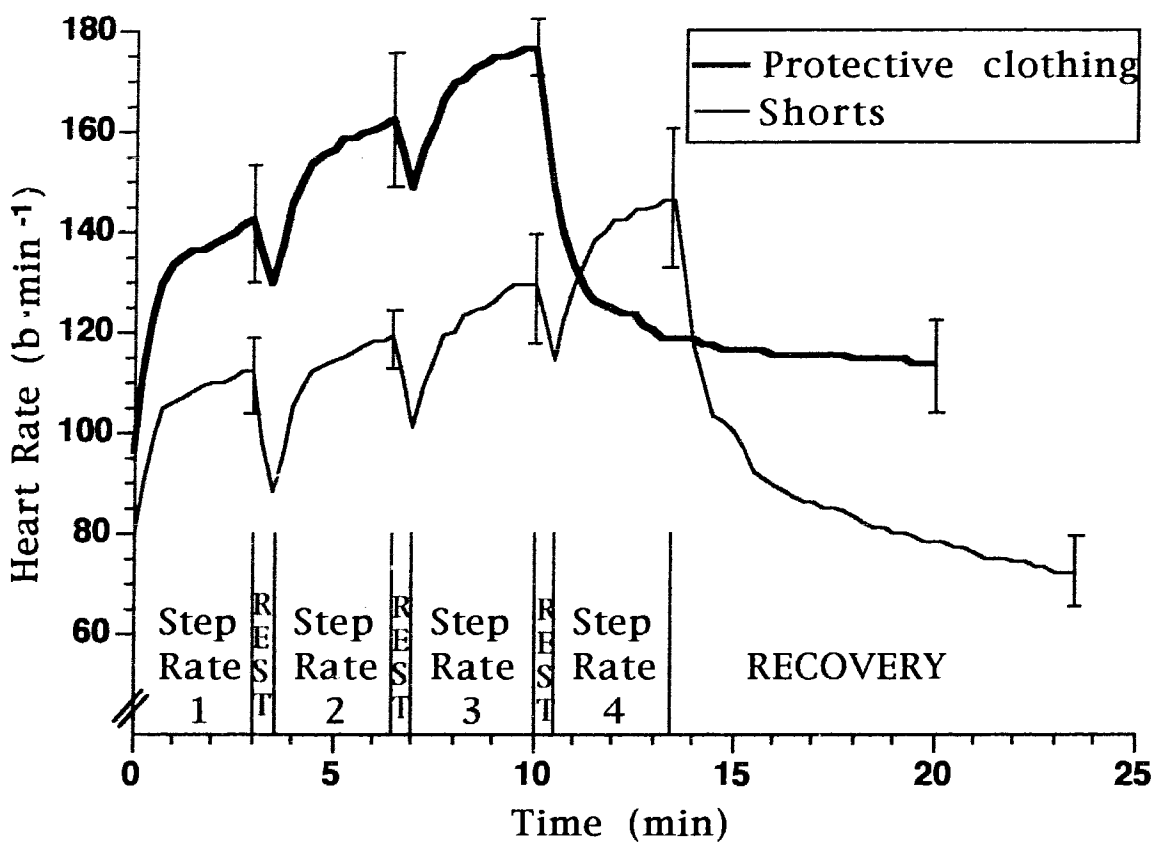
Individual subject data and the group mean value, with standard deviation, for each thermal response are given in Table 1. The values in the table refer to the immediate measurements at the end of exercise in the P trial and after the same amount of work in the S (10 minutes) trial. The physiological responses after a 10 minute recovery period in each trial are also given in Table 1.

**Table 1. Physiological responses of the individual subjects (mean  $\pm$  SD) for the shorts (S) and protective clothing (P) protocols.**

SUBJECT	1	2	3	4	5	MEAN	S.D.
Weight (kg)	76.4	79.8	75.2	90.1	82.5	80.8	$\pm$ 5.9
Height (cm)	177	185	178	180	174	178.8	$\pm$ 5.1
Age (yrs)	30	40	30	26	40	33.2	$\pm$ 5.8
Heart Rate (bpm)							
10 min (S)	142	116	125	126	138	129	$\pm$ 10
10 min (P)	183	168	176	180	174	176	$\pm$ 6
End Rec. (S)	66	69	69	73	84	72	$\pm$ 7
End Rec. (P)	125	104	103	116	118	113	$\pm$ 10
$\dot{V}O_2$ (l·min <sup>-1</sup> )							
10 min (S)	3.07	2.86	3.16	3.10	2.53	2.94	$\pm$ 0.26
10 min (P)	4.61	4.37	4.53	4.48	4.28	4.46	$\pm$ 0.13
Skin Temp (°C)							
10 min (S)	37.1	37.2	37.1	37.1	37.1	37.1	$\pm$ 0.1
10 min (P)	36.8	36.9	36.7	36.8	36.9	36.8	$\pm$ 0.1
End Rec. (S)	36.9	37.2	37.0	37.0	37.0	37.0	$\pm$ 0.4
End Rec. (P)	37.5	38.4	37.5	37.5	38.4	37.9	$\pm$ 0.5
Core Temp (°C)							
10 min (S)	37.7	37.5	37.5	37.4	37.5	37.5	$\pm$ 0.1
10 min (P)	38.3	38.2	38.0	38.1	38.4	38.2	$\pm$ 0.1
End Rec. (S)	38.0	37.9	37.4	37.3	37.7	37.6	$\pm$ 0.3
End Rec. (P)	38.9	38.9	38.6	38.9	38.9	38.8	$\pm$ 0.1
Dehydration (kg)							
During (S)	0.64	0.67	0.59	0.62	0.55	0.62	$\pm$ 0.04
During (P)	1.02	1.10	0.94	0.91	0.87	0.97	$\pm$ 0.09

## **Heart rate**

All subjects reached a near maximal individual heart rate ( $176 \pm 5.8$  b·min<sup>-1</sup>) after 10 minutes (3 stages) of stepping in protective clothing. The group mean heart rate ( $129 \pm 10$  b·min<sup>-1</sup>) was well below the mean maximum after 3 stages of stepping while wearing shorts. The group mean difference between the two conditions (P and S) was significant ( $p \leq 0.05$ ) for both the exercise and recovery heart rate. As shown in Figure 1, heart rate rose steadily within each step stage for both clothing conditions. The heart rate of a subject became progressively higher with each increase in step rate. In Figure 1 it may be observed that the group mean recovery in the P condition is slower than in the S condition. Thus a subject recovered faster and reached a significantly lower recovery heart rate after the step test in shorts than in full protective clothing. The difference between the group mean pre-exercise HR in the P and S condition was probably due to the physiological strain associated with wearing protective clothing in the resting condition. Wearing protective equipment caused the group mean peak exercise heart rate in the P condition to be elevated above the S condition by 47 b·min<sup>-1</sup>. These results are similar to other studies which have used a treadmill to simulate fire fighting work (Skoldstrom 1987).



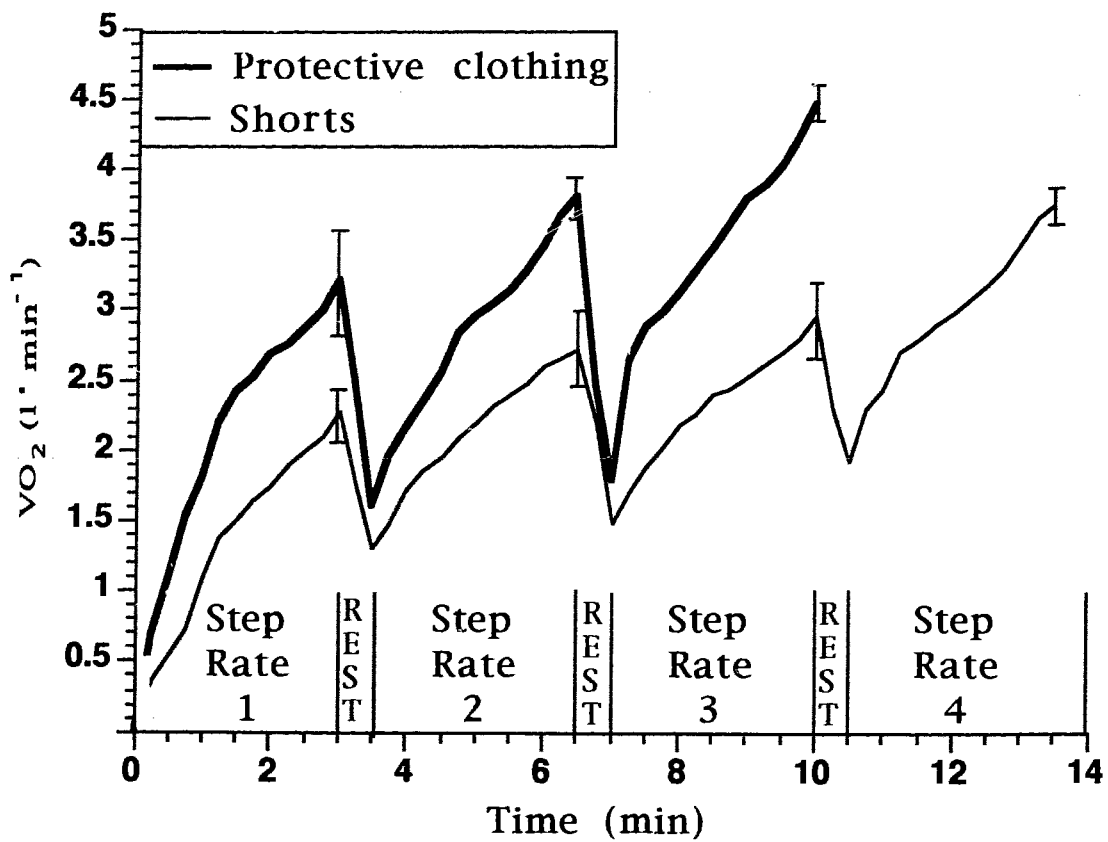
**Figure 1.** Mean ( $\pm$  SD) heart rate time course for 5 subjects wearing shorts (thin line) or protective clothing with SCBA (thick line) during incremental stepping and recovery in hot humid conditions (40 °C).



### Oxygen uptake

Oxygen uptake reached  $2.94 \pm 0.26 \text{ l}\cdot\text{min}^{-1}$  after 10 minutes of stepping in the S condition. The effect of wearing protective clothing under the same environmental conditions increased oxygen uptake to  $4.46 \pm 0.13 \text{ l}\cdot\text{min}^{-1}$  after 10 minutes in the P condition. The difference in oxygen consumption between the two conditions was significant ( $p \leq 0.05$ ). As shown in Figure 2, oxygen consumption rose steadily within each step stage and also rose with an increase in step rate for both conditions. The group mean peak oxygen consumption in the P condition was higher than recorded in other studies which used a treadmill (Faff and Tutak 1989, Skoldstrom 1987). The reason for the  $\dot{V}O_2$  value in this study might be due to the increased oxygen need of the working muscle to lift the weight of the fire fighter and his protective gear up a step.

The  $\dot{V}O_2$  values measured at the 4 stepping rates completed in the S condition agree quite well with the calculated cost of stepping at these rates (from Shephard 1969), when it is considered that the subject group is well trained, economical and efficient metabolically. At 30 steps/min the calculated  $\dot{V}O_2$  is  $2.97 \text{ l}\cdot\text{min}^{-1}$  while the measured is  $2.30 \text{ l}\cdot\text{min}^{-1}$ . At 35 steps/min the calculated  $\dot{V}O_2$  is  $3.24 \text{ l}\cdot\text{min}^{-1}$  while the measured is  $2.70 \text{ l}\cdot\text{min}^{-1}$ . At 40 steps/min the calculated  $\dot{V}O_2$  is  $3.51 \text{ l}\cdot\text{min}^{-1}$  while the measured is  $3.00 \text{ l}\cdot\text{min}^{-1}$ . At 45 steps/min the calculated  $\dot{V}O_2$  is  $3.78 \text{ l}\cdot\text{min}^{-1}$  while the measured is  $3.60 \text{ l}\cdot\text{min}^{-1}$ . In the restricted thermoregulatory condition of the P trial the  $\dot{V}O_2$  cost of the same work increased to 3.2, 3.8, and 4.5  $\text{l}\cdot\text{min}^{-1}$  respectively for the 3 phases of work completed in the P condition.



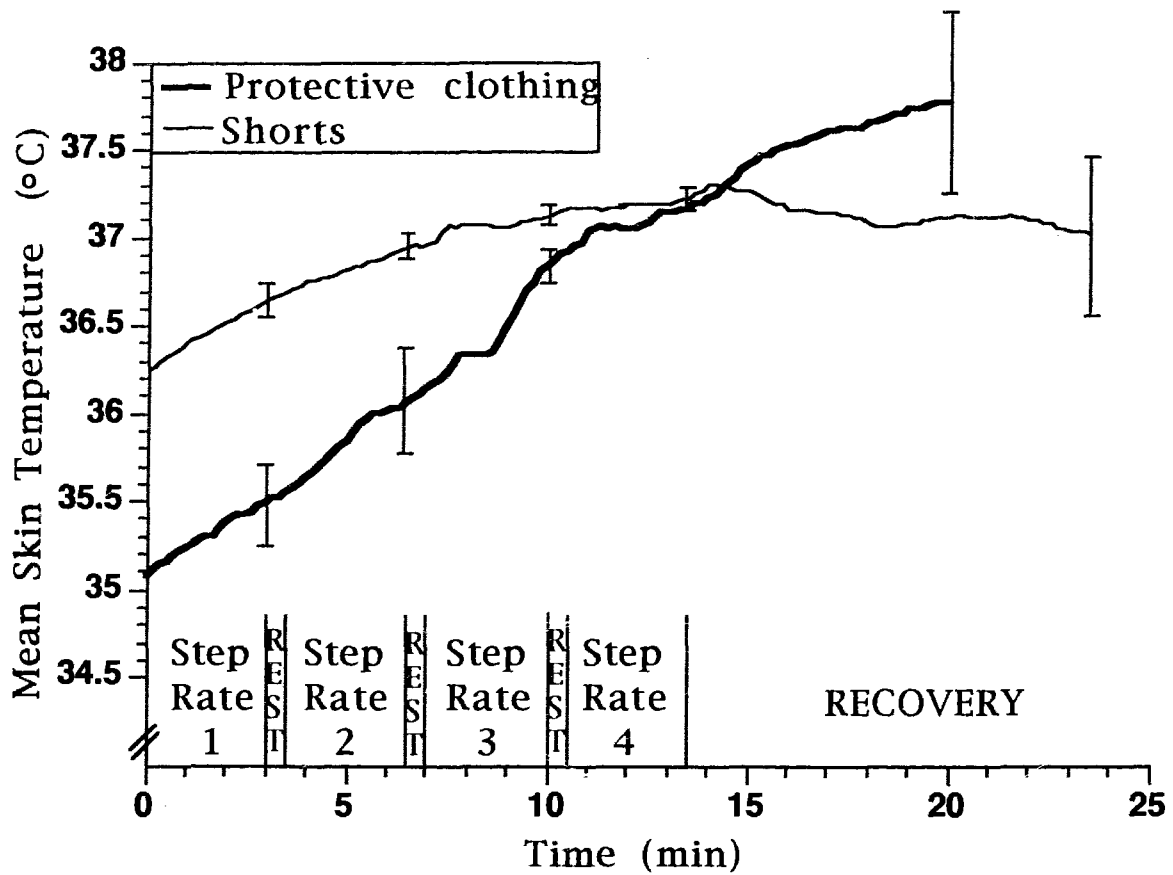
**Figure 2.** Mean ( $\pm$  SD) oxygen uptake time course for 5 subjects wearing shorts (thin line) or protective clothing with SCBA (thick line) during incremental stepping and recovery in hot conditions ( $40^\circ C$ ).

### **Skin temperature**

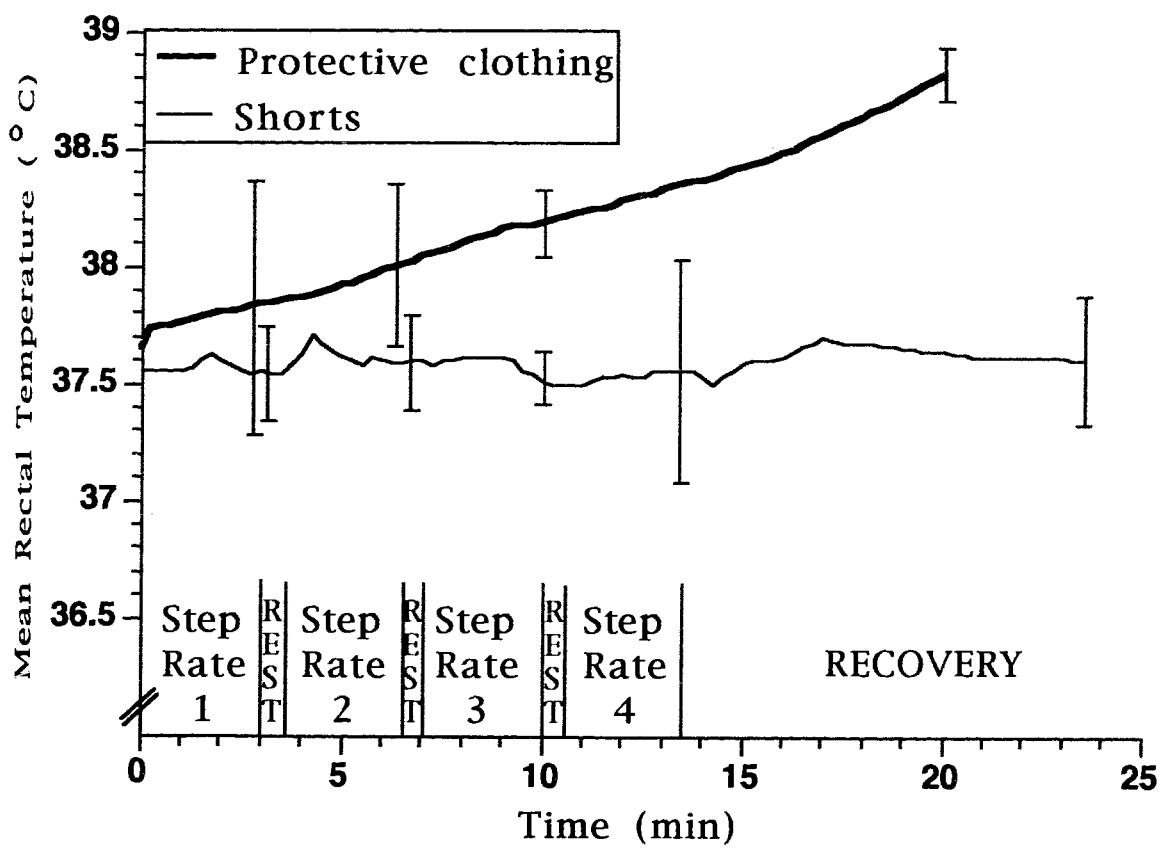
The group mean skin temperature of the subjects increased gradually during exercise in the S condition from  $36.25 \pm 0.13$  °C to  $37.22 \pm 0.05$  °C, and then gradually decreased during recovery to a level of  $37.01 \pm 0.44$  °C. The difference in peak skin temperature between the two conditions was significant ( $p \leq 0.05$ ). The continuously recorded group mean skin temperature increased steadily in the P condition from  $35.08 \pm 0.16$  °C at the start of exercise to  $37.86 \pm 0.5$  °C at the end of recovery. As shown in Figure 3, the mean skin temperature continued to increase and did not decrease during the recovery period in hot ambient conditions when the subjects wore protective clothing. The difference between the group mean pre-exercise skin temperature values in P and S was due primarily to the insulative properties of the protective clothing initially shielding a subject's skin from the surrounding heat.

### **Rectal temperature**

The group mean rectal temperature in the S condition remained relatively constant throughout exercise and recovery. At the start of exercise in the S condition the mean rectal temperature was  $37.55 \pm 0.23$  °C and fluctuated about this level reaching  $37.60 \pm 0.28$  °C at the completion of recovery. The group mean rectal temperature of the subjects increased steadily in the P condition from  $37.65 \pm 0.56$  °C at the start of exercise to  $38.82 \pm 0.11$  °C at the end of recovery. As illustrated in Figure 4, the rectal temperature increased throughout exercise and did not level off during recovery when the subjects wore protective clothing. The difference in rectal temperature between the two test conditions was significant ( $p \leq 0.05$ ). The significant increase in rectal temperature of  $1.17$ °C during the P condition, agrees with data from studies using other testing formats (Romet and Frim 1987).



**Figure 3.** Mean ( $\pm$  SD) skin temperature time course for 5 subjects wearing shorts (thin line) or protective clothing and SCBA (thick line) during incremental stepping and recovery in hot conditions (40 °C).



**Figure 4.** Mean ( $\pm$  SD) rectal temperature time course for 5 subjects wearing shorts (thin line) or protective clothing and SCBA (thick line) during incremental stepping and recovery in hot conditions (40 °C).

## **Dehydration**

Body weight loss is an indicator of thermal strain, as most of the weight is lost through sweating (Parsons 1993). During work in the hot ambient conditions in the P trial the group mean body weight decreased by  $0.97 \pm 0.09$  kg. During the S trial in the same hot ambient conditions, the group mean body weight decreased by only  $0.62 \pm 0.04$  kg of body weight. The significant difference in weight loss between the 2 trials may be attributed to a very high sweat rate during exercise and recovery while wearing full protective clothing.

## **Discussion**

The relatively benign stress due to ambient conditions and physical stimulus when appropriate light weight clothing is worn is reflected in the mild physiological response of the subject group to wearing only shorts (Table 1, Figs 1,2,3,4). The physiological response to work in the standard shorts clothing condition serves to emphasize the extreme disruptive effect of protective clothing on temperature regulation, and on the metabolic energy cost of working in hot humid conditions (Table 1, Figs 1,2,3,4).

The increase and decrease in heart rate (HR), oxygen uptake ( $\dot{V}O_2$ ) and mean skin temperature ( $T_{sk}$ ) in response to the 3 minute incremental step rate exercise stimulus's (30, 35 and 40 steps/min), show the typical growth and decay exponential response to a step increase in work rate followed by an off-response (rest). The on-off exercise stimulus enables quantitative examination of the on-off exercise response of each physiological variable in the S and P conditions of the work trials. The amplitude of rise in heart rate at each step rate measured in both the S and P condition is remarkably similar (approx.  $30 \text{ b}\cdot\text{min}^{-1}$ ). The overall large absolute greater increase in the peak HR of the subject group in the P condition is due to the shorter decay time constant (approx. 30 sec) in the S condition, than in the P condition (approx. 90 sec), affording a faster decay towards baseline during the brief recovery period allowed at the end of each stepping interval. The final decay of HR to the respective baseline levels of the initial conditions (approx.  $95 \text{ b}\cdot\text{min}^{-1}$  for the P

condition) and (approx. 80 b·min<sup>-1</sup> for the S condition) again emphasizes the aroused metabolic state of the P condition where the steady state decay value of HR in the P condition recovers only to 113 b·min<sup>-1</sup>, while in the S condition recovery is to 72 b·min<sup>-1</sup>, which was less than its baseline HR prior to exercise.

The results of the present study show that the combined effect of wearing protective clothing and breathing apparatus during stepping caused the peak exercise heart rate to be elevated by a mean 47 b·min<sup>-1</sup> more than peak heart rate wearing light clothing. This result is similar to other studies which have used a treadmill to provide the exercise stimulus (Skoldstrom 1987).

A disproportionate increase in  $\dot{V}O_2$  during each step rate increase in the P condition (approx. 2.9 l·min<sup>-1</sup> compared with a 1.5 l·min<sup>-1</sup> average increase in the S condition), again reflects the metabolic arousal stimulated by wearing protective clothing. In the present study the group mean oxygen uptake was  $2.94 \pm 0.26$  l·min<sup>-1</sup> after subjects stepped for 10 minutes in shorts. The effect of the protective clothing and SCBA increased oxygen uptake to  $4.46 \pm 0.13$  l·min<sup>-1</sup> after the same 10 minutes of stepping. The mean peak oxygen consumption value for the five subjects was higher than reported in other studies which used a treadmill stimulus (Faff and Tutak 1989, Skoldstrom 1987). The higher oxygen uptake value may be attributed to the generally high level of fitness of the present group of fire fighters tested, as well as the added cardiovascular demand of the step test versus a treadmill test. During stepping the added load of a fire fighter's clothing and SCBA increased the relative work rate, and increased oxygen uptake. The oxygen uptake values in the study were considered low for the corresponding high heart rates found during the protective clothing step test. These results support those of other studies which have found that the linear relationship between heart rate and oxygen uptake cannot be used in a hot environment (O'Connell *et al.* 1986, Sothman *et al.* 1991).

Skin temperature may vary considerably over the body due to the presence of clothing and a difference in the movement of air across various parts of the body (Parsons 1993). The results of the

present study show that skin temperature is clearly difficult to regulate in the P condition (Fig. 3). While initial skin temperature is suppressed by being insulated from the ambient conditions by the protective clothing, it rises progressively throughout both the work and recovery period, to reach a mean value of 37.9°C. Other studies have also shown that mean skin temperature increases significantly more when a subject wears protective clothing than when light clothing is worn (Skoldstrom 1987, White *et al.* 1989).

Rectal temperature (Fig. 4) in the P condition gives a clear indication of the thermal threat incurred from working in protective clothing. The core temperature rises continually throughout work and recovery when a subject wears protective clothing. The control of core temperature to a small oscillation about basal level during exercise in the S condition, contrasts markedly with the severe and increasing core temperature which continues to rise during both work and recovery in the P condition. The increase in core temperature during recovery found in this study and in others (Duncan *et al.* 1979, Faff and Tutak 1989, White *et al.* 1991), indicates that it is extremely doubtful that a fire fighter's body recovers appreciably during a short rest period. Thus a fire fighter may enter a fire in a much worse physiological condition than he left it 10 minutes previously, but with a false sense of recovery. The significantly higher rectal temperature response in the P condition, above that of the S condition in this study, clearly demonstrates a failure of thermoregulation to deal with heat stress, resulting in uncontrollable heat strain. The results also indicate that by removing a heat stressed fire fighter from active work, you do not necessarily reduce the heat strain suffered by the individual. During the P trial ethics guidelines required that the subjects stop work after the third stage, as all subjects would have reached a heart rate above 180  $\text{b}\cdot\text{min}^{-1}$  during the fourth stage.

Both null hypotheses of the study were rejected. The P condition in the study demonstrated that protective clothing and an SCBA significantly increases heart rate, oxygen uptake, skin and core temperature compared to work and recovery while wearing shorts.



## **Conclusions**

The experiments conducted in Chapter 2 have established:

- the significant elevation in the metabolic cost of performing a fire fighting task while wearing full protective clothing and SCBA compared with performing the same task in a lightly clad unloaded condition.
- the combined weight of protective clothing and SCBA coupled with the impermeable property of a fire fighter's clothing increases the physical work rate, inhibits evaporative cooling, heightens heat stress and secondarily increases heart rate, breathing frequency, skin temperature, and core temperature.
- the range and group mean value of thermoregulatory responses of fit, well trained fire fighters to heavy work and recovery in hot humid conditions.
- the measured quantitative rise in amplitude of several physiological indices of stress including rectal temperature,  $\dot{V}O_2$ , heart rate, and mean skin temperature in response to several on-off step increases in physical loading, has discriminated the probable time course of the rise and fall of these indices in response to the pattern of activity and rest pauses followed in the course of general fire fighting activity.
- the experiments have identified a critical after-rise in core temperature after work in hot humid conditions. This poses a potential heat exhaustion/heat stroke hazard to a naive fire fighter performing a repetitive schedule of work in heat. After a short rest period a fire fighter's core temperature may not have been reduced, and he may enter a fire in a much worse physiological condition than he left.
- the change in size and variability of physiological measurements induced by work and recovery profiles in hot humid conditions have been used to establish the minimum number of subjects required to establish an alpha level of 0.05 and a power of 80% in the investigation of optimal strategies to reduce heat stress in fire fighters completing repetitive work schedules interspersed with recovery periods.

## Chapter 3

### Effectiveness of rest pauses and cooling in alleviation of heat stress in simulated fire fighting activity in hot humid conditions

#### Introduction

It has been demonstrated in the previous section of this thesis that the combined effect of environmental heat, the high energy cost of fire fighting work, and the weight and impermeability of protective clothing places an extreme physiological demand on a fire fighter. Figure 2, in Chapter two shows the degree of increase in  $\dot{V}O_2$  induced by heavy impermeable protective clothing and SCBA. This finding is supported by other studies which have found that protective clothing significantly increases the energy expenditure of a fire fighter (Bishop *et al.* 1994, Duncan *et al.* 1979, Faff and Tutak 1989). The increased energy expenditure is mainly attributed to heat stress generated at the body-garment interface. The impermeable property of a fire fighter's clothing prevents the evaporation of sweat, leading to an increase in heart rate, oxygen consumption, skin temperature, and core temperature. The primary physical stress of protective clothing and SCBA is compounded by occasional loads such as ladders and hoses which are routinely moved during fire fighting activities (Duncan *et al.* 1979).

During fire suppression activity a fire fighter attains a near maximal heart rate (HR), for prolonged periods, of time, while performing heavy work in a hot polluted environment (Romet and Frim 1987, Sothman *et al.* 1992, White *et al.* 1989). Chapter two of the present work has demonstrated the extreme danger of body heat accumulation to the fire fighter. Even when work stops, the after-rise of core temperature continues to rise and pose a potential heat stress threat (Figure 3 and 4 of Chapter 2, Bone *et al.* 1994, Duncan *et al.* 1979, Smith *et al.* 1995). During a simulated fire fighting task a fire fighter wearing full protective clothing and breathing apparatus demonstrates a significantly higher skin and rectal temperature than

when lightly clothed (Bone *et al.* 1994, Duncan *et al.* 1979, Skoldstrom 1987, Smith *et al.* 1995, White *et al.* 1989).

The physiological response of a fire fighter acting in an emergency situation is very difficult or impossible to measure as most portable measuring devices become impractical to use in such dangerous situations. Additionally the heat exposure that a fire fighter faces during emergency work varies in severity and is irregularly presented. However, the energy cost of performing simulated fire fighting activity has been measured and classified as heavy work, varying in energy cost being from 11 to 12.7 kcal min<sup>-1</sup> (Gavhed and Holmer 1989, Romet and Frim 1987).

### **Rationale for experiments**

The rationale for the present study was to investigate methods to alleviate the amount of physiological stress protective clothing produces in a fire fighter during work and recovery. There have been relatively few studies on the fire fighter's physiological response during real or simulated activity in a hot environment. Fewer still have studied the effect on thermoregulation of different cooling devices, such as cooling vests worn either during work or in recovery under different clothing ensembles. There are no reported studies which have investigated the simpler approach of aggressive intermittent cooling during staged rest periods in the course of fire suppression activity. Existing studies have been conducted using treadmill and cycle ergometer tests in environmentally controlled rooms. The present study used stepping exercise to represent a typical fire fighting task. The majority of the experiments were conducted in an environmentally controlled room, however some field tests were performed to record the physiological response during real fire suppression and auto extrication training. The physiological effect of providing aggressive direct body cooling to a subject during a recovery period was investigated. The objective of the study was to provide recommendations on how to improve the effectiveness of recovery periods and reduce the environmental stress placed on fire fighters.

## **Hypothesis**

Staged recovery periods with superficial protective clothing removed, and fan cooling during recovery, reduces total heat storage during the course of fire suppression, compared with an equal number of staged recovery periods without fan cooling. By removing their turnout coat and utilizing a fan during recovery, a fire fighter can significantly reduce heat strain and reduce the risk of heat exhaustion.

## **Methodology**

### **Subjects**

Twelve professional fire fighters volunteered for the experiment. The subjects were all healthy, physically active, and non-smokers. Each subject signed an informed consent prior to the study. A physical examination of each subject was made before the start of testing to ensure they were capable of completing the experiments safely. The protocol for the experiments received ethical approval from the Ethics Committee at Simon Fraser University. Physical characteristics of the subjects (mean  $\pm$  SD) are shown in Table 2. The subjects averaged  $6.2 \pm 3.8$  yrs of fire fighting experience. Each subject had numerous hours of experience working in protective fire fighting gear during training sessions and at real fires. The subjects wore their own NFPA 1500 standard protective fire fighting clothing for the experiments.

**Table 2. Physical characteristics of the 12 subjects (mean  $\pm$  SD).**

Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
Age (yrs)	36	25	41	33	28	30	41	22	29	28	42	27	31.8 $\pm$ 6.73
Body fat (%)	8.0	13.1	11.7	12.2	15.0	8.1	8.4	7.3	6.3	8.9	8.9	11.7	9.96 $\pm$ 2.67
Height (cm)	174	185	167	185	179	175	184	175	182	187	173	183	179.0 $\pm$ 6.22
Weight (kg)	73.2	88.9	83.5	93.2	85.8	76.5	82.9	75.4	73.9	81.8	73.6	90.0	81.6 $\pm$ 7.0
$\dot{V}O_2$ max ml/min·kg	62.5	53.1	56.0	59.0	61.2	69.3	62.1	62.8	61.7	61.5	62.2	61.1	61.0 $\pm$ 3.9
Max HR (beats/min)	206	182	179	185	194	203	188	202	189	204	201	184	193 $\pm$ 10

### **Experimental design**

The height, weight, and percent body fat of all subjects were measured prior to experimentation. Each subject completed a ramp exercise  $\dot{V}O_2$ max test on a bicycle ergometer in order to determine their maximal oxygen uptake and maximum heart rate. The  $\dot{V}O_2$ max test was completed in an environmentally controlled room with the dry bulb temperature  $40 \pm 1^\circ\text{C}$  and a relative humidity  $70 \pm 5\%$ . These environmental conditions were used for all of the controlled experiments, in order to simulate a hot humid working environment.

Each subject completed two work/recovery trials. Each trial involved 10 minutes of stepping, 10 minutes of recovery, 10 more minutes of stepping, then a final 10 minute recovery period. In an optimal recovery (OR) trial each subject removed their coat and sat in front of a fan during both recovery periods. In the normal recovery (NR) trial a subject only unbuckled their coat and were not fanned while they sat during both recovery periods. Subjects wore

the full complement of protective clothing during each stepping portion of each trial. The subject wore their breathing apparatus but did not breath air from the tank as they were breathing from a ventilation mask used for gas analysis.

### **Task**

The work portion of each trial was completed on a step test box comprised of two 22.9 cm (9") steps totaling 45.8 cm (18"). During a test a subject completed two 22.9 cm upward steps and two downward steps, to complete two steps. The 10 minute work period was divided into 3 stages each consisting of three minutes of stepping with a 30 second rest period between each stage, in which the subject stood still. The first level exercise intensity required the subject to step at a rate of 25 steps per minute, the second level required 30 steps per minute and the third level required 35 steps per minute. The stepping rate is based on the Canadian Standardized Test of Fitness, and is regarded as a safe sub-maximal test for assessing cardiovascular fitness. Following each work period a subject sat down and was monitored during a 10 minute recovery period. Each trial took 40 minutes and involved 2 stepping periods and two recovery periods. Each subject completed two 40 minute trials which were separated by 7 or 8 days. Each of the two trials had different recovery conditions. Six subjects completed the optimal recovery (OR) trial first, while the other six subjects completed the normal recovery (NR) trial first.

### **Trial One**

During both recovery periods of the first trial a subject removed their coat, gloves, Nomex® hood, helmet, and breathing apparatus. During both recovery periods a subject sat with a 16 inch fan 1 meter away, directing air toward their head and torso. A subject was asked to sit quietly and was allowed to drink 500 ml of water. This trial was called the optimal recovery (OR) trial.

## Trial Two

In the second trial a subject wore protective clothing and breathing apparatus during the stepping portions of the trial. During both recovery periods the subject removed their gloves, Nomex® hood, and helmet, but left their breathing apparatus on their back, and only unbuckled their coat. During the recovery period a subject was asked to sit quietly and was allowed to drink 500 ml of water. This trial was called the normal recovery (NR) trial.

**Table 3. Experimental design.**

	<b>Exercise 1</b>	<b>Recovery 1</b>	<b>Exercise 2</b>	<b>Recovery 2</b>
<b>Trial #1</b>	3 stages x 3 min with 30 sec rest between stages	Coat off fan water	3 stages x 3 min with 30 sec rest between stages	Coat off fan water
<b>Trial #2</b>	3 stages x 3 min with 30 sec rest between stages	Coat unbuckled no fan water	3 stages x 3 min with 30 sec rest between stages	Coat unbuckled no fan water

## **Clothing**

The protective clothing consisted of NFPA 1500 standard turnout pants and coat. The subjects also wore standard fire fighting gloves, boots, Nomex® hood, and a Scott 4.5 breathing apparatus which weighed 18 kg. Under the protective clothing a subject wore a t-shirt and shorts. The combined weight of the protective equipment and breathing apparatus was  $27 \pm 2$  kg.

## **Dependent measures**

The physiological measures taken and recorded during each experiment were heart rate, oxygen consumption, skin temperature, rectal temperature, and tympanic temperature. Heart rate (HR) was continuously monitored and recorded with a Polar Vantage® heart rate monitor system. Oxygen consumption was determined by recording expired oxygen (O<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>) gas fractions

and gas volume measurements every 5 seconds. Expired gas was sampled from a mixing box and analyzed for O<sub>2</sub> (Applied Electrochemistry, model S-3A) and CO<sub>2</sub> content (Applied Electrochemistry, model CD-3A). Expired ventilation was measured with an Alpha Technologies Ventilation Module (module VMN110). Electrical signals from the ventilation modules and gas analyzers were processed on-line by analog to digital conversion (National Instruments A/D conversion board NB-MIO-16). A software program in National Instrument LabVIEW (Version 2.1.1) was used to align the signals in time, and correct for the specific response time for each gas analyzer.

Rectal temperature ( $T_{re}$ ) was measured, and recorded every 5 seconds, with a flexible vinyl-covered thermister probe (Yellow Spring Instruments) inserted 10 to 15 cm in the rectum. Tympanic temperature ( $T_{tym}$ ) and skin temperature ( $T_{sk}$ ) were measured and recorded with a Mini-Logger<sup>®</sup> (Series 2000) and then downloaded into a IBM PC. Tympanic temperature was recorded by placing a tympanic thermister (SHER-I-TEMP<sup>™</sup>) in the left ear of the subject, securing it in position with surgical tape. Skin temperature was recorded with three skin thermisters (YSI 4499E) taped to the skin of the arm (over right deltoid), chest (over right pectoralis major) and thigh (mid thigh over rectus femoris) with surgical tape. A group mean skin temperature (n=12) was calculated for each of the three skin sites. Before each experimental trial a subject was instrumented with a rectal thermister, tympanic thermister, 3 skin thermisters, a Polar<sup>®</sup> heart rate belt, and a breathing mask which was connected to the equipment used for measuring oxygen consumption. To determine the dehydration which occurred in each condition a subject was weighed nude and dry, before and after each trial.



## **Data analysis**

Physiological responses were analyzed by a two-factor, repeated measures analysis of variance (ANOVA) to determine whether the group means from the two trials were distinct. Descriptive statistics were computed for heart rate, oxygen uptake, skin temperature, tympanic temperature, and rectal temperature. Statistical analysis was performed on the physiological responses of each subject at the end of each work and recovery period. A difference between the two trials was considered to be statistically significant when  $p \leq 0.05$ . All values for the twelve subjects are given as mean  $\pm$  SD.

## **Results**

### **Physiological responses**

The physiological responses of each subject are listed in Tables 4 through 11. Each value in a table refers to the physiological measurement taken at the end of the work period (End Work 1 and End Work 2) and at the end of the recovery periods (End Rec. 1 and End Rec. 2). In the Tables, trial 1 is referred to as the optimal recovery (OR) trial since the subjects removed their coat and sat in front of a fan during recovery. Trial 2 is referred to as the normal recovery (NR) trial as the subjects only unbuckled their coat and did not use a fan for cooling during recovery.

### **Heart rate**

The mean heart rate for the 12 subjects at the end of the first work period was the same for both trials. This result was expected since the 2 trials used the same protocol for the first work period. Figure 5 illustrates that the group mean HR declined fastest during the first 3 minutes of recovery in both recovery conditions. During the next 7 minutes of recovery the OR group mean HR decreased more the NR group mean. The difference in recovery HR between the two conditions was significant ( $p \leq 0.05$ ) after the first recovery period.

At the end of the second work period the group mean HR for the OR condition was  $90.0 \pm 5.30$  % of the mean maximum HR. The mean HR for the NR condition was  $94.6 \pm 5.17$  % of the mean

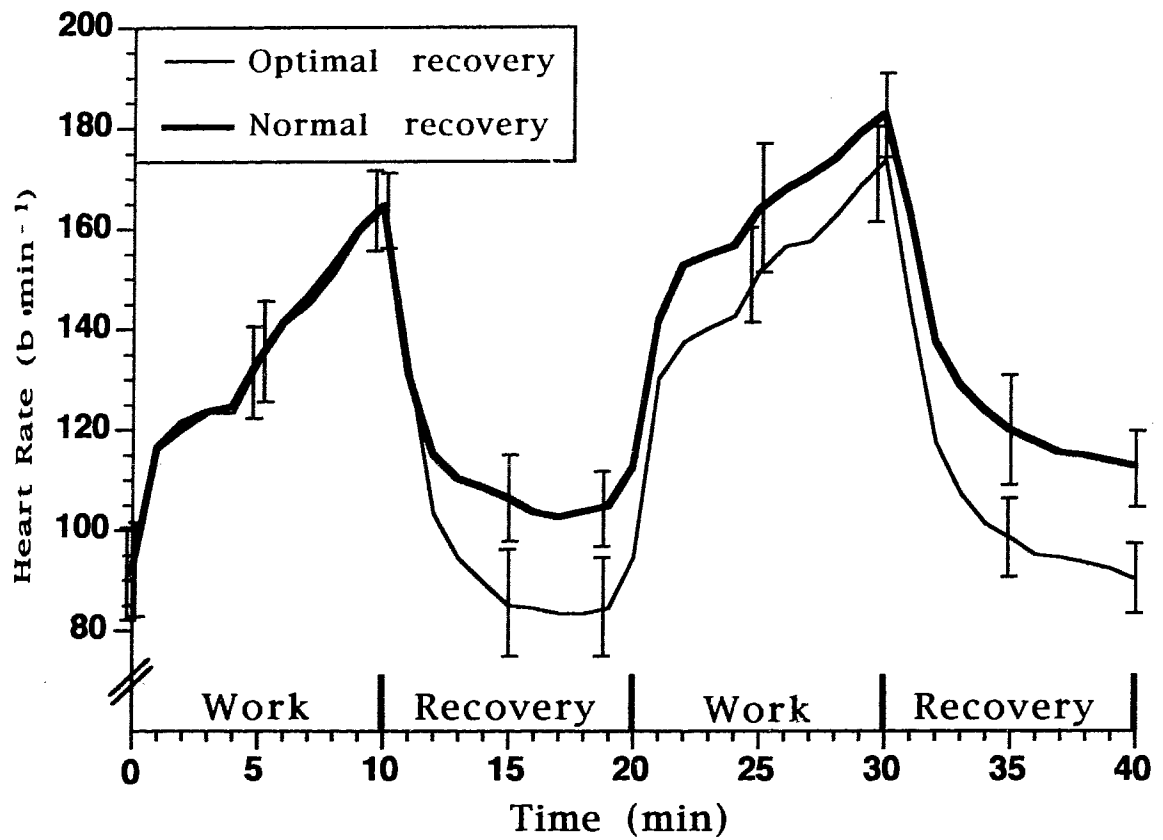
maximum HR. The difference between the two conditions at the end of the second work period was again significant ( $p \leq 0.05$ ). As illustrated in Figure 5, heart rate rose at the same rate during the main period of work for both conditions during the second work period. However the mean HR in the OR condition remained  $10 \text{ b}\cdot\text{min}^{-1}$  lower than the NR work heart rates.

During the second recovery period the group mean HR for the OR subjects decreased to  $90 \pm 7 \text{ b}\cdot\text{min}^{-1}$ , but only to  $112 \pm 7 \text{ b}\cdot\text{min}^{-1}$  for the NR subjects. Figure 5 illustrates that heart rate decreased fastest during the first 3 minutes of recovery in both conditions. For the remainder of the recovery period, the group mean heart rate decreased more in the OR condition than in the NR condition. The group mean difference in recovery HR between the two conditions was again significant ( $p \leq 0.05$ ). It is interesting to note that the mean heart rate decreased to the same level  $112 \text{ b}\cdot\text{min}^{-1}$  at the end of both recovery periods in the NR condition. In the OR trial mean HR decreased to  $90 \text{ b}\cdot\text{min}^{-1}$  at the end of the second recovery period, this value was lower than at the end of the first recovery period ( $94 \text{ b}\cdot\text{min}^{-1}$ ).

Figure 5 illustrates that the group mean heart rate during the stepping work rises asymptotically towards a steady state within each phased step rate of a trial. This is due to the increase in step rate throughout each work period. Clearly the OR condition induced a significantly lower recovery heart rate during both recovery periods, than recovery in the NR condition. The OR condition also produced a final lower group mean heart rate during the second work period than the NR condition. This may reflect the reduction in heat stress effected by efficient cooling in the OR condition after the first work period.

**Table 4. Individual heart rate response of 12 subjects (mean  $\pm$  SD) at the end of each recovery and work period for the optimal (OR) and normal (NR) recovery trials respectively.**

<b>Subject</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>Mean <math>\pm</math> SD</b>
<b>(OR) End Work 1</b>	163	153	162	163	158	151	158	175	168	178	169	165	164 $\pm$ 8
<b>(NR) End Work 1</b>	164	157	163	165	159	153	156	174	167	180	165	159	164 $\pm$ 8
<b>(OR) End Rec. 1</b>	82	96	101	84	92	89	84	105	93	103	96	103	94 $\pm$ 8
<b>(NR) End Rec. 1</b>	105	94	128	104	113	107	105	121	117	127	111	117	112 $\pm$ 10
<b>(OR) End Work 2</b>	172	170	170	172	168	156	170	190	177	187	182	167	173 $\pm$ 9
<b>(NR) End Work 2</b>	183	179	178	184	178	167	180	192	180	203	185	179	182 $\pm$ 9
<b>(OR) End Rec. 2</b>	80	81	94	92	84	85	85	105	94	92	93	96	90 $\pm$ 7
<b>(NR) End Rec. 2</b>	106	98	116	116	112	101	111	122	118	121	108	111	112 $\pm$ 8
<b>% of max HR at End Work2 (OR)</b>	83.5	93.4	95.0	93.0	86.6	76.8	90.4	94.1	93.7	91.7	90.5	90.8	90.0 $\pm$ 5.3%
<b>% of max HR at End Work2 (NR)</b>	88.8	98.4	99.4	99.5	91.8	82.3	95.7	95.0	95.2	99.5	92.0	97.3	94.6 $\pm$ 2.2%



**Figure 5.** Group mean heart rate ( $\pm$  SD) increase and decline during work and recovery throughout a heat stress trial for the optimal recovery condition (thin line) and the normal recovery condition (thick line).

## **Rectal temperature**

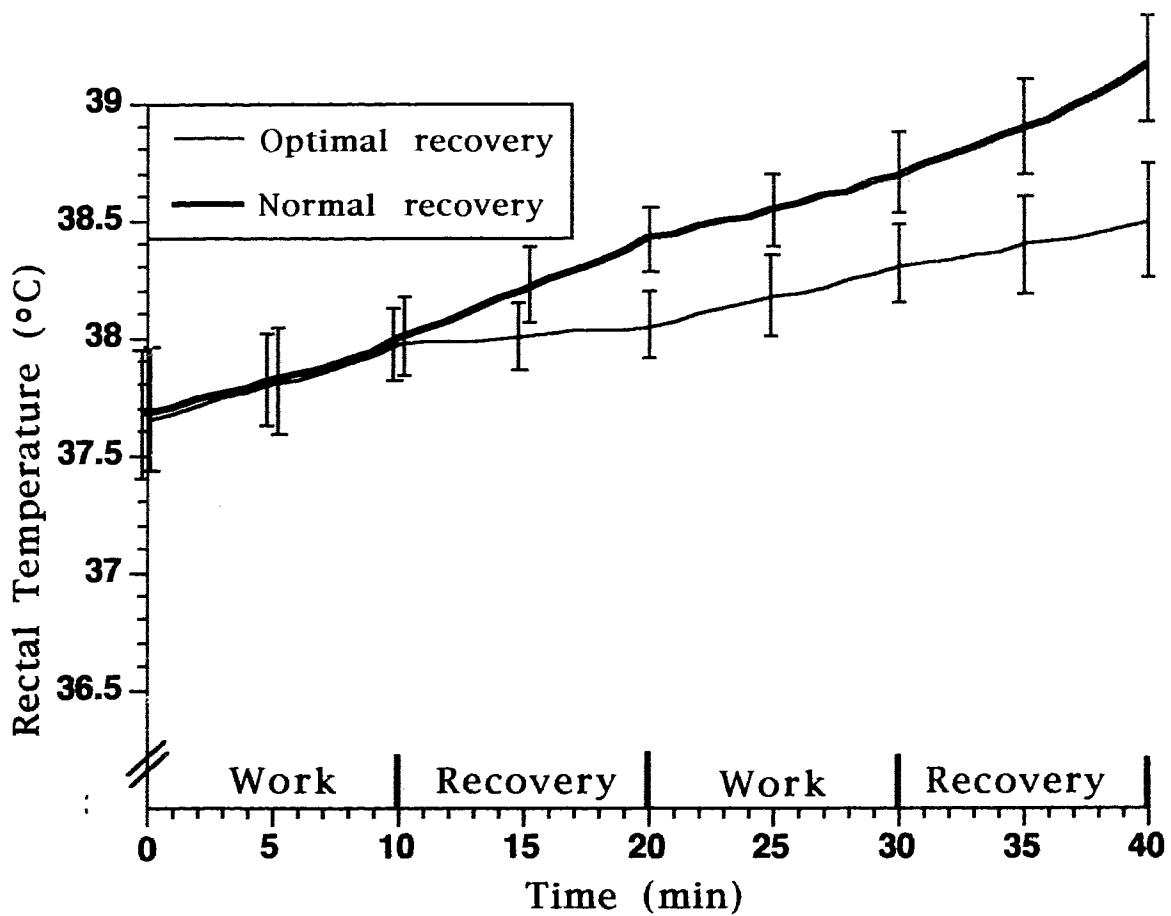
The group mean rectal temperature ( $T_{re}$ ) of the subjects in the NR condition (Fig. 6) increased approximately linearly throughout each work and recovery cycle of the experimental period. During the OR condition the initial rise in rectal temperature during work slowed dramatically during the first recovery period and continued to rise through the second work period at a diminished rate before slowing, less dramatically, in the second recovery period. The temperature gap between the OR and NR conditions steadily widened throughout, since the recovery period in the NR trial afforded no modification in the rate of  $T_{re}$  rise during the trial (see Table 5).

During the first work period of each trial, mean rectal temperature increase is almost equal in the OR and NR cycles, reflecting the equivalent protocol of the first work cycle for both trials. Mean  $T_{re}$  again increased by 0.27 °C during the second work period in both the OR and NR condition. During the NR condition the total increase in mean  $T_{re}$  during both recovery periods was 0.90 °C. During the OR condition however, mean  $T_{re}$  increased by only 0.25°C during both recovery conditions. The mean  $T_{re}$  increased by 1.5 °C and 0.81 °C during the entire trial for the NR and OR condition respectively.

The difference in rectal temperature between the two conditions both at the end of the second work period and at the end of the two recovery periods was significant ( $p \leq 0.05$ ). The total increase in rectal temperature in the NR condition compared with the OR condition clearly demonstrates the physiological advantage of the more efficient cooling experienced by a subject in the optimal recovery condition.

**Table 5. Rectal temperature (°C) response of 12 subjects (mean  $\pm$  SD) at the end of each recovery and work period for the optimal (OR) and normal (NR) recovery trials respectively.**

<b>Subject</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>11</b>	<b>12</b>	<b>Mean <math>\pm</math> SD</b>
<b>(OR) End Work 1</b>	38.1	38.0	37.7	38.0	38.0	37.8	38.0	37.9	38.2	38.0	38.1	38.1	38.0 $\pm$ 0.2
<b>(NR) End Work 1</b>	38.1	38.0	37.7	38.2	38.0	37.8	37.9	37.9	38.2	38.1	38.0	38.2	38.0 $\pm$ 0.2
<b>(OR) End Rec. 1</b>	38.1	37.9	37.9	38.0	37.9	37.9	38.0	38.0	38.3	38.1	38.2	38.2	38.0 $\pm$ 0.1
<b>(NR) End Rec. 1</b>	38.4	38.5	38.3	38.5	38.4	38.2	38.4	38.4	38.6	38.6	38.4	38.4	38.4 $\pm$ 0.1
<b>(OR) End Work 2</b>	38.3	38.4	38.1	38.3	38.0	38.1	38.3	38.3	38.6	38.4	38.5	38.5	38.3 $\pm$ 0.2
<b>(NR) End Work 2</b>	38.5	38.7	38.5	38.9	38.5	38.4	38.7	38.7	38.9	39.0	38.7	38.7	38.7 $\pm$ 0.2
<b>(OR) End Rec. 2</b>	38.5	38.4	38.4	38.3	38.0	38.3	38.5	38.6	38.8	38.6	38.8	38.7	38.5 $\pm$ 0.2
<b>(NR) End Rec. 2</b>	39.2	39.1	38.9	39.4	38.9	38.9	39.2	39.2	39.4	39.6	39.2	39.0	39.2 $\pm$ 0.2



**Figure 6.** Group mean rectal temperature ( $\pm$  SD) increase and decline during work and recovery throughout a heat stress trial for the OR condition (thin line) and the NR condition (thick line).

**Table 6. Tympanic temperature (°C) response of 12 subjects (mean  $\pm$  SD) at the end of each recovery and work period for the optimal (OR) and normal (NR) recovery trials respectively.**

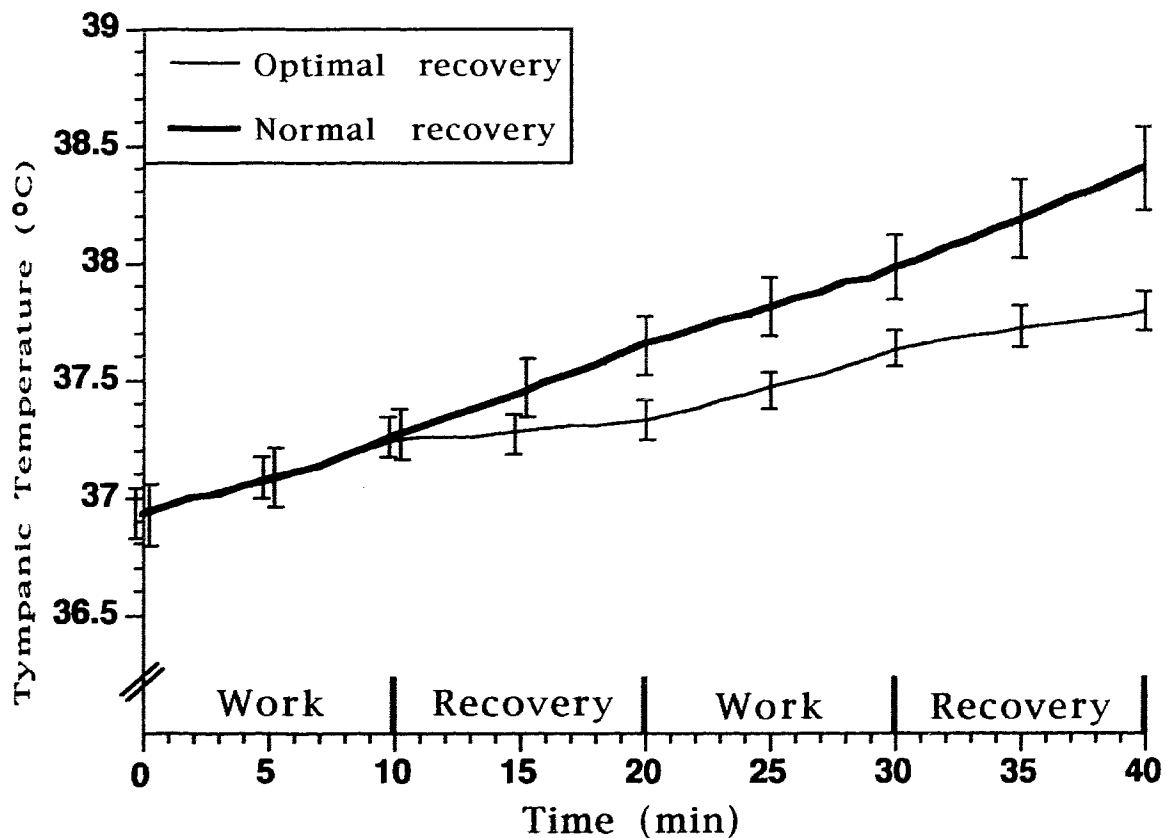
Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
(OR) End Work 1	37.2	37.4	37.1	37.2	37.2	37.2	37.3	37.3	37.4	37.3	37.2	37.3	37.3 $\pm$ 0.1
(NR) End Work 1	37.2	37.4	37.0	37.3	37.2	37.3	37.2	37.4	37.3	37.4	37.2	37.2	37.3 $\pm$ 0.1
(OR) End Rec. 1	37.3	37.4	37.2	37.3	37.3	37.3	37.3	37.4	37.4	37.4	37.3	37.4	37.3 $\pm$ 0.1
(NR) End Rec. 1	37.6	37.7	37.4	37.6	37.6	37.6	37.7	37.8	37.7	37.8	37.6	37.6	37.7 $\pm$ 0.1
(OR) End Work 2	37.7	37.7	37.5	37.6	37.5	37.6	37.6	37.7	37.7	37.7	37.6	37.7	37.6 $\pm$ 0.1
(NR) End Work 2	37.9	38.0	37.8	38.1	37.8	37.9	38.0	38.1	38.1	38.2	38.0	37.9	38.0 $\pm$ 0.1
(OR) End Rec. 2	37.8	37.8	37.7	37.7	37.7	37.7	37.8	37.9	37.8	37.9	37.8	37.9	37.8 $\pm$ 0.1
(NR) End Rec. 2	38.3	38.4	38.2	38.5	38.1	38.3	38.4	38.5	38.6	38.7	38.4	38.3	38.4 $\pm$ 0.2

### **Tympanic temperature**

The mean tympanic temperature of the subjects increased steadily throughout the trial in the optimal recovery condition. The overall increase of 0.84 °C during the period of the OR trial was the same as the observed rectal temperature increase. During the normal recovery condition the mean tympanic temperature of the subjects increased at a faster rate than in the OR condition. The overall increase of 1.46 °C during the NR condition was again very similar to the overall rectal temperature increase of 1.50 °C.



As illustrated in Figure 7 the mean tympanic temperature increased throughout both work periods and did not level off during the recovery periods in the NR condition. In the OR condition mean  $T_{\text{ty}}m$  increased during the two work periods at the same rate as during the NR trial. However, during both recovery periods in the OR condition mean  $T_{\text{ty}}m$  increased minimally, and considerably less than during the NR condition. The difference in mean tympanic temperature between the two conditions at the end of the second work period and at the end of the 2 recovery periods was significant ( $p \leq 0.05$ ) in each case.



**Figure 7.** Group mean tympanic temperature ( $\pm$  SD) increase and decline during work and recovery throughout a heat stress trial for the OR condition (thin line) and the NR condition (thick line).

## Skin temperature

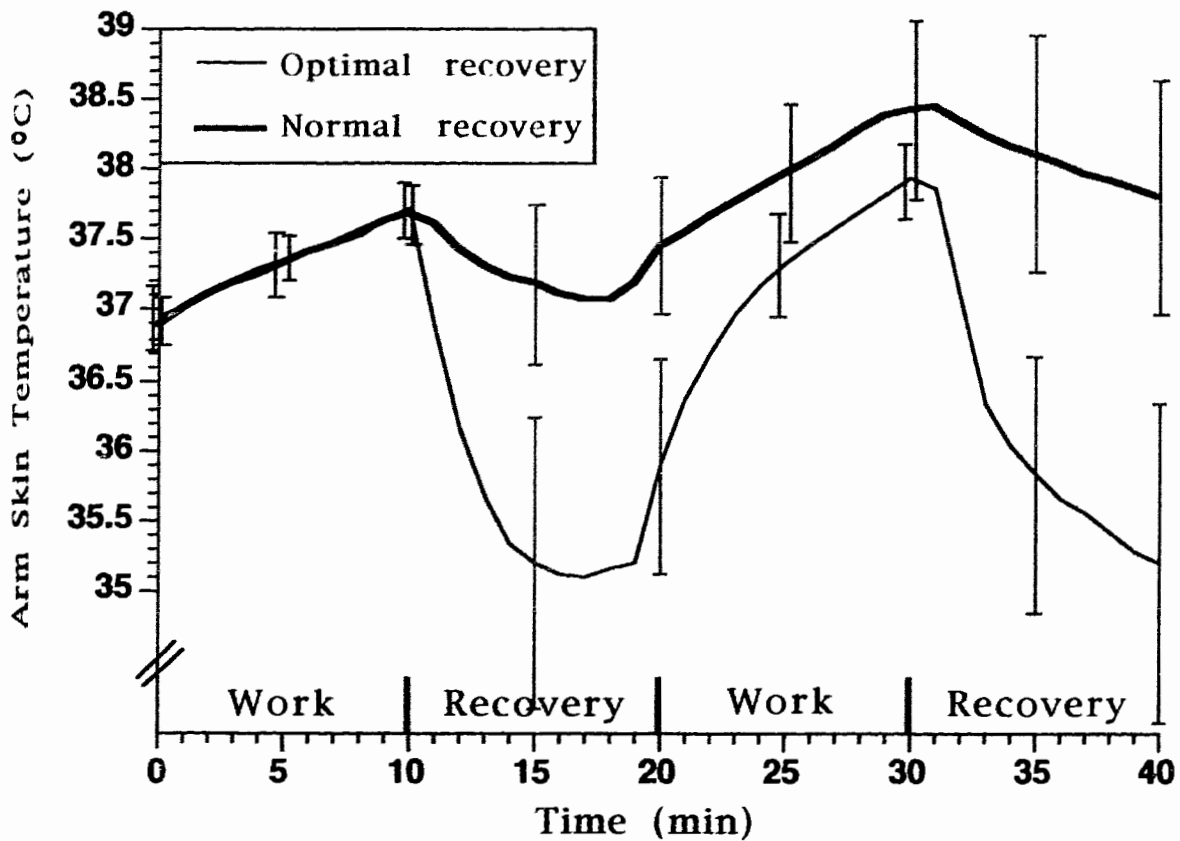
**Table 7. Arm skin temperature ( $^{\circ}\text{C}$ ) response of 12 subjects (mean  $\pm$  SD) at the end of each recovery and work period for the optimal (OR) and normal (NR) recovery trials respectively.**

Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
(OR) End Work 1	37.3	37.6	37.6	37.6	37.7	37.9	37.8	37.6	37.9	38.0	37.9	38.0	37.7 $\pm$ 0.2
(NR) End Work 1	37.8	37.4	37.3	37.8	37.7	37.8	37.8	37.6	37.8	37.9	37.8	37.5	37.7 $\pm$ 0.2
(OR) End Rec. 1	34.3	35.3	35.3	35.4	35.8	35.5	36.7	36.2	36.5	36.5	37.0	36.4	35.9 $\pm$ 0.8
(NR) End Rec. 1	37.4	36.7	36.7	37.4	37.4	37.2	38.3	37.2	37.8	37.9	38.0	37.3	37.4 $\pm$ 0.5
(OR) End Work 2	37.6	37.5	38.0	37.7	37.8	38.2	38.1	37.9	38.1	38.2	38.2	38.2	38.0 $\pm$ 0.3
(NR) End Work 2	38.5	37.6	37.5	38.5	38.2	38.2	39.5	38.3	38.8	39.2	39.0	37.8	38.4 $\pm$ 0.6
(OR) End Rec. 2	33.9	35.6	35.2	35.2	33.4	33.6	34.7	35.6	36.7	36.4	36.6	35.7	35.2 $\pm$ 1.1
(NR) End Rec. 2	38.1	37.0	37.0	38.1	38.0	36.0	38.3	37.8	38.6	38.8	38.5	37.4	37.8 $\pm$ 0.8

### Arm skin temperature

The group mean arm skin temperature of the subjects increased steadily during the 2 work periods of each condition. Despite the large skin temperature change in the OR condition, the group mean OR skin temperature was always lower than the NR group mean after the first work period. During the OR trial the group mean arm skin temperature decreased considerably more during both recovery periods than in the NR condition.

Figure 8 emphasizes the superiority of mean skin temperature cooling in the OR condition compared with the NR condition. The difference in group mean arm skin temperatures between the OR and NR groups at the end of the second work period ( $p \leq 0.05$ ) and at the end of the 2 recovery periods ( $p \leq 0.05$ ) were both significant.



**Figure 8.** Group mean arm skin temperature ( $\pm$  SD) increase and decline during work and recovery throughout a heat stress trial for the OR condition (thin line) and the NR condition (thick line).

**Table 8. Chest skin temperature ( $^{\circ}\text{C}$ ) response of 12 subjects (mean  $\pm$  SD) at the end of each recovery and work period for the optimal (OR) and normal (NR) recovery trials respectively.**

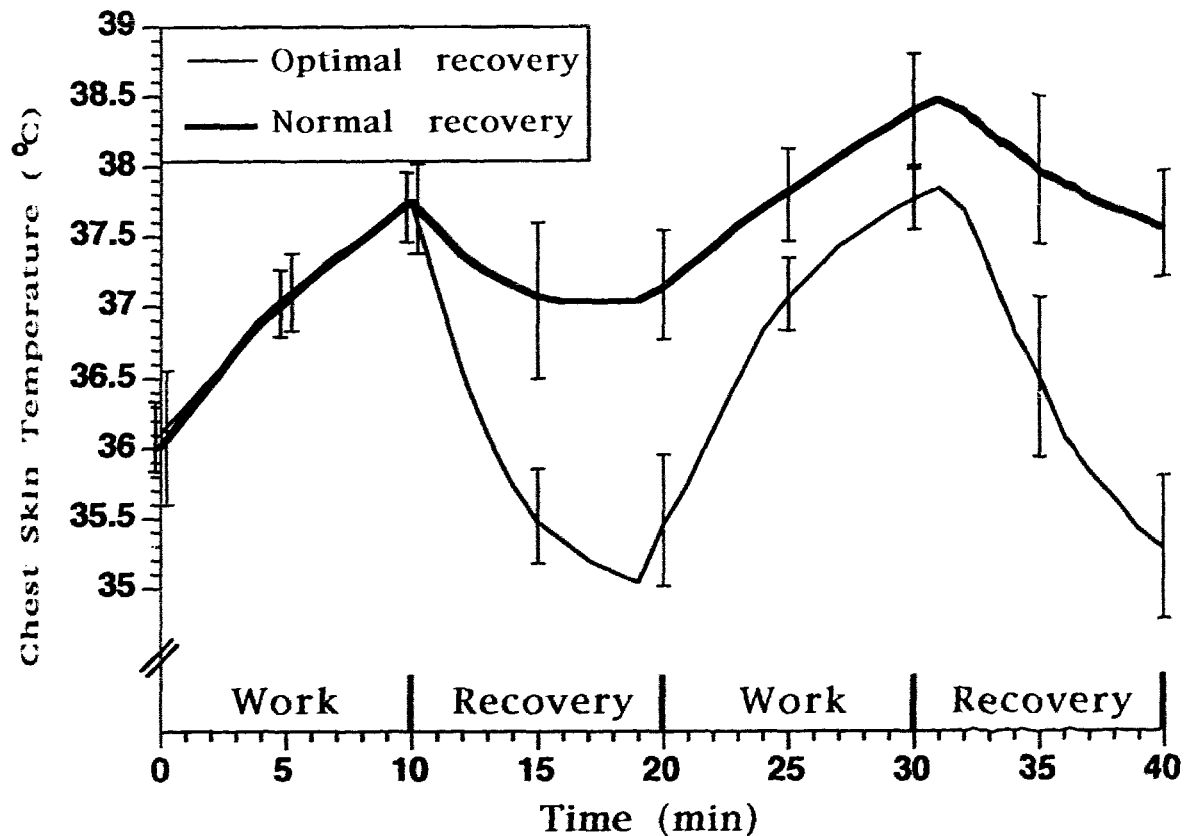
Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
(OR) End Work 1	37.5	37.8	37.9	37.4	37.2	37.8	38.0	37.9	37.9	37.9	37.7	38.0	37.8 $\pm$ 0.3
(NR) End Work 1	37.4	37.9	37.9	37.4	37.2	37.9	38.2	38.1	38.0	37.9	37.6	37.5	37.7 $\pm$ 0.3
(OR) End Rec. 1	34.5	35.7	35.7	35.2	35.9	34.9	35.0	35.9	35.6	35.6	35.6	36.2	35.5 $\pm$ 0.5
(NR) End Rec. 1	36.7	37.2	37.1	36.7	37.0	36.5	37.7	37.1	37.2	37.8	37.3	37.3	37.1 $\pm$ 0.4
(OR) End Work 2	37.4	37.8	37.8	37.6	37.4	37.9	37.8	38.1	37.9	37.9	37.8	37.9	37.8 $\pm$ 0.2
(NR) End Work 2	38.1	38.1	38.0	38.1	38.0	38.0	39.1	38.8	38.6	38.9	38.5	38.3	38.4 $\pm$ 0.4
(OR) End Rec. 2	35.0	36.2	35.9	35.5	35.0	34.5	35.0	35.4	35.0	35.0	35.1	35.8	35.3 $\pm$ 0.5
(NR) End Rec. 2	36.7	37.7	37.7	37.0	37.4	36.9	37.8	37.6	38.5	37.9	38.1	37.5	37.5 $\pm$ 0.5

### Chest skin temperature

The time course of chest skin temperature (Fig. 9) was very similar to that of arm skin temperature. Mean chest skin temperature increased steadily during the 2 work periods of each condition. Despite the large OR skin temperature change, the group mean OR chest skin temperature was always lower than the NR group mean after the first work period. During the OR trial mean chest skin temperature decreased considerably more during the recovery periods than in the NR condition.

The wide variations in chest skin temperature during both work and recovery periods of the OR condition is obviously due to

the direct convective air flow over the body during a recovery period. At the end of the first recovery period the difference in mean chest skin temperature between the two conditions was significant ( $p \leq 0.05$ ). It is interesting that the OR group mean temperature at the chest site increased rapidly from the end recovery position during the second work period. This increase still remained significantly depressed ( $p \leq 0.05$ ) below the peak chest skin temperature in the NR condition. By the end of the second work period the OR group mean skin temperature again rapidly decreased in the fan assisted recovery to a level significantly ( $p \leq 0.05$ ) below the NR condition.



**Figure 9.** Group mean chest skin temperature ( $\pm$  SD) increase and decline during work and recovery throughout a heat stress trial for the OR condition (thin line) and the NR condition (thick line).

**Table 9. Thigh skin temperature (°C) response of 12 subjects (mean  $\pm$  SD) at the end of each recovery and work period for the optimal (OR) and normal (NR) recovery trials respectively.**

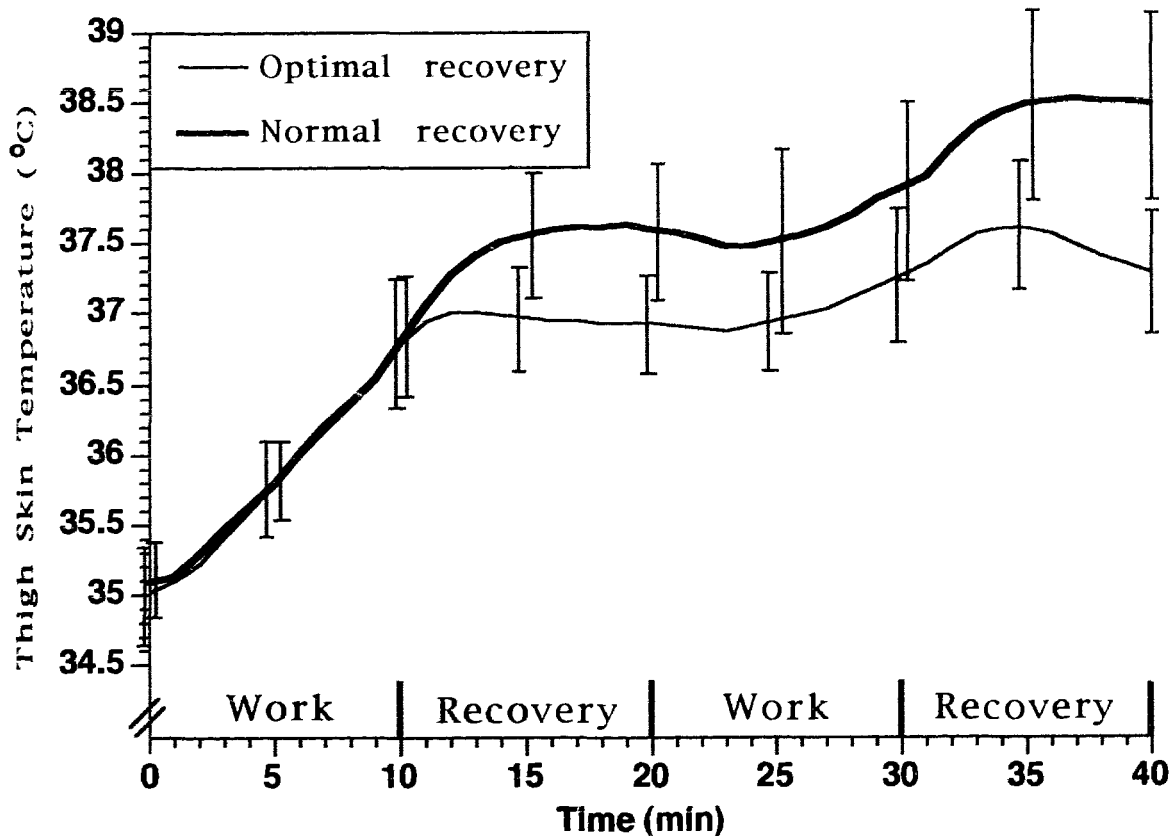
Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
(OR) End Work 1	36.9	35.9	36.0	36.4	36.9	37.3	37.1	36.9	37.0	37.2	37.2	36.8	36.8 $\pm$ 0.5
(NR) End Work 1	36.9	36.0	36.0	36.6	36.8	37.2	37.1	36.8	37.0	37.1	37.2	36.8	36.8 $\pm$ 0.4
(OR) End Rec. 1	36.6	36.6	36.6	36.8	36.5	37.1	37.4	37.1	37.4	36.6	37.4	36.9	36.9 $\pm$ 0.4
(NR) End Rec. 1	37.7	37.1	37.1	37.8	37.2	37.2	38.3	37.1	38.1	38.3	37.8	37.2	37.6 $\pm$ 0.5
(OR) End Work 2	36.7	36.8	36.8	37.5	37.5	37.8	37.6	37.8	37.6	36.4	37.6	37.3	37.3 $\pm$ 0.5
(NR) End Work 2	38.1	37.0	37.0	38.0	37.4	37.4	38.8	37.9	38.7	38.8	38.0	37.4	37.9 $\pm$ 0.7
(OR) End Rec. 2	36.9	37.4	37.6	37.2	36.7	37.2	37.8	37.6	37.5	36.4	37.5	37.6	37.3 $\pm$ 0.4
(NR) End Rec. 2	38.6	38.1	38.1	38.6	37.8	37.6	39.6	38.2	39.1	39.6	38.7	37.9	38.5 $\pm$ 0.7

### Thigh skin temperature

Thigh skin temperature differed considerably from the arm and chest skin temperatures. The difference may be attributed to several factors which changed the thermal environment around the thigh thermister. The thigh thermister remained covered by the subject's pants during both the OR and NR conditions. This would have reduced the effectiveness of the fan-assisted recovery. The stepping motion during the work period would have created an airflow around the thigh thermister. When a subject sat down during the recovery period the warm material from the turnout pants was

compressed over the thigh thermister. Despite these factors the difference in group mean thigh skin temperatures between the two conditions was significant at the end of the second work period ( $p \leq 0.05$ ) and at the end each of the two recovery periods ( $p \leq 0.05$ ).

As illustrated in Figure 10, there is a considerable difference in mean thigh  $T_{sk}$  regulation between the two conditions. The large difference between the two trials at the end of the second recovery period clearly demonstrates the benefit of fan-assisted cooling, on mean thigh skin temperature, during the optimal recovery condition .



**Figure 10.** Group mean thigh skin temperature ( $\pm$  SD) increase and decline during work and recovery throughout a heat stress trial for the OR condition (thin line) and the NR condition (thick line).

## Oxygen uptake

The group mean oxygen uptake value for the 12 subjects at the end of the 2 work periods are given in Table 10. Oxygen uptake was not recorded during the recovery periods. At the end of the first work period the group mean oxygen uptake values for the OR and NR trials are almost identical since the ambient conditions and work rate is the same for the first work period in each trial. The oxygen uptake value for both conditions was higher in the second work period than the first, even though the work was the same in both periods. At the end of the second work period the mean oxygen uptake value was  $42.4 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$  for the OR condition and  $45.2 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$  for the NR condition, this was a significant difference ( $p \leq 0.05$ ). These values represent  $70.3 \pm 4.5\%$  of maximal oxygen uptake for the OR condition and  $74.8 \pm 4.8\%$  of  $\dot{V}O_2\text{max}$  for the NR condition.

**Table 10.** Oxygen uptake ( $\text{l}\cdot\text{min}^{-1}$ ) response of 12 subjects (mean  $\pm$  SD) at the end of each work period for the optimal (OR) and normal (NR) recovery trials respectively.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
(OR) End Work 1	3.31	3.17	3.30	3.27	3.28	3.29	3.24	3.36	3.27	3.27	3.15	3.44	3.28 $\pm$ 0.08
(NR) End Work 1	3.30	3.24	3.33	3.29	3.27	3.21	3.40	3.31	3.31	3.17	3.39	3.30	3.30 $\pm$ 0.07
(OR) End Work 2	3.40	3.44	3.48	3.52	3.51	3.41	3.47	3.61	3.41	3.52	3.33	3.59	3.47 $\pm$ 0.08
(NR) End Work 2	3.58	3.67	3.70	3.75	3.76	3.56	3.69	3.84	3.63	3.79	3.54	3.84	3.70 $\pm$ 0.10
% of $\dot{V}O_2$ max at End Work2 (OR)	74.4	72.9	74.4	64.0	66.9	64.3	67.4	76.3	74.8	70.0	72.8	65.3	70.3 $\pm$ 4.5%
% of $\dot{V}O_2$ max at End Work2 (NR)	78.3	77.8	79.1	68.2	71.6	67.2	71.7	81.2	79.6	75.3	77.4	69.8	74.8 $\pm$ 4.8%



## Dehydration

The group water loss during the OR trial and NR trial are given in Table 11. Subjects were significantly ( $p \leq 0.05$ ) more dehydrated during the normal recovery condition. The increased dehydration may be attributed to an increased sweat rate during recovery in the latter case in which a subject left their coat on and did not utilize a fan for extra cooling.

**Table 11. Water loss (kg) from the 12 subjects (mean  $\pm$  SD) determined by weighing the subjects nude before and after the optimal (OR) and normal (NR) recovery trials respectively.**

Subject	1	2	3	4	5	6	7	8	9	10	11	12	Mean $\pm$ SD
Optimal Recovery	1.10 kg	1.20	0.90	1.05	1.10	1.10	1.00	1.00	1.17	0.90	1.10	1.25	1.07 $\pm 0.11$
Normal Recovery	1.25	1.60	1.10	1.20	1.50	1.55	1.20	1.15	1.30	1.15	1.25	1.40	1.30 $\pm 0.17$

# **Field study of physiological responses to fire suppression and auto extrication**

## **Introduction**

Gathering research data on the physiological responses of a fire fighter during fire suppression activity is very difficult since most portable measuring devices are not of practical use in a dangerous situation. Very few studies have measured simulated fire fighting activity to determine the physiological response to different tasks. Two field studies were completed during the present work in order to supplement laboratory findings with fire scene measurements and gain insight into the physiological responses to the real conditions that a fire fighter faces. Due to the difficulty in staging the field studies only 4 subjects were used: two in each task. The purpose of the field studies was to document the physiological responses of a fire fighter to two common fire fighting tasks. The tasks chosen were fire suppression and auto extrication.

## **Subjects**

Four fire fighters, from the group of twelve used in the laboratory study, volunteered for the two studies. Physical characteristics of the subjects (mean  $\pm$  SD) are found in Table 13. Subjects 1 and 2 completed the fire suppression field study, while subjects 3 and 4 completed the auto extrication field study. The subjects averaged 4.1  $\pm$  1.3 years of fire fighting experience. Each subject had previous experience completing the task which they were asked to perform in the field study. The subjects wore their own NFPA 1500 standard protective fire fighting clothing during the field studies. This was the same equipment which they used during the laboratory studies.

**Table 12. Physical characteristics of the 4 subjects used in the field studies (mean  $\pm$  SD).**

<b>Subject</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Mean <math>\pm</math> SD</b>
Age (years)	28	22	29	27	26.5 $\pm$ 3.1
Body fat (%)	15.0	7.3	6.3	11.7	10.08 $\pm$ 4.04
Height (cm)	179	175	182	183	179.8 $\pm$ 3.57
Weight (kg)	85.8	75.4	73.9	90.0	81.3 $\pm$ 7.9
$\dot{V}O_2$ max (ml/min·kg)	61.2	62.8	61.7	61.1	61.7 $\pm$ 0.8
Max HR (beats·min <sup>-1</sup> )	194	202	189	184	192 $\pm$ 8

### **Experimental design**

#### Fire suppression

A subject advanced a 200 foot 1<sup>1</sup>/<sub>2</sub> inch hose through a second story door, across a room, down a set of stairs and then extinguished 2 separate small wood fires. The subject was told to look for potential victims while advancing the hose, and they had no prior knowledge of where the fires were located. The monitored subject held the nozzle and advanced the line slowly while keeping low to the ground. An assistant followed behind the subject to back him up and help advance the hose. It is normal fire fighting procedure for two fire fighters to advance a hose. The temperature inside the room where the fire fighter extinguished the 2 small fires was approximately 40 °C on the floor and 75 °C five feet above the floor. The subjects spent approximately 4 to 5 minutes inside the fire room. The temperature in the other rooms and stairway was approximately 25 °C. The task was designed to take 10 minutes and once the time had elapsed the subject was asked to come outside to a recovery area. During recovery the subject sat on a bench for 10 minutes with their coat unbuckled and their helmet, Nomex™ hood and gloves removed. This was the same recovery protocol used during the NR trial of the laboratory experiments. The outside temperature in the recovery area was 13 °C. Two subjects completed the trial under almost identical environmental conditions.

### Auto extrication

A monitored subject was asked to perform auto extrication for 10 minutes. The auto extrication involved using heavy hydraulic tools to dismantle a car and gain access to a patient. The tools used included hydraulic jaws (30 kg) and a hydraulic cutter (20 kg). The subject was asked to adopt a pace at which they would normally work when performing auto extrication involving a real patient. After completing 10 minutes of auto extrication the subject was asked to sit down on the tail gate of a truck for a ten minute recovery period. During recovery the subject unbuckled their coat and removed their helmet, Nomex™ hood and gloves, and no fan cooling was provided. The outdoor temperature during the extrication and recovery was 24 °C. Two subjects completed the trial while performing very similar activities during the auto extrication.

### **Clothing**

Protective clothing consisted of NFPA 1500 standard turnout coat and pants, gloves, boots, and Nomex™ hood. During fire suppression a Scott 4.5 breathing apparatus was used. The combined weight of the protective equipment and breathing apparatus was  $27 \pm 2$  kg. During auto extrication the subject did not wear a breathing apparatus. It is common policy for a fire fighter not to wear a breathing apparatus during auto extrication if there is no threat of fire.

### **Dependent measures**

The physiological measures taken and recorded during the field studies were heart rate, skin temperature and tympanic temperature. Heart rate (HR) was continuously monitored and recorded with a Polar Vantage heart rate monitor system. Tympanic temperature ( $T_{\text{tym}}$ ) and skin temperature ( $T_{\text{sk}}$ ) were measured and recorded with a Mini-Logger® (Series 2000) and then downloaded into an IBM PC. Tympanic temperature was recorded by placing a tympanic thermister (SHER-I-TEMP™) into the left ear of the subject and then securing it in position with surgical tape. Skin temperature was recorded with three skin thermisters (YSI 4499E) taped to the

skin of the arm, chest and thigh with surgical tape. Before each trial the subjects were equipped with the tympanic thermister, skin thermister, and polar heart rate monitor.

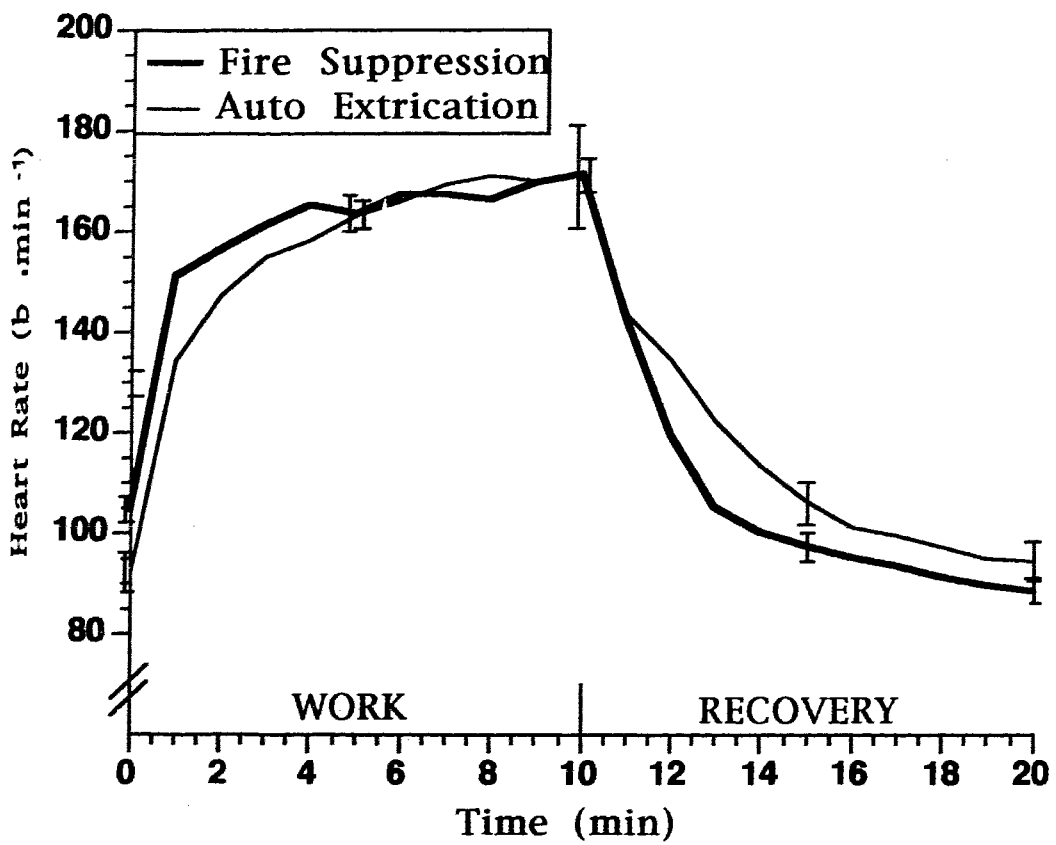
### **Analysis**

Only 2 subjects were used for each field study, so no analysis for statistical significance was attempted. The average physiological response of the 2 subjects for each physiological variable during work and recovery was determined. The results were then compared with the physiological responses of the laboratory study.

### **Results**

#### **Heart rate**

The average heart rate response of the 2 subjects during each field study are shown in Figure 11. The individual heart rate recorded during the work and recovery periods of the field experiments was very similar to the group mean subject heart rates encountered in the laboratory experiments. The average heart rate of the 2 subjects during the 10 minute work period was 154 b·min<sup>-1</sup> during auto extrication and 158 b·min<sup>-1</sup> during fire suppression. The results indicate that during a normal fire fighting task an individual works at a heart rate approximately 81 % of their maximum. The heart rate rapidly increased from rest to a steady high state which was then sustained throughout the work period. Recovery heart rate from both the above tasks also was relatively rapid with each individual reaching a rate close to 100 b·min<sup>-1</sup> after 10 minutes of recovery. The heart rate results of the 2 field studies suggest that a fire fighter automatically self-selects a common relatively high work intensity (75 to 85 % of maximum heart rate), when performing a physically demanding task.



**Figure 11.** Average heart rate (with range) for 2 subjects completing a fire suppression (thick line) and auto extrication (thin line) field study trial respectively.

## **Tympanic temperature**

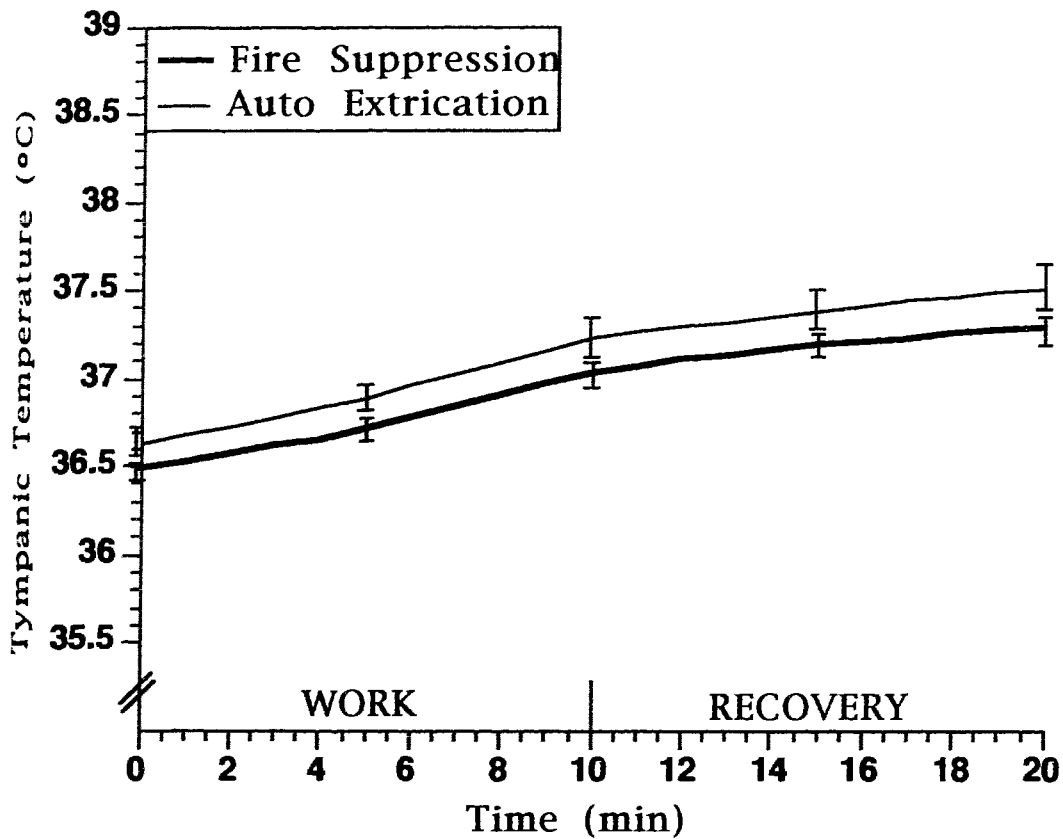
The average tympanic temperature response for the 2 subjects during the fire suppression and auto extrication field studies are shown in Figure 12. The tympanic temperature of the 2 subjects increased by an average of 0.55 °C during the 10 minute work period of the fire suppression study and by 0.64 °C during the 10 minutes of auto extrication work. Both these values are slightly higher than the 0.30 °C increase in mean tympanic temperature recorded during the first 10 minute work period of the laboratory study. This difference may be explained by the cooler ambient conditions of the field study and the lower work intensity at the beginning of the laboratory stepping exercise in the first work period.

The tympanic temperature of the 2 subjects continued to increase by an average of 0.25 °C during the fire suppression 10 minute recovery period and by 0.28 °C during the auto extrication recovery period. These values are slightly lower than the 0.39 °C mean tympanic temperature recorded during the first normal recovery period of the laboratory study. The field study recovery values are also considerably higher than the 0.08 °C mean tympanic temperature recorded during the first OR period of the laboratory study. The increase in tympanic temperature during the recovery period of the field studies was lower than in the NR condition of the laboratory study, probably because of the lower ambient temperatures during field study recovery. The tympanic temperature change recorded during the recovery period of the field studies was larger than in the optimal recovery period of the laboratory study because the subjects did not remove their coat and sit in front of a fan during the recovery period of the field studies.

The tympanic temperature recorded during the fire suppression and auto extrication field studies increased at approximately the same rate during work and recovery. The tympanic temperature recorded during the fire suppression field study is routinely about 0.2 °C lower than recorded during the auto extrication study. The tympanic temperature recorded during the auto extrication field study was again routinely about 0.3 °C lower

than each corresponding measurement recorded during the first work and recovery periods of the laboratory study.

The tympanic temperature results of the 2 field studies shows that a fire fighter's core temperature will increase significantly during a relatively intense 10 minute work period and continues to increase during recovery for at least 10 minutes after work is completed.



**Figure 12.** Tympanic temperatures (with range) for 2 subjects completing a fire suppression (thick line) and auto extrication (thin line) field study trial respectively.



## **Discussion**

### General

The present study has focused on how protective clothing retards physiological recovery, and how more efficient cooling during rest pauses is able to decrease the chance of heat exhaustion during repetitive fire fighting activity. The study was designed to be practical and examined the cooling effect of removing the fire fighter's turnout coat and utilizing a fan to cool an individual during a recovery period. Most fire trucks carry ventilation fans, and it was theorized that the use of these fans in conjunction with a fire fighter removing their turnout gear would provide the least expensive and most practical way of cooling a fire fighter at a fire scene. This easily implemented practice has been evaluated and found to decrease the physiological stress experienced by a fire fighter significantly during moderate work in a hot humid environment.

The study indicates that the combined effect of environmental heat and the high energy cost of stepping work places a severe physiological demand on a fire fighter. The heavy protective clothing a fire fighter wears is a significant heat stress hazard. Further physiological strain is placed on a fire fighter by the impermeable nature of the clothing worn. Fire fighting clothing prevents the dissipation of the heat load properly, and thus increases heart rate, oxygen consumption, skin temperature, core temperature, and sweat rate. By removing their coat and sitting in front of a fan during a recovery period, a fire fighter can significantly decrease the degree of physiological strain encountered and reduce their chance of heat exhaustion during repetitive fire fighting work.

The physiological strain caused by strenuous work in protective clothing is a very serious issue, currently debated in the Fire Service. Some proponents feel that protective clothing should provide less thermal protection in order to improve temperature regulation in the fire fighter. In 1993, 7.8 % of all fire fighting deaths in the United States resulted from burns (Washburn *et al.* 1994). However, in the same year 50.6 % of fire fighting deaths were attributed to heart attacks (Washburn *et al.* 1994). According to the

National Fire Protection Association (NFPA) 95 % of the 1993 fire fighter deaths from heart attack were due to stress or overexertion. These statistics suggest that more lives could be saved by improving the cooling capability of protective equipment and by implementing more efficient work/rest periods, than would be lost from burns.

In 1975, legislation was introduced in the U.S.A. to develop protective clothing for a fire fighter which would provide greater protection from burns. Fully encapsulated protective clothing, called "NFPA 1500", was developed subsequent to this legislation. The multiple fabric layers of this protective clothing provides excellent thermal protection for the fire fighter, but is bulky, heavy, restrictive and impermeable (Bone *et. al.* 1994, Huck 1991, Venghte 1989). It produces a high relative humidity close to the skin and retards the vaporization of moisture from the skin surface to the exterior of the fabric, and significantly inhibits and even prevents evaporative cooling (Parsons 1993).

### Overall Design

The experimental design used in the present study has tried to mirror typical fire fighting activity and was based on practical work/rest periods generally used by fire fighter in the field. An investigation of the optimal use of recovery time during fire fighting activity, in effecting the greatest reduction possible in heat stress of the fire fighter in the simplest manner possible, was a major intent of the study. A 10 minute period was chosen for the work interval as this would not be too stressful on a subject and it represents a reasonable time limit for the execution of many fire fighting tasks. A 10 minute recovery period was chosen because it was the same length as the work period and it represents a typical recovery period in some fire fighting situations. The second work period was set at the same length and intensity as the first in order to determine what effect on repetitive effort was produced by optimal recovery (OR) between work periods, compared with a conventional normal recovery (NR) practice. A second recovery period was selected in

order to compare it with the first, and to determine the effects of both preceding work and recovery periods on the fire fighter.

The recovery protocols were designed to determine the effect of more efficient cooling during recovery, compared with conventional practice. The normal recovery experimental condition, where a subject unbuckled their coat and removed their helmet, gloves and hood, is the typical way in which a fire fighter recovers during a permitted rest pause. Results show that by leaving their coat on during recovery, a fire fighter limits evaporative cooling and significantly hampers his recovery. An optimal recovery experimental protocol has been described in the present work which requires only two simple changes to current practice. This optimal recovery design improves a fire fighter's recovery rate from heat strain significantly. By removing their coat and sitting 1 meter in front of a 16 inch fan a fire fighter can dramatically improved evaporative cooling. A fan was chosen to improve evaporative cooling during recovery because it is standard equipment found on almost all fire vehicles. Fans are frequently used during fire suppression to remove smoke from a building. Thus it would be relatively easy to utilize such equipment in a recovery area(s) at the fire scene.

A major problem in proposing a standard work/rest protocol is that each fire situation is different. Fire fighters typically work at a very high intensity until an emergency situation is under control, or until they run out of air and have to rest while their air bottle is being changed. Actually being able to take a rest period during fire fighting depends on the severity of the situation and the number of fire fighters at the scene. The proper proportionate length of the individual work/rest distribution is dependent on work intensity and environmental heat. The heat exposure a fire fighter faces during a work period varies in severity, is irregular and often of short duration. However, a common minimal standard of an equal rest to work period ratio should be set.

### Existing Studies

Most existing studies on fire fighters have been conducted using treadmill or cycle ergometer tests in environmentally controlled rooms. This present study chose stepping exercise to simulate a typical fire fighting task better. During stepping a fire fighter has to lift the weight of their protective clothing and SCBA, while performing a motion that is common to many fire fighting tasks. On the fire ground fire fighters have to climb stairs, ladders and clamber over obstacles.

There is very little research data on the physiological response of a fire fighter to an emergency situation. Every emergency situation is different, and it is very difficult to use most portable measuring devices in dangerous situations. There have been a few studies which have measured simulated fire fighting activity to determine the physiological response to different tasks. In this study two field experiments were added in order to measure the reliability with which the simulated physiological response measured in the laboratory, represented the real field response of a fire fighter performing two common fire fighting tasks. Although the field studies were not carried out under absolute emergency conditions, they were reasonable simulations. The two common fire fighting tasks were auto extrication and fire suppression. The physiological responses measured in the field were very similar to the laboratory measures.

### Physiological Effects of Heat Stress

#### **Heart rate**

Heart rate is elevated during fire fighting activity in order to supply oxygen to the working muscles. Heart rate is also increased in order to lower mean body temperature by increasing blood flow to the peripheral vasculature (Skoldstrom 1987). Near maximal heart rates have been reported during fire fighting situations (Romet and Frim 1987, Sothman *et al.* 1992, White *et al.* 1989). These high heart rates are caused by environmental stress, work stress, psychological arousal, and the high motivation of fire fighters (Duncan *et al.* 1979,

Faff and Tutak 1989, Romet and Frim 1987). Several researchers have suggested that the observed high heart rates found in actual fire fighting situations may be dependent more on the environmental temperature experienced by the fire fighter, than the work or the weight of the protective clothing worn (Duncan *et al.* 1979, Romet and Frim 1987, Skoldstrom 1987). The above findings are also reflected in the results of the present study.

In this study the mean heart rate of the subjects decreased significantly ( $p \leq 0.05$ ) during the first and second recovery periods of the OR condition compared with the NR condition. The heart rate results demonstrate that the OR condition produced not only a significantly lower recovery heart rate, but also a lower working heart rate during the second work period. Since heart rate is a sensitive indicator of physiological strain, it is apparent that the subjects were always under a greater physiological strain during the NR condition. Since work undertaken in each laboratory trial was the same it may be concluded that the increase in heart rate between the 2 conditions was due to heat stress. By removing their coat and sitting in front of a fan during the OR trial, a subject significantly reduced heat stress. Decreasing this source of physiological stress will significantly increase the safety of the fire fighter.

The similarity of the group mean heart rate recorded during the work and recovery periods of the field studies, to the laboratory means, confirmed the validity of the laboratory work and the feasibility of the proposed cooling techniques in the field. During the 10 minute fire suppression work period the 2 subjects worked at an average of 79.8 % of their maximum heart rate. During the auto extrication work period the subjects averaged 82.5 % of their maximum heart rate. The results of the 2 field studies and the laboratory work indicate that the heart rate of a fire fighter tends to increase gradually during a work period. This cardiac drift is expected as heart rate must increase in response to the accumulating physiological strain. The heart rate results of the 2 field studies seem to suggest that fire fighters self select a similar, and relatively high work intensity, when performing a physically demanding task.

### Oxygen uptake

In the present study the oxygen uptake response of a subject to each step increase in work rate is easily observed in the early portion of the stage. Later the distinctive exponential growth of  $\dot{V}O_2$  in response to a step stimulus increase in work rate is blurred and appears more linear in the latter stage of each work rate. This blurring of the normal exponential gas exchange response is probably due to the added cardiovascular strain induced by the deteriorating thermal balance of the exercising subject.

The oxygen uptake values for both the NR and OR conditions were higher in the second work period, even though the work was the same in both periods. This indicates that the degree of fatigue and heat strain caused by the first work period increased oxygen uptake in the second work period. The more efficient recovery provided in the OR condition resulted in a significantly lower mean oxygen uptake for subjects at the start of the second work period. The increasing  $\dot{V}O_2$  of the NR condition for equivalent work compared with the OR condition, emphasizes that when thermal balance is threatened more of the circulation is diverted to cooling than to oxygen supply to the working muscle.

In the present study at the end of the second work period a subject reached a mean heart rate that was  $90.0 \pm 5.3$  % of maximum in the OR condition, and  $94.6 \pm 2.2$  % of maximum in the NR condition. At this same point in time a subject only reached  $70.3 \pm 4.5$  % of their maximum oxygen uptake in the OR condition and  $74.8 \pm 4.8$  % of their maximum oxygen uptake in the NR condition. These results support findings from other studies which suggest that prediction of energy expenditure and oxygen uptake from heart rate is not accurate during work in a hot environment (Duncan *et al.* 1979, Gavhed and Holmer 1989, O'Connell *et al.* 1986, Skoldstrom 1987). In a hot environment the heart rate is higher, than in a cool environment at the same work rate (Gavhed and Holmer 1989). However a person's oxygen uptake does not increase proportionally as much as heart rates in hot conditions (Duncan *et al.* 1979).

## Temperature Regulation

### Rectal temperature

In the present study rectal temperature increased significantly more during the NR condition compared with the OR condition. This result clearly demonstrates the physiological advantage of more efficient cooling during recovery from stressful work in the heat. In the NR condition rectal temperature actually increased more during recovery periods than during work periods. This increase in core temperature during each recovery period is obviously due more to heat stress, and the changing contour of heat accumulation in the body, than to physical stress. This point is supported by the fact that a subject performed no work during the recovery period, and the rise in core temperature was considerably less in the OR condition.

While a fire fighter's heart rate rises rapidly during work in a hot environment, rectal temperature shows a delayed response. The results of the experiments in Chapter 2, and several other studies, have shown that rectal temperature continues to rise during recovery, while the heart rate declines (Bone *et al.* 1994, Duncan *et al.* 1979, Faff and Tutak 1989, Geladas and Banister 1989, Givoni and Goldman 1972, Smith *et al.* 1995, Webb 1986). This after-rise in core temperature during recovery could be explained as a phase lag in the dynamic response of the core to heat generated during work. Nevertheless, the increase in rectal temperature whatever its real cause cannot afford to be discounted as a risk indicator for heat exhaustion until the phenomenon is thoroughly explained.

### Tympanic temperature

In the laboratory study tympanic temperature increased significantly more during the NR condition compared with the OR condition. However, the absolute tympanic temperature was consistently 0.75 °C lower than the rectal temperature. Other studies have reported that tympanic temperature is usually 0.4 °C lower than rectal temperature concomitantly measured (Clark and Edholm 1985). The heavy insulative protective pants worn by the subjects

may also have increased rectal temperature compared with tympanic temperature.

The results from the study demonstrate that the body core temperature increase is related to both physical and environmental stress which occur during fire fighting in protective clothing. This rise in core temperature during recovery can be attributed to heat stress as no physical work is performed. This point is confirmed by the fact that under a more efficient cooling protocol the rise in core temperature is significantly less. During both recovery periods in the OR condition rectal temperature increased by only 0.25 °C compared with an increase of 0.90 °C during the NR condition. This result clearly indicates that a fire fighter can reduce heat stress by implementing a more efficient cooling practice during spaced recovery periods at a fire scene.

The tympanic temperature increase from rest during work in both field studies was similar to the rise observed during stepping work in the laboratory trials. This indicates that the stepping work performed in the laboratory study was a reasonable simulation of the real work performed in a fire fighting task. The 2 field study results indicate that a fire fighter's core temperature will increase significantly during a relatively intense 10 minute work period. The field study results also indicate that a fire fighter's core temperature will continue to gradually increase during recovery for at least 10 minutes after completion of work. It should also be noted that an increase in core temperature occurs even at the relatively cool temperatures encountered during the field studies. Thus in hot field conditions heat stress may be much worse than that produced in the laboratory study.

### **Skin temperature**

Skin temperature is a complex resultant of the environment, clothing, metabolic rate and the individual's state of hydration (Clark and Edholm 1985). Many different methods have been used to determine mean skin temperature, most methods take a mean temperature from 4 or 6 skin sites. It is usually considered that fewer skin sites



need to be recorded in the heat where skin temperature is homogeneous (due to vasodilation) and more points are required in the cold where skin temperature is heterogeneous (due to vasoconstriction) (Parsons 1993). In this study skin temperature was recorded from three thermisters taped to the skin of the arm, chest and thigh. A mean skin temperature for the 12 subjects was calculated for each of the three skin sites so that the skin temperatures from the three sites could be compared. Since the protective clothing was thought to have a different effect on the three skin sites during work and recovery, a mean skin temperature over the whole body was not calculated. Whole body mean skin temperature was also not calculated because only three skin temperature responses could be recorded with the portable measuring device used in the study.

If a body is to maintain thermal equilibrium, body heat (core temperature) will flow to the skin, through the clothing, and finally released to the outside environment. If a body is continually generating heat (by metabolic heat production), the thermal gradient from the body core to the external environment is negative. When a fire fighter performs work in a hot environment the insulation in their protective clothing is designed to slow the flow of heat from the environment to the skin. However, the protective clothing also prevents the flow of heat from the body core to the exterior. Thus a fire fighter's core and skin temperature will increase in proportion to the intensity of their work, and the thermal load of the ambient conditions.

The skin temperature change of several sites during work and recovery cycles reflects the fluctuating surface thermal stress of these respective conditions. Unlike core temperature, skin temperature decreased rapidly during a recovery period in the hot environment when appropriate cooling was undertaken (OR). During a work period skin temperature increased rapidly again because of the resumed convection of heated blood to the skin and the deterioration of the local skin environment with protective clothing cover. During the recovery periods in the OR condition skin

temperature was significantly reduced by the evaporative cooling effect of the fan and possibly by reduced convection of core heat to the periphery as the heart rate dropped. The results from the 3 skin sites show the considerable local variations in skin temperature of a clothed body due to the difference in flow of air across various parts of the body and the covering effect of clothing which can prevent access of the skin to cooler ambient conditions. The skin temperature results emphasize the cooling benefit of removing clothing and using a fan during a recovery period in the heat.

### **Dehydration**

Body weight loss is an indicator of thermal strain, as most of the weight is lost through sweating (Parsons 1993). A small portion of weight loss is evaporative loss through breathing. During the OR condition of the present study the group mean loss of weight was  $1.07 \pm 0.11$  kg. During the NR condition the average weight loss was  $1.30 \pm 0.17$  kg. The subjects were significantly ( $p \leq 0.05$ ) more dehydrated after the NR trial. The increased dehydration may be attributed to an increased sweat rate during the recovery periods when a subject left their coat on, and were not cooled by a fan.

If there was a significant increase in sweat rate during the NR condition, there should also be an increase in evaporative cooling. The fact that  $T_{re}$  increased more in the NR condition indicates that the sweating efficiency was impaired in the NR condition. Thus the evaporative rate is likely greater in the OR condition, even with a lower sweat rate, resulting in greater cooling efficiency.

### **Body composition**

Although the difference was not significant it was noted in the study that the greatest increase in rectal temperature during the NR condition was by the subjects with the lowest percent body fat and the largest height/weight ratio. During the OR condition there was no difference between a lean or heavy subject. The group mean rectal temperature of the 6 heavy subjects increased by  $1.45$  °C during the 40 minutes of the NR condition. In comparison the mean rectal

temperature of the 6 lean subjects increased by 1.55 °C during the NR condition. These results suggest that a heavier subject has a greater mass throughout which to distribute heat storage.

Research into the relation between body composition (physique) and core temperature change in a hot environment is inconclusive. However, it is generally considered that a heavier subject will have a slower rise in core temperature in a hot environment due to the better insulative and heat storage quality of their thicker muscle and adipose tissue (White *et al.* 1992). It has been reported that skeletal muscle has a greater insulative property than adipose tissue (White *et al.* 1992). Thus it seems that a heavier subject is at an advantage and may be able to work for a longer period of time before heat exhaustion. However, a leaner fire fighter will be able to recover faster, as their core temperature will fall at a faster rate during the recovery period. Although the difference in core temperature responses between heavy and lean subjects were not significant in this study, it appears that it is an area of inquiry which requires more research.

#### Effect of age

The subjects in the present experiment ranged from 22 to 42 years of age. There was no significant difference between the older subjects and the younger subjects in any of the physiological conditions tested. The results show that a healthy 40 year old fire fighter, in good physical condition, is as fit for fire fighting tasks as those of a younger age.

#### Artificial Cooling Methods

In order to reduce the effect of heat stress, the military and industry have investigated the use of air, ice, freon<sup>®</sup> and liquid cooled suits (Pascoe *et al.* 1994a, Speckman *et al.* 1988, White *et al.* 1991). These suits are expensive to manufacture and have been met with mixed and limited success. White *et al.* (1991) found that ice water and freon<sup>®</sup> cooling garments, under a fully encapsulating chemical suit, significantly reduced heart rate, skin temperature, core temperature

and dehydration. Torso cooling is more effective than head and neck cooling, and air cooling is considered inferior to water cooling because of the low heat capacity of air and mechanical limitations in current equipment (Epstein *et. al.* 1986). Cooling the torso by a water- or air-cooled vest has a similar effect but is not as effective as an ice bag vest.

Air, ice, freon<sup>®</sup> and liquid cooled suits could definitely benefit a fire fighter during work and recovery. However, they may be too bulky and restrictive to work in, and they are currently too expensive for many fire departments to consider. The present study used fan cooling during recovery, even though cooling the torso with a fan is less effective than the above methods. However, fan cooling remains the most practical and least expensive of the above alternatives, while remaining highly effective, as was demonstrated in the present study. Almost every fire truck currently carries a large powerful ventilation fan. Thus the fire fighter has easy access to a fan which could be used to enhance individual cooling during recovery periods at a fire scene.

#### Implementation of Fire Fighter Rest Periods

This study has demonstrated the significant advantage of removing a coat and utilizing a fan to reduce the developed physiological strain of heat stress during a fire fighter's recovery period. An increasing number of fire trucks are also being equipped with air-conditioned enclosed cabs. This cool location could also be used to provide optimal cooling for a fire fighter during a recovery period. Fire jurisdictions should also consider purchasing ice, water, freon<sup>®</sup>, or air-cooled vests to improve the recovery of a fire fighter at a fire scene.

Determination of work/rest cycles requires accurate assessment of the heat load and the heat transfer interactions between the body, clothing and the external ambient conditions (Pascoe *et al.* 1994a). In fire fighting situations it is very difficult to monitor and determine the optimum work/rest cycle. Fire fighters perform different tasks under different conditions and there may not

be the time, or a desire, to take a rest break. It is also important to consider the thermoregulatory variability between individuals. The difference in performance between individuals during work in a hot environment is influenced by an individual's present state of acclimation, level of fitness, and state of hydration.

In fire fighting situations exposure time must be regulated, as it is almost impossible to limit temperature exposure. Results from this study indicate that short term exposure (10 minutes) to heavy work in a hot environment will not endanger a healthy fire fighter. However long term exposure, such as those associated with a large structure fire, can lead to an accumulation of heat stress that may endanger the fire fighter. Repeated exposure with inadequate recovery will also increase the fire fighter's risk of heat exhaustion and heat stroke. Inadequate recovery can be defined as a recovery period which does not decrease a fire fighter's core temperature. The potential danger of heat stress requires that maximal permissible limits be put on work duration. Although in each fire situation it is difficult to account for all of the variables contributing to physiological strain, some type of recovery period must be implemented. As this study has demonstrated optimal cooling during recovery will have a dramatic effect on reducing heat stress.

The present work indicates that after heavy work in a hot environment core temperature will continue to rise. The rise in core temperature during a recovery period however, can be suppressed by more efficient cooling practices. Recovery time should be at least equal to working time and should take place in a cool environment which has adequate ventilation. The fire fighter should remove his helmet, hood, gloves and turnout coat to facilitate evaporative cooling. Water loss should be replaced during recovery as dehydration can reduce a fire fighter's capacity to work.

Current recovery practice is not very stringent and depends on the policy of the fire department, the severity of a situation, and the number of fire fighters available. In many fire departments the timing and extent of a recovery period is based on the subjective opinion of the fire fighter, who takes a break when he thinks he

needs one, or is timed to coincide with the depletion of an SCBA air bottle. Both of these current practices have severe limitations. A fire fighter is unable to sense what his core temperature is, and he may have no idea that he is close to heat stroke. An SCBA air bottle comes in 2 standard sizes (1 hour and 1/2 hour) and the time that it takes to deplete the bottle is based on a number of factors. How long a fire fighter worked before using the air, the initial air capacity of the bottle, the work performed by the fire fighter, and the oxygen requirements of the fire fighter all can effect the time that it takes to deplete an air bottle.

### Continuous Versus Intermittent Work

An important issue that has received very little attention is the physiological consequence of intermittent work compared with continuous work in a hot environment. Results from the present study indicate that in some situations it may be beneficial to implement a long continuous work period, followed by an extended recovery, instead of intermittent work with partial recovery periods. It appears that a fire fighter who works for 20 minutes continuously may endure less physiological strain than if he worked for 10 minutes, recovered for 10 minutes and then worked for another 10 minutes. This would be especially true if the fire fighter recovered in a hot environment, or was not cooled optimally during recovery. During the NR condition of the present study a subject's core temperature increased more during the first recovery period (0.43 °C) than during the 2 work periods (0.33 °C and 0.27 °C). The increase in rectal temperature of the subjects for the 2 work periods was 0.60 °C. If the subjects completed the 2 work periods without a recovery period, the increase in rectal temperature would probably be more than the 0.60 °C obtained by adding the increases from both work periods. Without the recovery period, fatigue would increase rectal temperature in the second work period. However, the added increase in  $T_{re}$  in the second work period would probably not be more than the 0.43 °C increase in  $T_{re}$  obtained during the recovery period. In the OR condition  $T_{re}$  only increased by 0.07 °C during the

first recovery period. Therefore in the OR condition intermittent work would probably be safer than continuous work.

### Summary

This discussion has addressed the major causes of heat stress in a fire fighter. The combined effects of environmental heat and the high energy cost of fire fighting work, places severe physiological demand on a fire fighter. Additional physiological stress is caused by the impermeable nature of fire fighter clothing. Heat stress could be reduced by designing breathable fabrics with heat retarding properties for use in turnout gear. Even lighter more permeable clothing would reduce the heat stress placed on fire fighters and would result in a lower heart rate, oxygen consumption, skin and core temperatures. Protective clothing is essential in order to protect the fire fighter, however, the adverse effect of this item should be recognized and weighed in its contribution to the total hazard facing a fire fighter. The present work has shown that by removing their coat and sitting in front of a fan during a recovery period, a fire fighter can decrease the physiological strain of a marked thermal imbalance accumulating during fire suppression work, and reduce the chance of heat exhaustion during repetitive fire fighting action. Currently there are only minimal guidelines for fire fighting work/rest periods. Considering the vast number of fire fighters, and the harsh environments in which they must work, more research must be conducted into proper work/rest periods and more efficient ways to cool fire fighters during work and recovery.

### **Limitations of the study**

The most serious limitation of this study was the ability to simulate a real fire fighting situation. The ability to control the environment, as well as the amount of work that a subject performed, was excellent for comparing the difference between the two recovery conditions. However, rarely will a fire fighter work under exactly the same conditions at a fire scene. Every fire situation is different, and a fire fighter routinely works at a very high intensity until a fire situation

is under control or until they are exhausted. During real fire fighting situations the individual motivation of the fire fighter is an important factor which can not be simulated in an experiment. An auto extrication and fire suppression field study were conducted to verify that the individual physiological response and work performed during the laboratory study were similar to that recorded during an actual fire fighting task.

Another limitation of the study was the narrow range of fitness level among the twelve subjects. As illustrated by the  $\dot{V}O_2\text{max}$  and percent body fat values (Table 2) of the subjects, they were all very fit individuals. This group of subjects was not a very good representation of the variation of fitness levels found in the fire service. However, the 12 subjects still represent a wide spread level of fitness found among fire fighters.

### **Conclusions**

The present study has demonstrated that protective clothing retards thermal regulation and physiological recovery during heavy work in a hot environment. This increases the potential of heat strain during repetitive fire fighting action. The recovery achieved by taking short rest breaks, while wearing protective clothing, has been shown to be inadequate. By removing protective clothing, and utilizing a fan during a recovery period, a fire fighter can reduce the risk of heat exhaustion during a subsequent fire fighting task following a rest period. Most fire trucks carry large powerful ventilation fans, and these fans should be used to enhance individual cooling during the standard recovery period at a fire scene. More research is needed into the areas of fire fighting work/rest periods and efficient cooling practices. Fire departments might also consider purchasing ice, freon<sup>®</sup>, water, or air-cooled vests to improve the recovery of a fire fighter at a fire scene.



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