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DEPARTMENT OF MECHANICAL
ENGINEERING

Thermophysiological Safety Methods of Fighting Fires – a Numerical Study

Submitted Dissertation to Obtain a Master's Degree in Mechanical Engineering,
Field of Energy & Environment

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“First ask yourself: What is the worst that can happen? Then prepare to accept it. Then proceed to improve on the worst.”

Dale Carnegie

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ABSTRACT

It’s a fact that a firefighter during a wild fire exposure faces a great physical and physiological fatigue due to the exposure of hot dynamic environments. The use of effective methodologies in reducing this fatigue, or like is frequently called heat stress; it’s a reality to be encountered. Those can avoid fatalities and assure that firefighters can return to the fire bouts without any aggravated health risks.

There are several factors that could influence the performance and effectiveness of a firefighter during a fire. In the present study the aim is to quantify and qualify the firefighter’s behavior during these exposures, studying the influence of the following factors: individual physiologies, protective clothing, fluid ingestion, planned duties and effective cooling methods.

Keywords Cooling, Core Temperature, Fire, Firefighters, Heat Stress, Thermoregulation.

RESUMO

É sabido que um bombeiro durante o combate a incêndios, onde o ambiente é imprevisível, está sujeito a situações de grande fadiga física e psicológica.

O uso de metodologias eficazes na redução desta fadiga, ou como é frequentemente chamada de stress térmico, é uma realidade a ter em conta, de forma a evitar fatalidades bem como garantir que os bombeiros possam voltar à "acção" sem riscos agravados para a sua saúde.

São vários os factores que podem afectar o desempenho e a performance de um bombeiro durante um incêndio. No presente estudo pretende-se quantificar e qualificar o comportamento dos bombeiros durante o combate a incêndios, estudando a influência de factores como: fisiologia do indivíduo, fatos de protecção, reposição de fluidos, programação e rotação de tarefas bem como métodos de arrefecimento efectivos do corpo humano.

Palavras-chave: Arrefecimento, Bombeiros, Fogo, Stress Térmico, Termorregulação, Temperatura interna.

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NOMENCLATURE

Symbol	Description	Units
ε	External Surface Emissivity	[%]
A_D	Body Surface Area	$[m^2]$
A_{sk}	Specific Human Body Segment of Skin Area	$[m^2]$
$B_{i,j}$	Exchange of Heat Between all Local Layers and the Central Blood Compartment	[W]
C	Heat exchanges Via Convection	[W]
Cond1	Heat Lost by Conduction to Clothing	[W]
Cond2	Heat Lost by Direct Contact of Uncovered Parts With External Surfaces	[W]
Conv	Heat Lost by Convection to the Environment	[W]
cp_b	Specific Heat of Human Body Blood	$[J/kg.K]$
$cp_{i,j}$	Specific Heat of the node	$[J/kg.K]$
$E_{máx}$	Maximal Attainable Evaporative Cooling for a given Environment and Clothing Configuration	[W]
E_{req}	Required Evaporative Cooling	[W]
E_{resp}	Evaporation Accompanying Ventilation	[W]
H	Metabolic Energy Transformation	[W]
h_{conv}	External Dry Convection Coefficient	$[W/m^2.°C]$
h_{rad}	External Dry Radiation Coefficient	$[W/m^2.°C]$
HR	Heart Rate	[beats/min]
I_{cl}	Clothing Insulation	[clo]
I_m	Moisture Permeability Index	[ ]
I_{TOT}	Total Insulation, Including the Trapped Boundary Layer and Clothing Insulation	$[m^2.K.W^{-1}]$
I_{vp}	Vapour Permeability Efficiency	[%]
M	Exercising Metabolism	[W]
m_b	Mass of Human Body Blood	[kg]

$m_{i,j}$	Mass of the node	[kg]
$MB_{i,j}$	Basal Metabolism of the node	[W]
p_a	Water Vapour Pressure of the Air	[kPa]
P_{sk}	Water Vapour Pressure at the Skin Surface	[kPa]
$Persp_{i,j}$	Perspiration at the skin surface	[W]
$Q_{i,j}$	Heat Transferred Through the Tissues	[W]
R	Heat Exchanges via Radiation	[W]
$Rad1_{i,j}$	Heat Transfer by Radiation with the Environment	[W]
$Rad2_{i,j}$	Heat Transfer by Radiation With a Specific Source	[W]
$Resp_{i,j}$	Loss of Heat by Respiration	[W]
RH	Relative Humidity	[%]
$Sh_{i,j}$	Heat Production by Shivering	[W]
$Sw_{i,j}$	Evaporative Heat Loss at Skin Surface by Sweating	[W]
T_{air}	Air Temperature	[°C]
T_c	Body Core Temperature	[°C]
T_{cl}	Temperature on External Surface of Clothing	[°C]
T_g	Black Globe Temperature	[°C]
T_{nbw}	Natural Wet Bulb Temperature	[°C]
T_{sk}	Skin Temperature	[°C]
v_{air}	Air Velocity	[m/s]
$We_{i,j}$	External Work or Motion	[W]
$Wi_{i,j}$	Internal Work	[W]

ABBREVIATIONS

DEM	Mechanical Engineering Department
FCTUC	Faculty of Sciences and Technology from University of Coimbra
HHH	Heavy Work / Heavy Work / Heavy Work
HLH	Heavy Work /Light Work /Heavy Work
HSI	Heat Stress Index
ISO	International Standards Organization
OSHA	Occupational Safety and Health Administration
SCBA	Self Contained Breathing Apparatus
UHS	Uncompensable Heat Stress
US	United States
WBGT	Wet Bulb Globe Temperature
WRW	Heavy Work / Rest / Heavy Work
WWW	Heavy Work / Heavy Work / Heavy Work

1. INTRODUCTION

Humans are homoeothermic creatures, thus can regulate their body temperature within a narrow range over the entire course of their lives. When heat is generated by increased activity, humans are generally successful in maintaining a thermal steady state by activating heat-loss mechanisms to dissipate the excess heat (Figure 1.1) (McLellan & Selkirk, 2006).

From a clinical perspective, body-core temperature (T_c) is normally regulated at approximately 36.7 ± 0.3 °C. If T_c varies by more than 2 °C either side of 37 °C, then one can assume that thermal balance has been lost or thermoregulatory failure has occurred. In this state, the regulation of body temperature has been transiently compromised, resulting in either hypothermia (< 35 °C) or hyperthermia ($> 39\ °C$), with the possibility of death accompanying a T_c reduction of about 10 °C, or an elevation of only 5 °C (Taylor, 2006).

Thermal equilibrium can be obtained through the balance between the loss and heat gain by the body, depending on which direction thermal gradient walks into. In a particular way this equilibrium can only be achieved through the thermoregulatory system of the human body, in other words by the hypothalamus, that is located at the base of the brain. Hypothalamus is the coordinating centre for the various processes of temperature regulation. This is considered the "thermostat" for temperature regulation.

As reported above, heat can be absorbed or dissipated by the body depending on the thermal gradient. This energy exchanges occur in majority due to few heat transfer mechanisms, stated as conduction, convection, radiation, evaporation and respiration.

Conduction only occurs where the body is in direct contact with another surface and usually plays a very minor role in heat loss/gain from/to the body. Convection is a much more significant avenue for heat loss/gain provided when the ambient air is cooler/warmer than the skin. Radiation can also be a significant mean of heat transfer if the surface temperature of the body is much different than the surface temperature of the objects in the environment (Carter et al., 2008). On the other hand Evaporation is one of the main means of heat dissipation, required to maintain a thermal steady state, and it is responsible for about 80% of heat dissipation from the body (Carter et al., 2008). Respiration is responsible nearly 10% of heat dissipation from de body (Ross, 2005).

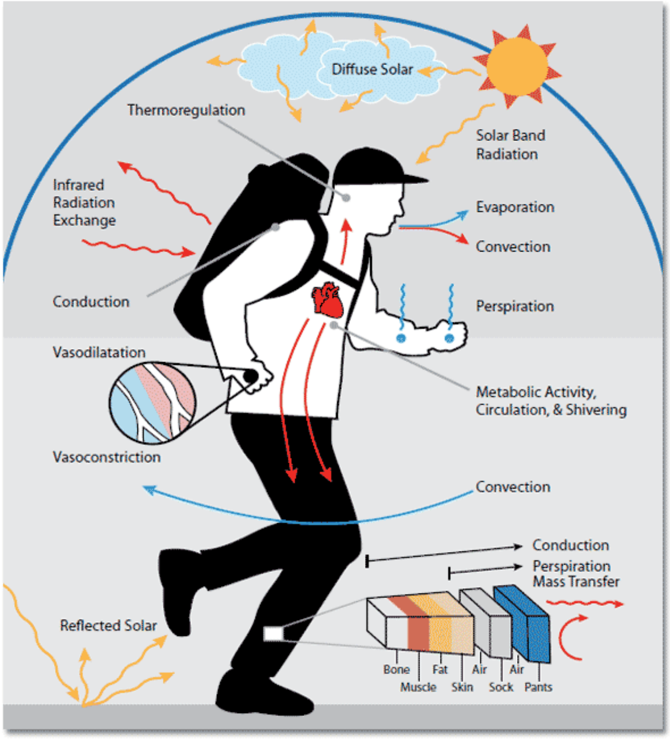

Figure 1.1 - Human thermoregulatory system (ThermoAnalytics).

The main goals of this work are to study in detail firefighters, during wildland fires, which is one of the most adverse circumstance in terms of heat exposure and work rate, resulting in both physically and psychological strain; and to study strategies to attenuate heat stress, caused by hot environments exposure and heavy tasks, and so extend the operational effectiveness of a firefighter.

1.1. Wildfires

There are four conditions that need to be present in order for a wildfire to burn (Figure 1), which firefighters refer to, as the fire tetrahedron (Figure 1.2): fuel, oxygen, heat source and a possible chemical chain reaction (Viegas, 2005). Fuel is any flammable material surrounding a fire, including trees, grasses, brush, even homes. The greater an areas fuel load, the more intense the fire. Air supplies the oxygen a fire needs to burn. Heat sources help spark the wildfire and bring fuel to temperatures hot enough to ignite.

Lightning, burning campfires or cigarettes, hot winds, and even the sun can all provide sufficient heat to spark a wildfire (National Geographic).

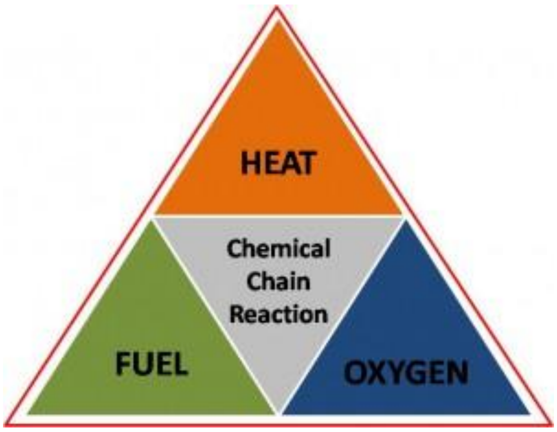

Figure 1.2 – Fire Tetrahedron (Amfine, 2010).

Firefighters fight wildfires by depriving them of one or more of the fire tetrahedron fundamentals. Traditional methods include water dousing and spraying fire retardants to extinguish existing fires. Clearing vegetation to create firebreaks starves a fire of fuel and can help slow or contain it. Firefighters also fight wildfires by deliberately starting fires in a process called controlled burning. These prescribed fires remove undergrowth, brush, and ground litter from a forest, depriving a wildfire of fuel (National Geographic).

1.2. Firefighters

Firefighters are often required to perform prolonged periods of strenuous work under conditions of high environmental heat strain (Figure 1.3) (Barr et al., 2009).

This stress is partly caused by the energy cost of the firefighting tasks which include the mass of heavy protective clothing, partly by the heat exposure. An elevated blood flow to the muscles is necessary to perform physical work. Muscle blood flow is linearly related to the increase in exercise intensity. Also, skin blood flow is elevated in hot environments to increase heat loss from the body. Skin blood flow increases linearly with core temperature after a given period of time or from a given core temperature threshold of vasodilatation. The circulatory demand of the combined effects of heat stress, dynamic muscular work and load carrying elevates heart rate (HR) to high levels in the fireman at work (Gavhed & Holmér, 1989).

In order to complete such tasks successfully the firefighters must possess certain physiological characteristics. Successful completion of fire-fighting activities requires high levels of contribution from both aerobic and anaerobic energy systems and is associated with high levels of muscular strength and endurance (Barr et al, 2010).

The major thermal phenomena that a firefighter must be concerned with are the heat produced by their own metabolism, the thermal radiation from flames, the convection with surrounding hot gas (air and smoke) and the conduction from ground at high temperature. The combination of this energy with the heat produced by human metabolism has a significant impact on the thermo-physiological behavior of firefighters and can cause important, undesired reactions, namely introversion (violent sweating, loss of judgment, amnesia, etc.), superficial skin damage (pain and first degree burns), heat stroke (fainting, cessation of sweating, central nervous system alteration, etc.) and permanent injuries (burn degree greater than first, brain damage or, in more serious cases, death) (Raimundo & Figueiredo, 2008).

Figure 1.3 – Firefighters suppressing a fire front (Parafinavicius, 2009).

1.3. Motivation

Firefighters are frequently involved in wildland fires, therefore exposed to hot environments, which means that their body core temperature may reach high levels that are hazardous for their health. Other country experiences show that is necessary to have efficient methods to cool down the body, thus attenuating heat stress.

The aim of the present report is to compare several different methods of body cooling through a program that simulates the thermoregulatory behaviour of the human body.

2. HEAT STRESS

Heat stress can be defined as the amount of heat that has to be dissipated or produced to keep human body in a steady state (OMS, 1969).

Any process or activity that is likely to raise the human body deep core temperature raises the risk of heat stress. Operations involving high air temperatures, radiant heat sources, high humidity, direct physical contact with hot objects, or strenuous physical activities have a high potential for inducing heat stress in people. In addition, age, weight, degree of physical fitness and acclimatization, dehydration, metabolism, use of alcohol or medications, and a variety of medical conditions all affect an individual sensitivity to heat (Berry).

As said above, we can apprehend that heat stress refers to heat load on the body (Figure 6) (McLellan & Selkirk, 2006). Still, there are two sources of heat stress (Figure 2.1): internal and external. Internal heat is generated by metabolism and is determined mainly by the exercise or the intensity of work. External heat stress is that from the environment and includes the insulation effects of clothing (McLellan & Selkirk, 2006).

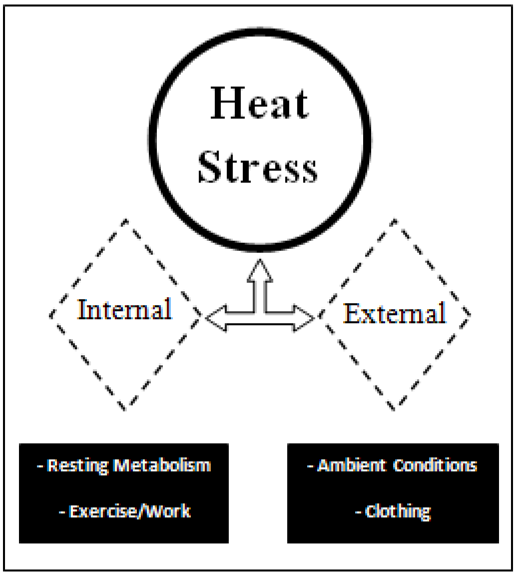

Figure 2.1 – Sources of Heat Stress, adapted from (McLellan & Selkirk, 2006).

As extensively reported there are many factors that could cause heat stress, so the first task is to identify that source and try to attenuate that effect at maximum. The next step should be evaluate the intensity of heat strain that an individual is being exposed, and when this effect reaches a certain limit the individual should apply an effective methodology to attenuate it, for example active cooling strategies.

In this report, the goal is to set work limits by assessing the maximal heat stress that a subject could handle, limiting the rise of subjects deep core temperature to a maximum value of 39 ℃, and after that apply efficient, and different, cooling methodologies to attenuate it.

2.1. Heat Stress Assessment

The hazards of excessive and repeated heat exposures are well established, but our ability to provide a universally-valid means through which to assess the risk of hyperthermia has proven to be elusive, due to the intricate interactions of a wide variety of physical and physiological phenomena that determine the probability of hyperthermia (Taylor, 2006). In spite of that, there are several indices that attempt to establish heat stress of an individual in a stressful environment (wildfires); the ones that have more expression currently, are the WBGT-index (**W**et-**B**ulb **G**lobe **T**emperature index) and the HSI (**H**eat **S**tress **I**ndex).

2.1.1. WBGT

The WBGT is the most frequently used index to assess heat stress in a stressful environment due to its simplicity of application. It was developed by Yaploplou and Minard with the purpose to reduce the incidence of heat illness like other used indexes (Taylor, 2006).

Indeed, general use of the WBGT-index was recommended by the OSHA (Occupational Safety and Health Administration), and subsequently adopted by the (ISO) International Standards Organization for quantifying thermal stress (Taylor, 2006).

The WBGT index can be described as,

$$WBGT_{(outdoors)} = 0.7T_{nwb} + 0.2T_g + 0.1T_{air}\ [℃] \tag{2.1}$$

where,

- T_{nwb} - Natural wet bulb temperature [℃];

- T_g - Black globe temperature [°C];
- T_{air} - Air temperature [°C];

A number of researchers have evaluated the physiological efficacy of using WBGT-index (Figure 5); these studies have identified several significant limitations of this method. One can generally attribute these limitations to the fact the WBGT-index is not a rational scale. That is, it is not based upon heat balance, and the thermodynamics of these heat exchanges, but solely upon quantifying the thermal environment; its greatest strength (simplicity) has thus become its greatest limitation (Taylor, 2006).

2.1.2. HSI

The ratio of the required evaporative heat loss ($\mathrm{E_{req}}$) and the maximal evaporative cooling that the environment, including clothing, will permit ($\mathrm{E_{max}}$) is called HSI (Heat Stress Index) (Taylor, 2006).

If $\mathrm{E_{req}}$ is greater than $\mathrm{E_{max}}$, then the environmental conditions are uncompensable (UHS) (Taylor, 2006).

This ratio was first suggested by Belding and Hatch, to relate thermal stress to physiological strain and can be described as

$$\mathrm{HSI} = \frac{\mathrm{E_{req}}}{\mathrm{E_{max}}} \tag{2.2}$$

where, required evaporative heat loss is described as

$$\mathrm{E_{req}} = \mathrm{H} - \mathrm{E_{resp}} \pm \mathrm{R} \pm \mathrm{C} \tag{2.3}$$

where:

- $\mathrm{E_{req}}$ - Required evaporative cooling [W];
- H – Metabolic energy transformation, or the nett result of resting and exercising metabolism, and external work ($\mathrm{M} - (\pm \mathrm{W_e})$) [W];
- $\mathrm{E_{resp}}$ – Evaporation accompanying ventilation [W];
- $\mathrm{R} \pm \mathrm{C}$ - Heat exchanges via radiation and convection [W];

On the other hand, maximal evaporative cooling that the environment, including clothing permit is described as

$$\mathrm{E_{max}} = \frac{6.45 \times \mathrm{A_D} \times \mathrm{I_m}}{\mathrm{I_{TOT}} \times 2.2 \times (\mathrm{P_{sk}} - (\mathrm{RH.P_a}))} \tag{2.4}$$

where:

- $\mathrm{E_{max}}$ - Maximal attainable evaporative cooling for a given environment and clothing configuration [W];
- $\mathrm{A_D}$ - Body surface area (Du Bois equation) $[\mathrm{m}^2]$;
- $\mathrm{i_m}$ – Moisture permeability index (0.45 if unknown) [ ];
- $\mathrm{I_{TOT}}$ – Total insulation, including the trapped boundary layer air and clothing insulation $[\mathrm{m^2.K.W^{-1}}]$;
- RH – Relative Humidity of the air [%];
- $\mathrm{P_a}$ - Water vapour pressure of the air [kPa];
- $\mathrm{P_{sk}}$ - Water vapour pressure at the skin surface [kPa];

The above analyses provide us with a first-principles means by which to evaluate the potential for thermal environments to induce physiological strain (Taylor, 2006).

However, this is a complex method, so much of the times is set away and is substituted by assessments methods like WBGT, in spite of his lower accuracy.

3. MATHEMATICAL MODEL

The present Mathematical model arises due to the necessity to simulate the thermoregulatory system of humans. The understanding of its principles and the development of mathematical models for its representation has begun about 40 years ago. The most extensively used model was created by Stolwijk and Hardy (1966, 1971) and since then has been improved by several authors. Many of these modified models have been validated against experimental results and are good research tools for the simulation of human body response to different thermal environments.

To obtain the results presented in this study, a computer program implemented by A.M. Raimundo is used for the simulation of heat and mass transfer and thermophysiological response of a man (firefighter) exposed to extreme environmental conditions, such as those occurring in the proximity of a high intensity forest fire line (Figure 7 and Figure 8) (Raimundo & Figueiredo, 2008).

The present 89-node thermoregulatory model considers the human body divided into 22 segments (Figure 3.1), which are face, scalp, neck, chest, abdomen, upper back, lower back, pelvis, left shoulder, right shoulder, left arm, right arm, left forearm, right forearm, left hand, right hand, left thigh, right thigh, left leg, right leg, left foot and right foot. Each body segment contemplates 4 layers, which are core, muscle, fat and skin. The 89^{th} node is the central blood compartment of the body.

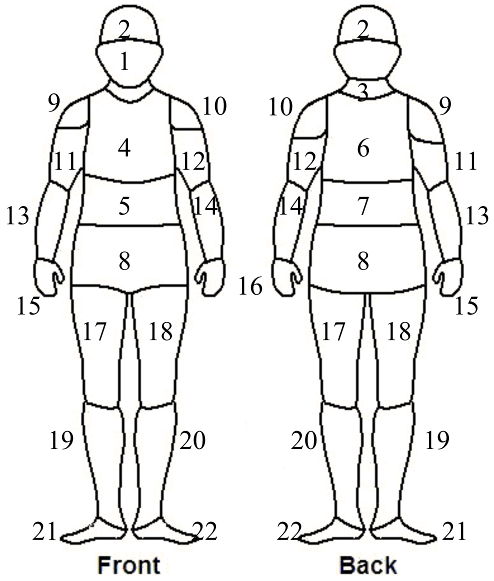

Figure 3.1 – 89^{th} node thermoregulatory model, adapted from Ross & Barker, 2005.

1 – Face
2 – Scalp
3 – Neck
4 – Chest
5 – Abdomen
6 – Upper Back
7 – Lower Back
8 – Pelvis
9 – Left Shoulder
10 – Right Shoulder
11 – Left Arm
12 – Right Arm
13 – Left Forearm
14 – Right Forearm
15 – Left Hand
16 – Right Hand
17 – Left Thigh
18 – Right Thigh
19 – Left Leg
20 – Right Leg
21 – Left Foot
22 – Right Foot

The temporal evolution of temperature (T) in each node (i) of the human body (except blood) is obtained by the following general equation:

$$\begin{aligned} m_{i,j}cp_{i,j}\frac{\partial T_{i,j}}{\partial t} = & \sum_{i=1}^{22}\sum_{j=1}^{4} Q_{i,j} + MB_{i,j} + Wi_{i,j} - We_{i,j} + Sh_{i,j} - B_{i,j} \\ & - Resp_{i,j} - Persp_{i,j} - Sw_{i,j} - Cond1_{i,j} - Cond2_{i,j} \\ & - Conv_{i,j} - Rad1_{i,j} - Rad2_{i,j} \qquad [W] \end{aligned} \tag{3.1}$$

Where $m_{i,j}$ and $cp_{i,j}$ are the mass and specific heat of the node, respectively. The term $Q_{i,j}$ represents the heat transferred through the tissues within individual segments by conduction (Figure 3.2). The rate of heat production is expressed by the result of the basal metabolism $(MB_{i,j})$, the internal work $(Wi_{i,2})$ the external work or motion $(We_{i,2})$ and shivering $(Sh_{i,2})$, with the heat production by work and shivering occurring only in the muscle layer $(j = 2)$. The exchange of heat between all local layers and the central blood compartment via blood circulation is taken into account by term $(B_{i,j})$. The loss of heat by respiration $(Resp_{4,1})$ is compounded by sensible and latent part and is supposed to occur only at core of chest segment. The evaporative heat loss at skin surface has two components, perspiration $(Persp_{i,4})$ and sweating $(Sw_{i,4})$, both function of clothing properties, man thermal status, ambient water vapour pressure and evaporative transfer characteristics at clothing external surface (or skin for a naked segment). At the skin layer surface, heat is lost by conduction to clothing $(Cond1_{i,4})$ and by direct contact of uncovered parts with external surfaces $(Cond2_{i,4})$. Also for uncovered skin layers, the transfer of heat can occur by convection with the environment air $(Conv_{i,4})$, by infra-red radiation with known temperature surroundings $(Rad1_{i,4})$ and by a radiation flux from specific source $(Rad2_{i,4})$. For clothed skin body parts, the components $Cond2_{i,j}, Conv_{i,j}, Rad1_{i,j}$, and $Rad2_{i,j}$ are not accounted at skin layer but at external surface of the corresponding exterior clothing. The heat balance on the central blood compartment is

$$m_b cp_b \frac{\partial T_b}{\partial t} = \sum_{i=1}^{22} \sum_{j=1}^{4} B_{i,j} \tag{3.2}$$

Where m_b and cp_b are the mass and specific heat of human body blood, respectively. The modeling of blood flow heat transfer with each node takes into account the blood flow rate, the counter-current heat exchange between arteries and veins, the vasodilatation and the vasoconstriction in this layer (Raimundo & Figueiredo, 2008).

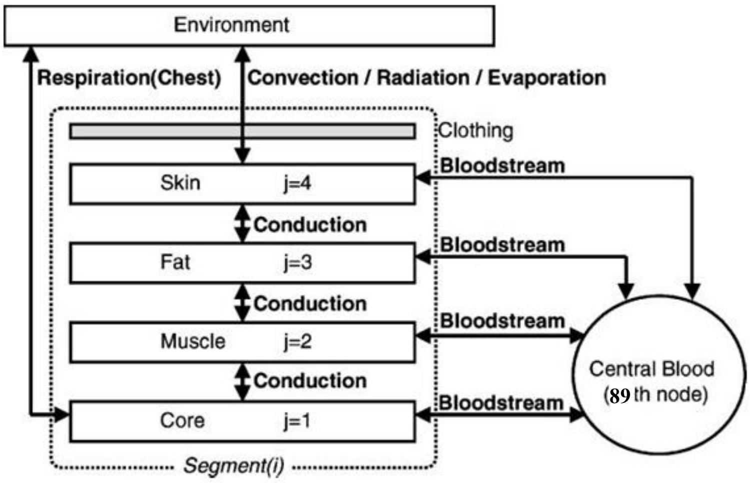

Figure 3.2 – Heat transferred through the tissues Tanabe et al., 2002.

The simulation of heat and water transport through clothing is a very complicated task due to the complex phenomena involved. This model is based on local values for the specific human body segment of skin area (A_{sk}), of clothing insulation (I_{cl}) and vapour permeability efficiency (i_{vp}) of saturate vapour pressure on the skin surface, of temperature on skin (T_{sk}) and external surface of clothing ($T_{cl} = T_{rad}$), of external surface emissivity (ε), of ambient air temperature (T_{air}), velocity (v_{air}) and relative humidity (RH) as well as external dry convection coefficients (h_{conv}) and external dry radiation coefficients (h_{rad}), as Havenith et al.(2004) and ISO 9920 suggest.

It is also required by the operator to set over exposure times that the individual (firefighter) faces, his respective metabolism related to his activity level and his posture and orientation. Man metabolism rate level was set in *met* ($1\ met\ =\ 58{,}2\ W/m^2$) and according to the table bellow (Table 3.1). On the other hand, man posture and orientation were defined for the beginning of the phase and after a possible fainting ocurrence.

Table 3.1 - Metabolism Description.

Metabolism Rate Level $[\mathbf{met}]$	Description
<= 0.00	Man is Dead
0.80	Man Resting on the Bed or Fainting
1.00	Seated Man at Rest
1.20	Stand Man at Rest or Seated Doing Soft Work
1.60	Stand Man Doing Soft Work
2.00	Man Doing Moderate Work
2.80	Man Doing Hard Work
3.60	Man Doing Very Hard Work
>= 4.0	Man Doing Sports

4. RESULTS AND DISCUSSION

In the present work, the author decided to study the influence of several parameters that affect the thermal steady state of a firefighter. The study was then divided into five indepent trials, which were related to the study of the impact in a hot stressfull environment of different subjects physiologies, diferent protective cloths, accessing the impact of performing with different schedules, the impact of fluid replacement and one final trial relating to active and passive cooling methods. All the trials referred above were performed as a result of a firefighter behaviour during wildland fires, with the purpose to quantify and qualify firefighters behaviour and alert them for the best decision when facing a fire.

In spite of that, one final trial intended to be performed with the aim of a critique evaluation of the thermoregulatory model, used to simulate the trials above described. This one could have been done by the comparison of an actual experimental trial and a simulated one performed by the researcher. So then we could assure that the thermoregulatory model used in the present dissertation would descride well the actual human thermoregulatory system and so pull out reliable conclusions.

Nevertheless, all the involved temperatures in the trials are related to hypothalamus temperature. This after a period of experiment seems to be the one that represents better the physiological behaviour of a human being. Still, in all the trials boundaries were established, in terms of maximum temperature that could be reached (39°C), in order to prevent heat illness (Table 4.1).

Table 4.1 – Important undesired incidents.

$34 < T_{hyp} < 39$ °C	Normal Thermoregulation
≥ 39 °C	Introversion
≥ 41 °C	Heat Stroke
≥ 42 °C	Brain Damage
≥ 44 °C	Death

4.1. Physiology Study

Nowadays people are becoming much more sedentary in their lives and in their jobs. Still, there are many careers that subject physiology isn’t a concern, but this does not apply to firefighters, since their job requires strenuous activity which comprises long periods of extreme work.

The present study aimed for the impact of different physiologies of possible firefighters. Height was set as a constant, and it was defined as 1,72 m, but weight was a variable and it was set according to three diferent physiologies: a leaner individual, a supposed normal one and an overweight (Table 4.2).

The trial was then divided into two phases; In phase one, neutral phase, as in phase two, work phase, both firefighters were set at the same external conditions, varying only, as said early, body weight, consequently the Dubois skin area and man body fat.

In other words subjects body weight and consequently the other factors referred above were set as:

Table 4.2 – Body characteristics of different subjects.

	Leaner	Normal	Overweight
Body Weight [kg]	56.43	74.43	92.43
Dubois Skin Area [m^2]	1.66	1.87	2.05
Man Body Fat [%]	8.20	14.50	18.35

- **Phase 1 – Neutral**

Neutral phase intended to simulate firefighters home preparation for his shift in firestation. This phase is caractherized by a lower metabolism (Table 4.3)

Table 4.3 – External conditions of neutral phase.

	Thin	Normal	Overweight
Phase Name	Neutral		
Time Duration [min]	120.000		
Metabolism Rate Level [met]	1.400		
Evolving Fluid	Air		
Beginning of the Phase:			
Posture:	Standing		
Orientation:	-		
Static Dry Clothing Insulation [clo]	0.047		
Average Cloth Vapour Permeability	0.616		
Average Skin or Cloth External Emissivity	0.924		
Fluid Temperature [℃]	29.000		
Relative Humidity (RH) [%]	50.000		
Fluid Velocity [m/s]	0.100		
Ext. Dry Convection Coefficient $[\mathrm{W/m^2.℃}]$	5.200		
Mean Radiant Temperature [℃]	29.000		
Ext. Dry Radiation Coefficient $[\mathrm{W/m^2.℃}]$	4.700		

- **Phase 2 – Work**

Work phase, as the name suggests, intend to simulate a day at work of firefighters with a high metabolism rate level associated (No fire exposure) (Table 4.4).

Table 4.4 – External conditions for work phase.

	Thin	Normal	Overweight
Phase Name	Work		
Time Duration [min]	100.000		
Metabolism Rate Level [met]	3.400		
Evolving Fluid	Air		
Beginning of the Phase:			
Posture:	Standing		
Orientation:	-		
Static Dry Clothing Insulation [clo]	0.969		
Average Cloth Vapour Permeability	0.406		
Average Skin or Cloth External Emissivity	0.903		
Fluid Temperature [°C]	35.000		
Relative Humidity (RH) [%]	40.000		
Fluid Velocity [m/s]	5.000		
Ext. Dry Convection Coefficient [$W/m^2.°C$]	5.200		
Mean Radiant Temperatures [°C]	30.000		
Ext. Dry Radiation Coefficient [$W/m^2.°C$]	4.700		

After all inputs settled, thermoregulatory model was able to simulate all the assumptions described, thus,

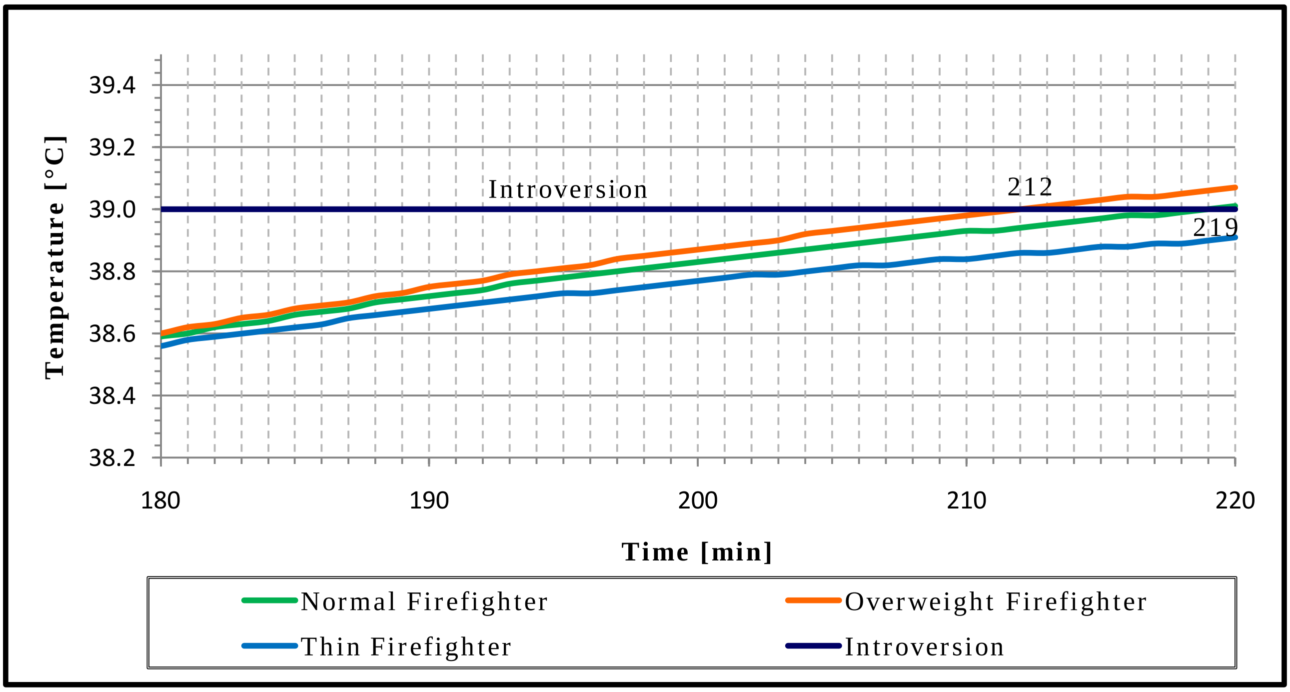

Figure 4.1 - Comparison between different physiologies (hypothalamus temperature).

Excess body fat impacts on a firefighter's performance in a number of ways. During exposure to hot environmental conditions, body fat acts as an insulator and hinders heat dissipation, thereby contributing to a greater rise in core temperature (Figure 4.1). Excess body fat is also associated with low levels of cardiorespiratory fitness, which along with being overweight is a risk factor for cardiovascular morbidities. One of the leading causes in-line deaths of firefighters is myocardial infarction (Barr et al., 2009).

In the acquired results are shown that the overweight individual reaches the heat strain level early then the others, normal and leaner individual (Figure 4.1). That was the expecting result considering what was said early. Still, the overweight individual in the present study reaches the introversion level 7 minutes early then a normal individual and that occurs with a difference of only 4% of body fat between these two subjects. Still, as it is shown in the results the leaner individual is the one with better performance in the work bout, during the exercise he never reaches the introversion state due to its lower body fat percentage, and lower weight.

In spite of that, in the author's opinion a proper body weight could not be enough to ensure that the individual is able to perform in such conditions with low risk of heat illness. Still, what makes the difference in these situations is the maximal oxygen uptake ($V_{O2_{máx}}$). In order, to improve that, firefighters should be set constantly to exercise, so they can improve their aerobic and anaerobic fitness and their muscular strength. In spite of that, firefighters should have to exercise in the heat in order to get use to it, this process is called heat adaptation or acclimation and consists in exposing firefighters to the heat while working. Therefore, when working at a given intensity, stroke volume is larger and cardiac frequency lower following heat adaptation, permitting superior regulation of blood pressure, an elevation in skin blood flow, and a lowering of vasodilatory threshold (Taylor, 2006). These physiological adaptations facilitate a more rapid transfer of heat from the body core to the periphery for dissipation. People report being less stressed, and are better able to tolerate work and heat stress (Taylor, 2006).

4.2. Protective Clothing Study

Indeed, protective clothing is a major avenue for thermal heat strain. The protective clothing worn by firefighters is typically heavy, thick with multiple layers, and also encapsulates the head (Figure 2). The reduced water-vapour permeability across the clothing layers also limits the rate of evaporative heat exchange with the environment conditions increasing the degree of physiological strain (Barr et al, 2010).

In the present trial the study focused on two diferent outfits exposed to the following external environments.

- **Test 1 – "Normal Environment"**

On the present test the point was to ascertain the impact of two diferent outfits, one light and one heavy, in a "normal environment" (Table 4.5), with no extra radiate heat flux, which tries to establish a regular day at work.

Table 4.5 – Settled inputs to establish a normal environment.

		Light Outfit	Complete Garments
Phase Name	**Neutral**	**Work**	
Time Duration [min]	120.000	195.000	
Metabolism Rate Level [met]	1.400	3.100	
Evolving Fluid	Air	Air	
Beginning of the Phase:			
Posture:	Sitting	Standing	
Orientation:	Turned to North	-	
Static Dry Clothing Insulation [clo]	0.047	0.969	2.952
Average Cloth Vapour Permeability	0.616	0.406	0.223
Average Skin or Cloth External Emissivity	0.924	0.903	0.884
Fluid Temperature [℃]	29.000	35.000	35.000
Relative Humidity (RH) [%]	50.000	40.000	40.000
Fluid Velocity [m/s]	0.100	5.000	5.000
Ext. Dry Convection Coefficient [W/m^2.℃]	5.200	5.200	5.200
Mean Radiant Temperatures [℃]	29.000	30.000	30.000
Ext. Dry Radiation Coefficient [W/m^2.℃]	4.700	4.700	4.700

Thus,

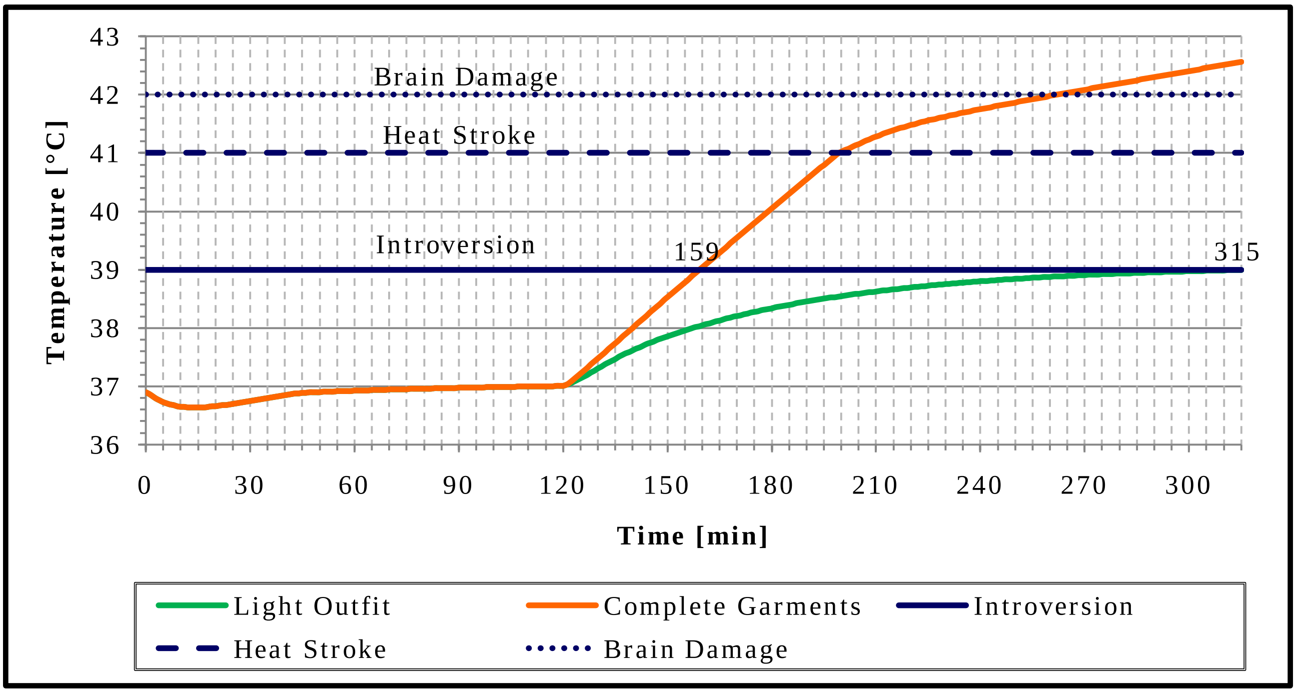

Figure 4.2 – Hypothalamus temperature of subjects with two different outfits exposed to a normal environment.

- **Test 2 – Fire Exposure**

As in the first test, both firefighters were set at the same external conditions, but now instead of a normal exposure, firefighters were set in a fire environment. Clothing ensembles were maintained and fire was supposed “come” from the north (Table 4.6).

Table 4.6 – Settled inputs to establish a fire exposure.

		Light Outfit	**Complete Garments**
Phase Name	**Neutral**	**Work**	
Time Duration [min]	120.000	25.000	
Metabolism Rate Level [met]	1.400	3.100	
Evolving Fluid	Air	Air	
Beginning of the Phase:			
Posture:	Sitting	Standing	
Orientation:	Turned to North	Turned to North	
Static Dry Clothing Insulation [clo]	0.047	0.969	2.952
Average Cloth Vapour Permeability	0.616	0.406	0.223
Average Skin or Cloth External Emissivity	0.924	0.903	0.884
Fluid Temperature [°C]	29.000	35.000	35.000
Relative Humidity (RH) [%]	50.000	40.000	40.000
Fluid Velocity [m/s]	0.100	5.000	5.000
Ext. Dry Convection Coefficient [W/m^2.°C]	5.200	5.200	5.200
Mean Radiant Temperatures [°C]	29.000	30.000	30.000
Ext. Dry Radiation Coefficient [W/m^2.°C]	4.700	4.700	4.700
Extra Radiative Flux Density [W/m^2]:			
From North:	0	2500.000	2500.000
From South:	0	50.000	50.000
From East:	0	1000.000	1000.000
From West:	0	1000.000	1000.000
From Top:	0	100.000	100.000
From Bottom:	0	50.000	50.000

Thus,

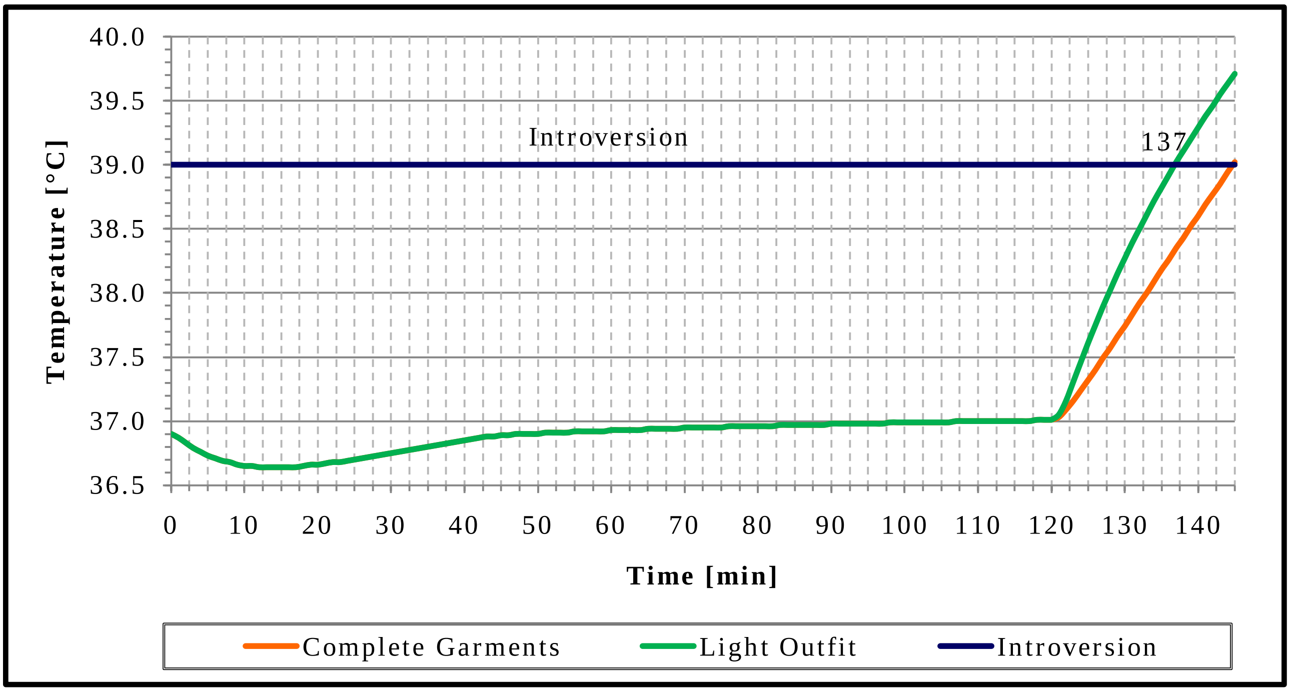

Figure 4.3 – Hypothalamus temperature of subjects with two different outfits and exposed to a fire front.

The firefighter protective clothing is made with high temperature resistance materials and can be decomposed in three parts: one for the head and neck, one for feet and legs lower sector and one for the other body parts. The head protection ensemble is formed by a covering head and neck (except eyes zone) beret, goggles and a helmet. The feet and the lower part of the legs are secluded with socks and boots (Raimundo & Figueiredo, 2008). The other body parts are protected by means of appropriate low thermal conduction suits. A typical fire-fighting ensemble, including SCBA (**S**elf **C**ontained **B**reathing **A**pparatus) weighs ~ 26kg (Barr et al., 2009).

Protective clothing worn during firefighting shields the firefighter from the extreme environmental temperatures which vary as function of how long the fire has been burning and the materials involved.

Since the personal protective ensemble of the firefighter is designed with impermeable and semi-permeable fabric layers that trap air, they create a microclimate between the skin and the clothing (Figure 4.4). This, in combination with the mass of these ensembles and other protective equipment, places a significant physiological burden upon the wearer, both in the form of increased metabolic rate and reduced heat dissipation.

Certainly, such ensembles minimize the penetration of external heat, but they also reduce the escape of metabolically produced heat.

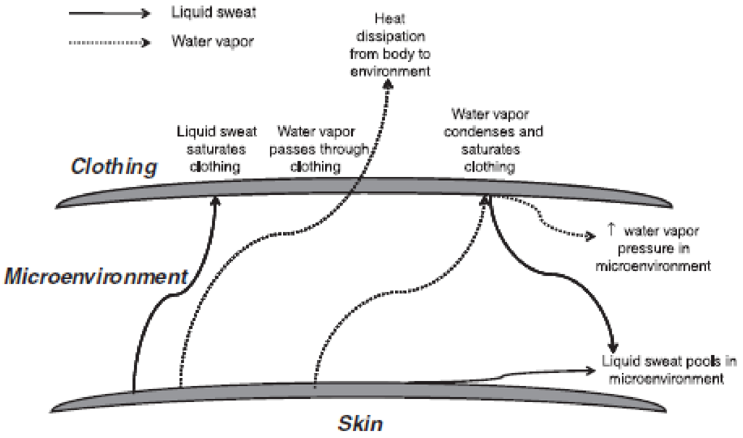

Figure 4.4 – Interactions between the skin and the protective ensemble (Cheung, Petersen, & McLellan, 2010).

Reporting to the obtained results, protective clothing has indeed a major impact on human thermoregulatory system. In fact, in the first trial, normal environment, the individual that wear the complete garments reached the introversion state at 159th minute performing only 39 minutes until this state were reached (Figure 4.2). On the other hand, the individual wearing the light outfit could complete the all task, without reaching the introversion state, boundary that was set as a limit when performing under these conditions (Figure 4.2). In the second trial, when subjects were set to a fire exposure environment, the one with better performance, completing all the trial successfully were the individual wearing all the protective ensembles (Figure 4.3). This confirms that protective clothing is a major prompter of thermal strain. Still, complete garments should be only used when firefighters face a fire, protecting them from the flames and from the high radiation flux that are associated to these environments. So concluding, clothing ensembles should be chosen based on the work rate level and on the surrounding environment.

4.3. Schedules Assessment

The present study intended to assess the impact of different schedules in firefighter steady state (Figure 4.5).

In fact, settle schedules can reduce thermal strain in a easy and effective way. This can be done, for example, if firefighters work in pairs, so they can rotate in a pre-determined time from task to task and while one perform a heavy task the other one perform a lighter one. The same applies to work and rest schedules.

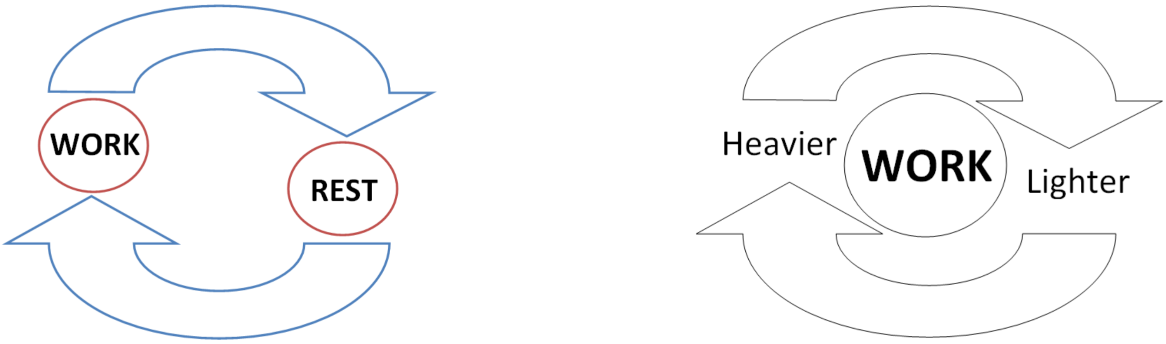

Figure 4.5 – Diagrams of work and rest schedules & heavier and lighter work.

As we can apprehend the point of these study is to assess the impact of alternating rest and light work periods with strenuous work instead of performing only strenuous work.

External conditions for each phase were set as (Table 4.7),

Table 4.7 – Different external conditions settled.

Phase Name	**Neutral**	**Heavy Work**	**Rest**	**Light Work**
Time Duration [min]	20.000	120.000	120.000	120.000
Metabolism Rate Level [met]	**1.200**	**3.150**	**1.200**	**2.000**
Evolving Fluid	Air	Air	Air	Air
Beginning of the Phase:				
Posture:	Sitting	Standing	Standing	Standing
Orientation:	-	-	-	-
Static Dry Clothing Insulation [clo]	0.047	0.969	0.969	0.969
Average Cloth Vapour Permeability	0.616	0.406	0.406	0.406
Average Skin or Cloth External Emissivity	0.924	0.903	0.903	0.903
Fluid Temperature [°C]	29.000	35.000	35.000	35.000
Relative Humidity (RH) [%]	50.000	40.000	40.000	40.000
Fluid Velocity [m/s]	0.100	5.000	5.000	5.000
Ext. Dry Convection Coefficient [$W/m^2.°C$]	5.200	5.200	5.200	5.200
Mean Radiant Temperatures [°C]	29.000	30.000	30.000	30.000
Ext. Dry Radiation Coefficient [$W/m^2.°C$]	4.700	4.700	4.700	4.700

Reporting to the table described above, it is perceptible that four diferent phases were defined. In the present study, three diferent work schedules were defined from the phases cited early, and can be caractherized as,

Schedule 1 – [Neutral – Heavy Work – Heavy Work – Heavy Work]
Schedule 2 – [Neutral – Heavy Work – Light Work – Heavy Work]
Schedule 3 – [Neutral – Heavy Work – Rest – Heavy Work]

On the process of assessing the impact of those three schedules, comparisons were made during this stage, in other words Schedule 1 was compared with Schedule 2 on the first trial, on the second Schedule 1 and Schedule 3, and at a final one a comparison between both Schedules was performed.

- **Trial 1 – Schedule 1 VS Schedule 2**

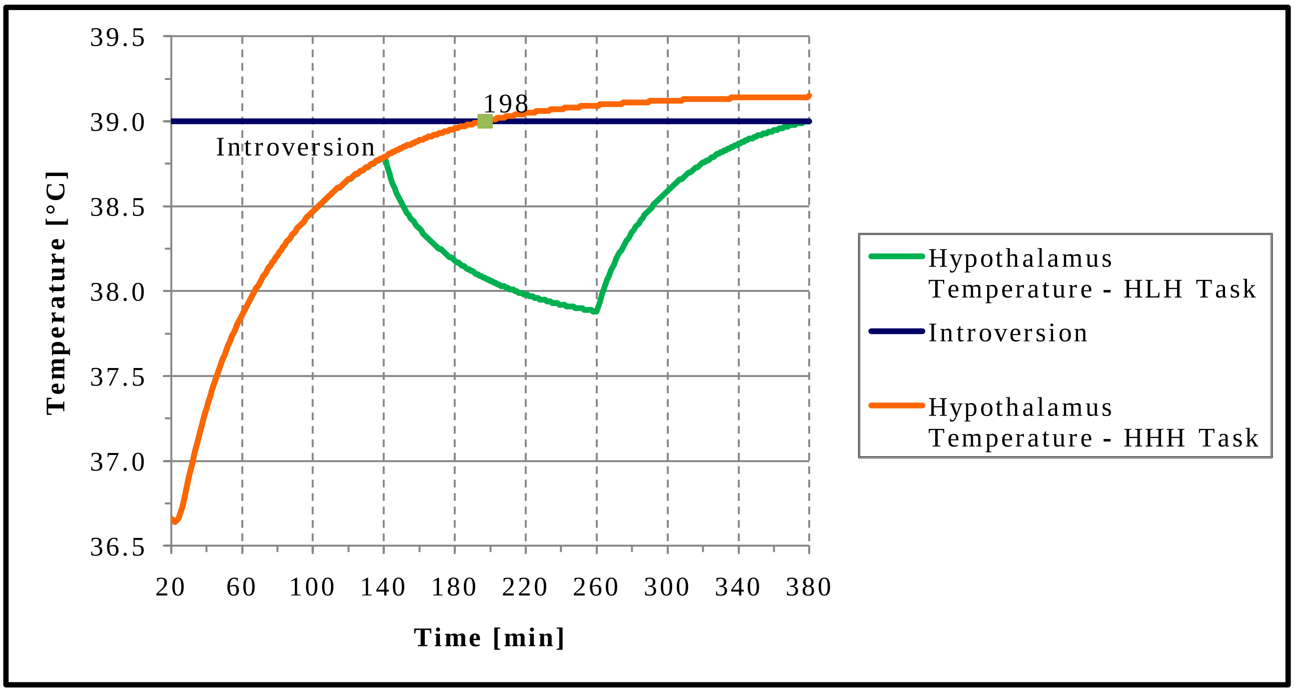

Figure 4.6 – Impact of rotating duties from heavier to lighter tasks.

where, H represents heavy work and is described by heavy work phase, and L represents light work and is described by light work phase.

- **Trial 2 – Schedule 1 VS Schedule 3**

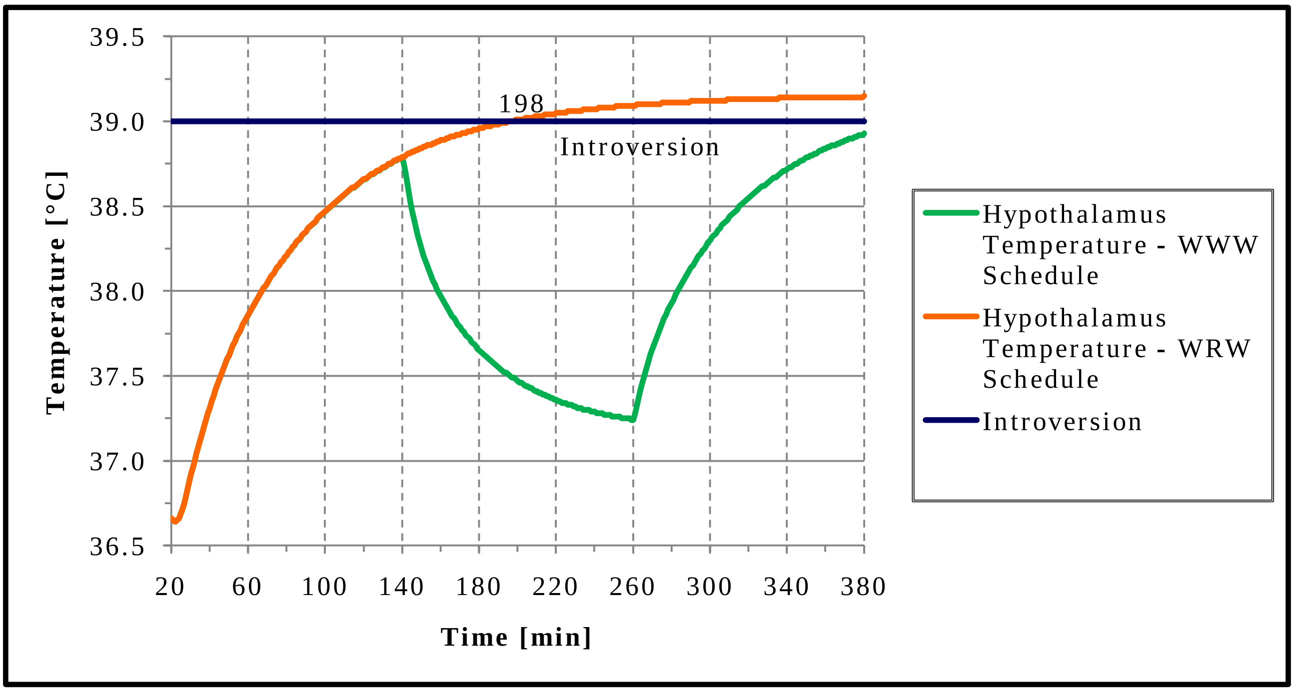

Figure 4.7 – Impact of work and rest schedules.

where, W represents heavy work and is described by heavy work phase, and R represents rest and is described by rest phase.

- **Comparison Between Schedules**

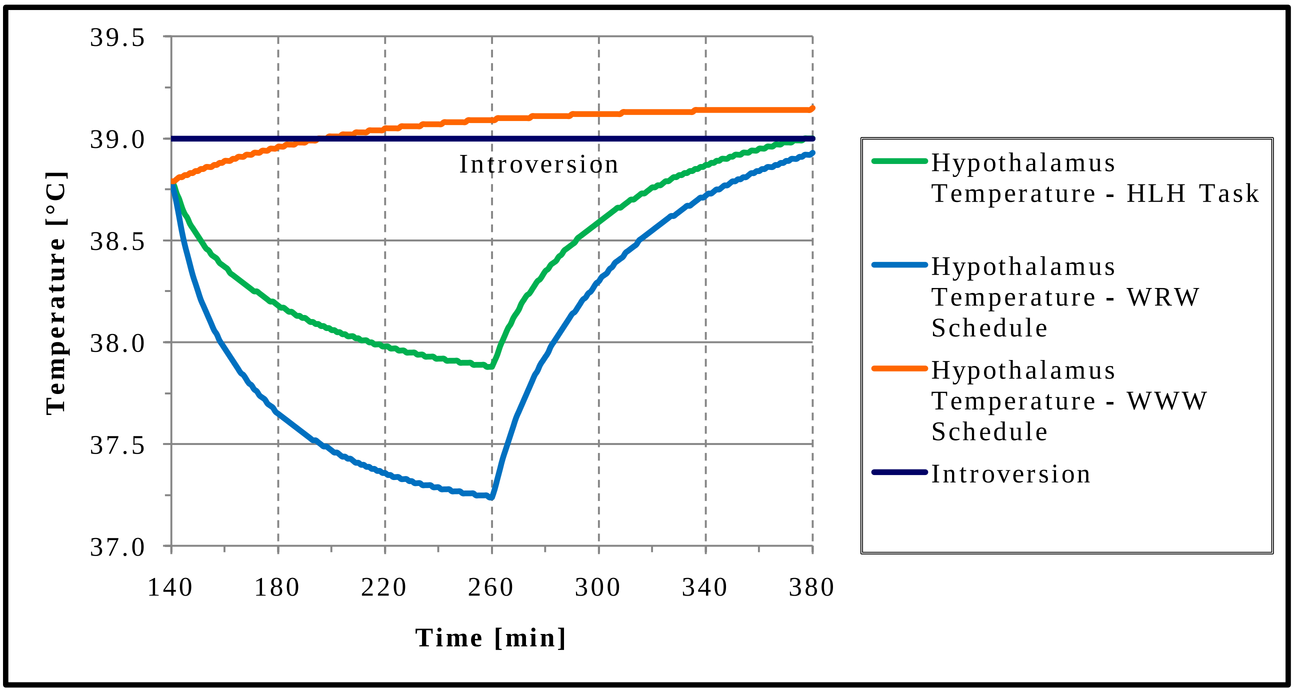

Figure 4.8 – Comparison between schedules.

In a more detailed approach,

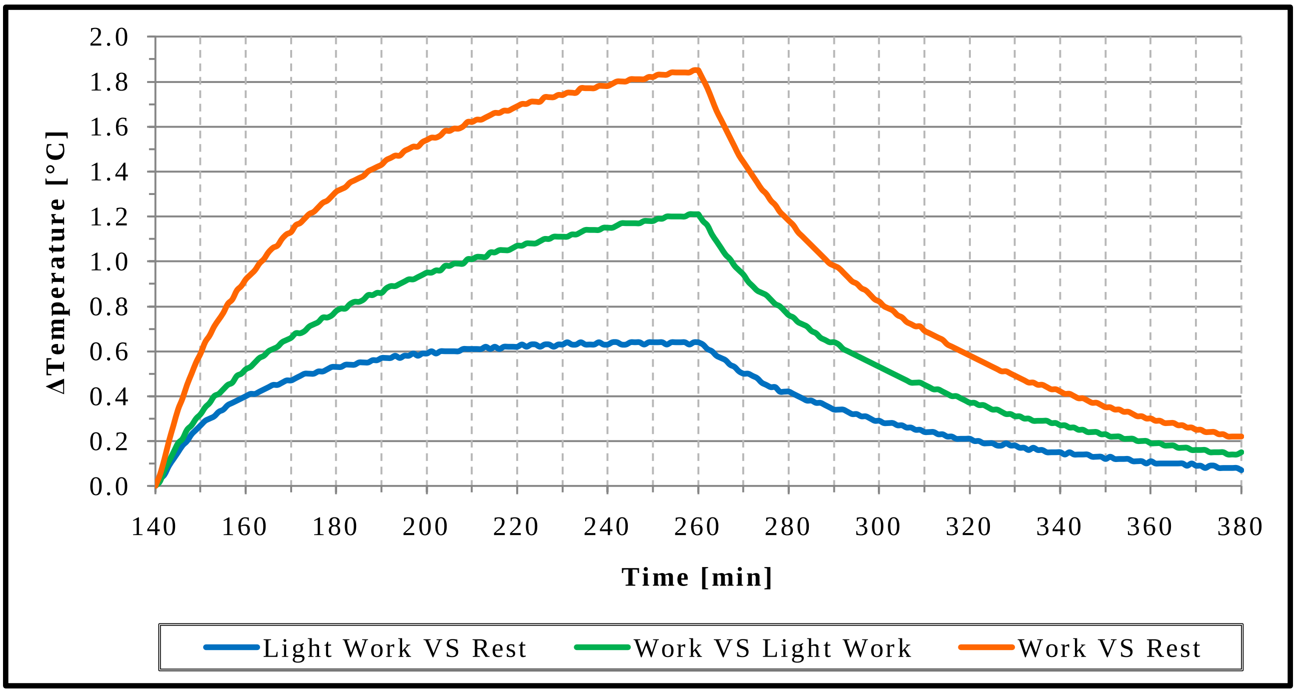

Figure 4.9 – Comparison between schedules.

where,

$$\begin{cases} \textbf{Light Work VS Rest} \rightarrow \Delta T_{t=140}^{380} = T(\text{Light Work}) - T(\text{Rest}) \\ \textbf{Work VS Light Work} \rightarrow \Delta T_{t=140}^{380} = T(\text{Work}) - T(\text{Light Work}) \\ \textbf{Work VS Rest} \rightarrow \Delta T_{t=140}^{380} = T(\text{Work}) - T(\text{Rest}) \end{cases} \quad (4.1)$$

A simple policy that may reduce heat strain injury is rotating duties while working on the fire front (Figure 4.5).

Reporting to results obtained it is perceptible that working through these conditions, work and rest schedules (Figure 4.7) or even rotating between a lighter and heavier work (Figure 4.6), are good policies to implement. Furthermore, the subject that performs a constant and heavy work during all the trial reach the introversion state at 198th minute, so he only could perform 198 minutes effectively. The other subjects set to schedules were able to perform 240 minutes the supposed heavy work, still none of them reached the introversion state (Figure 4.8 and Figure 4.9).

4.4. Fluid Ingestion

It is known that dehydration has a negative impact on the human body as well as in his performance.

So, in the subsequent trial, the aim was to study the impact of fluid/no fluid ingestion on the firefighter deep core temperature. Still, different amount of fluid ingested were intaked to assess if that has a major correlation with the decrease on body core temperature.

Figure 4.10 – Fluid ingestion during wildland fires (Schlags, 2009).

In addition, three fluid schedules were compared (Table 4.8, Table 4.9 Table 4.10), as it is shown bellow. Fire was supposed to come from north. External conditions for each one of those fluid schedules were set as:

Table 4.8 – No fluid ingestion schedule.

	No Fluid Ingestion			
Phase Name	**Neutral**	**Pre-Fire**	**Fire**	**Fluid**
Time Duration $[\mathrm{min}]$	20.000	40.000	18.000	**6.000**
Metabolism Rate Level $[\mathrm{met}]$	**1.200**	**2.200**	**3.200**	**2.000**
Evolving Fluid	Air	Air	Air	Air
Beginning of the Phase:				
Posture:	Sitting	Standing	Standing	Standing
Orientation:	Turned to North	Turned to North	Turned to North	Turned to North
Static Dry Clothing Insulation $[\mathrm{clo}]$	0.047	0.969	2.930	2.768
Average Cloth Vapour Permeability	0.616	0.406	0.224	0.282
Average Skin or Cloth External Emissivity	0.924	0.903	0.884	0.903
Fluid Temperature $[℃]$	29.000	35.000	35.000	35.000
Relative Humidity (RH) $[\%]$	50.000	40.000	40.000	40.000
Fluid Velocity $[\mathrm{m/s}]$	0.100	5.000	5.000	5.000
Ext. Dry Convection Coefficient $[\mathrm{W/m^2.℃}]$	5.200	5.200	5.200	5.200
Mean Radiant Temperatures $[℃]$	29.000	30.000	30.000	30.000
Ext. Dry Radiation Coefficient $[\mathrm{W/m^2.℃}]$	4.700	4.700	4.700	4.700
Extra Radiative Flux Density $[\mathrm{W/m^2}]$:				
From North:	0	0	**2500.000**	0
From South:	0	0	**50.000**	0
From East:	0	0	**1000.000**	0
From West:	0	0	**1000.000**	0
From Top:	0	0	**100.000**	0
From Bottom:	0	0	**50.000**	0
Fluid Ingestion:				
Mass of Fluid Intaked $[\mathrm{kg}]$	0	0	0	**0**
Temperature of Food Intaked $[℃]$	-	-	-	**-**
Specific Heat of Food Intaked $[\mathrm{J/kg.℃}]$	-	-	-	**-**

Table 4.9 – Fluid ingestion after work schedule.

	Fluid Ingestion After Work			
Phase Name	**Neutral**	**Pre-Fire**	**Fire**	**Fluid**
Time Duration $[\mathrm{min}]$	20.000	40.000	18.000	**6.000**
Metabolism Rate Level $[\mathrm{met}]$	**1.200**	**2.200**	**3.200**	**2.000**
Evolving Fluid	Air	Air	Air	Air
Beginning of the Phase:				
Posture:	Sitting	Standing	Standing	Standing
Orientation:	Turned to North	Turned to North	Turned to North	Turned to North
Static Dry Clothing Insulation $[\mathrm{clo}]$	0.047	0.969	2.930	2.768
Average Cloth Vapour Permeability	0.616	0.406	0.224	0.282
Average Skin or Cloth External Emissivity	0.924	0.903	0.884	0.903
Fluid Temperature $[\mathrm{°C}]$	29.000	35.000	35.000	35.000
Relative Humidity (RH) [%]	50.000	40.000	40.000	40.000
Fluid Velocity $[\mathrm{m/s}]$	0.100	5.000	5.000	5.000
Ext. Dry Convection Coefficient $[\mathrm{W/m^2.°C}]$	5.200	5.200	5.200	5.200
Mean Radiant Temperatures $[\mathrm{°C}]$	29.000	30.000	30.000	30.000
Ext. Dry Radiation Coefficient $[\mathrm{W/m^2.°C}]$	4.700	4.700	4.700	4.700
Extra Radiative Flux Density $[\mathrm{W/m^2}]$:				
From North:	0	0	**2500.000**	0
From South:	0	0	**50.000**	0
From East:	0	0	**1000.000**	0
From West:	0	0	**1000.000**	0
From Top:	0	0	**100.000**	0
From Bottom:	0	0	**50.000**	0
Fluid Ingestion:				
Mass of Fluid Intaked $[\mathrm{kg}]$	0	0	0	**1**
Temperature of Food Intaked $[\mathrm{°C}]$	-	-	-	**18.500**
Specific Heat of Food Intaked $[\mathrm{J/kg.°C}]$	-	-	-	**4186.000**

Table 4.10 – Fluid ingestion before and after work schedule.

	Fluid Ingestion Before and After Work				
Phase Name	**Neutral**	**Pre-Fire**	**Fluid1**	**Fire**	**Fluid2**
Time Duration [min]	20.000	40.000	**3.000**	18.000	**3.000**
Metabolism Rate Level [met]	**1.200**	**2.200**	**2.000**	**3.200**	**2.000**
Evolving Fluid	Air	Air	Air	Air	Air
Beginning of the Phase:					
Posture:	Sitting	Standing	Standing	Standing	Standing
Orientation:	Turned to North	Turned to North	Turned to North	Turned to North	Turned to North
Static Dry Clothing Insulation [clo]	0.047	0.969	2.768	2.930	2.768
Average Cloth Vapour Permeability	0.616	0.406	0.282	0.224	0.282
Average Skin or Cloth External Emissivity	0.924	0.903	0.903	0.884	0.903
Fluid Temperature [℃]	29.000	35.000	35.000	35.000	35.000
Relative Humidity (RH) [%]	50.000	40.000	40.000	40.000	40.000
Fluid Velocity [m/s]	0.100	5.000	5.000	5.000	5.000
Ext. Dry Convection Coefficient [$\mathrm{W/m^2.℃}$]	5.200	5.200	5.200	5.200	5.200
Mean Radiant Temperatures [℃]	29.000	30.000	30.000	30.000	30.000
Ext. Dry Radiation Coefficient [$\mathrm{W/m^2.℃}$]	4.700	4.700	4.700	4.700	4.700
Extra Radiative Flux Density [$\mathrm{W/m^2}$]					
From North:	0	0	0	**2500.000**	0
From South:	0	0	0	**50.000**	0
From East:	0	0	0	**1000.000**	0
From West:	0	0	0	**1000.000**	0
From Top:	0	0	0	**100.000**	0
From Bottom:	0	0	0	**50.000**	0
Fluid Ingestion:					
Mass of Fluid Intaked [kg]	0	0	**0.50**	0	**0.50**
Temperature of Food Intaked [℃]	-	-	**18.50**	-	**18.50**
Specific heat of Food Intaked [J/kg.℃]	-	-	**4186.00**	-	**4186.00**

Thus, once all data settled and the simulation of human thermoregulatory completed,

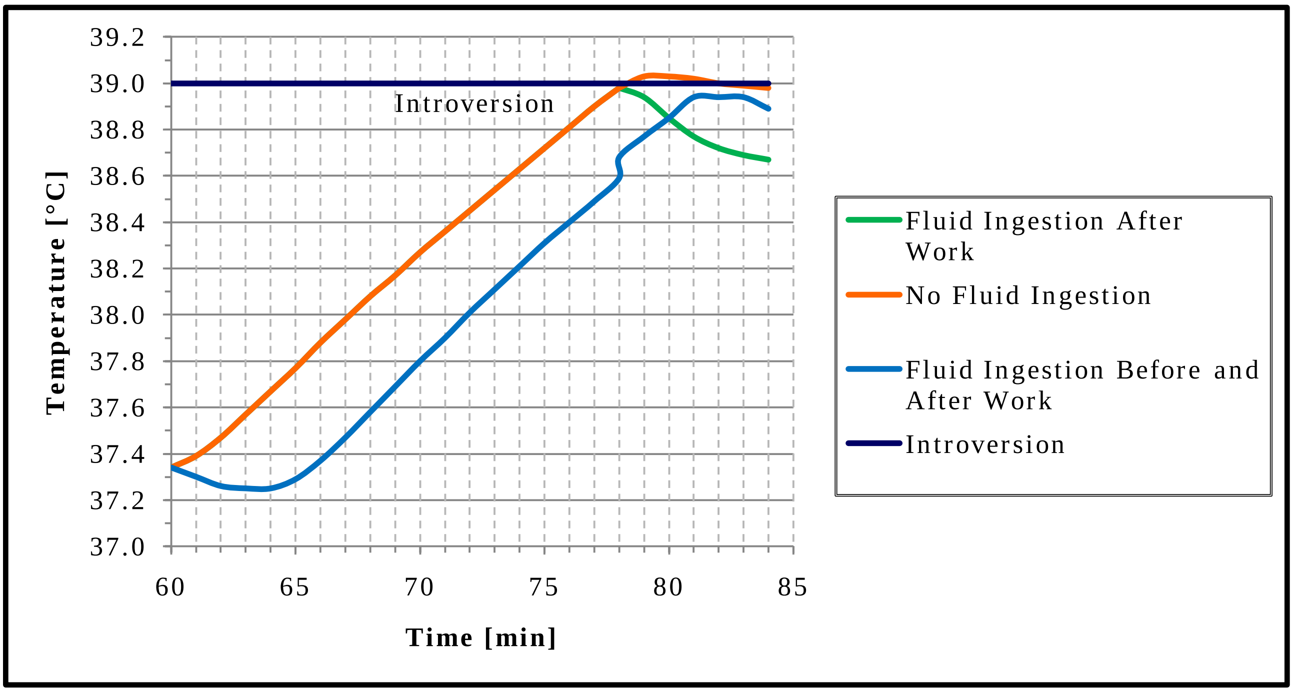

Figure 4.12 – Comparison between different fluid schedules (hypothalamus temperature).

As it is shown on the graphic above, at the final of the trial, the subject that ingested fluid only after work had a smaller core temperature and the one that had no fluid, the greatest. So the comparisons made bellow was related to this individuals.

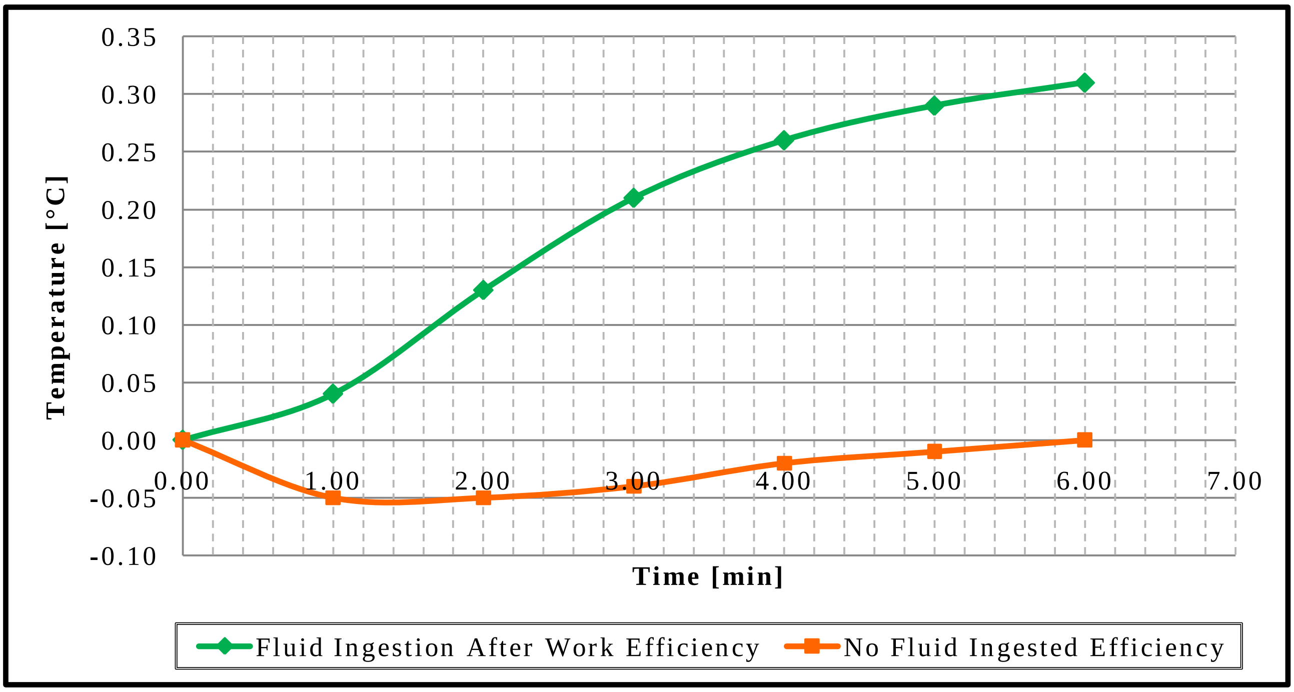

Figure 4.11 – Comparison of efficiencies between fluid ingestion after work and no fluid ingestion.

where efficiency, was obtained by the following expression,

$$\text{Efficiency}_i = \sum_{i=0}^{6} (T_0 - T_i) \tag{4.2}$$

On the other hand effectiveness of fluid replacement is given by

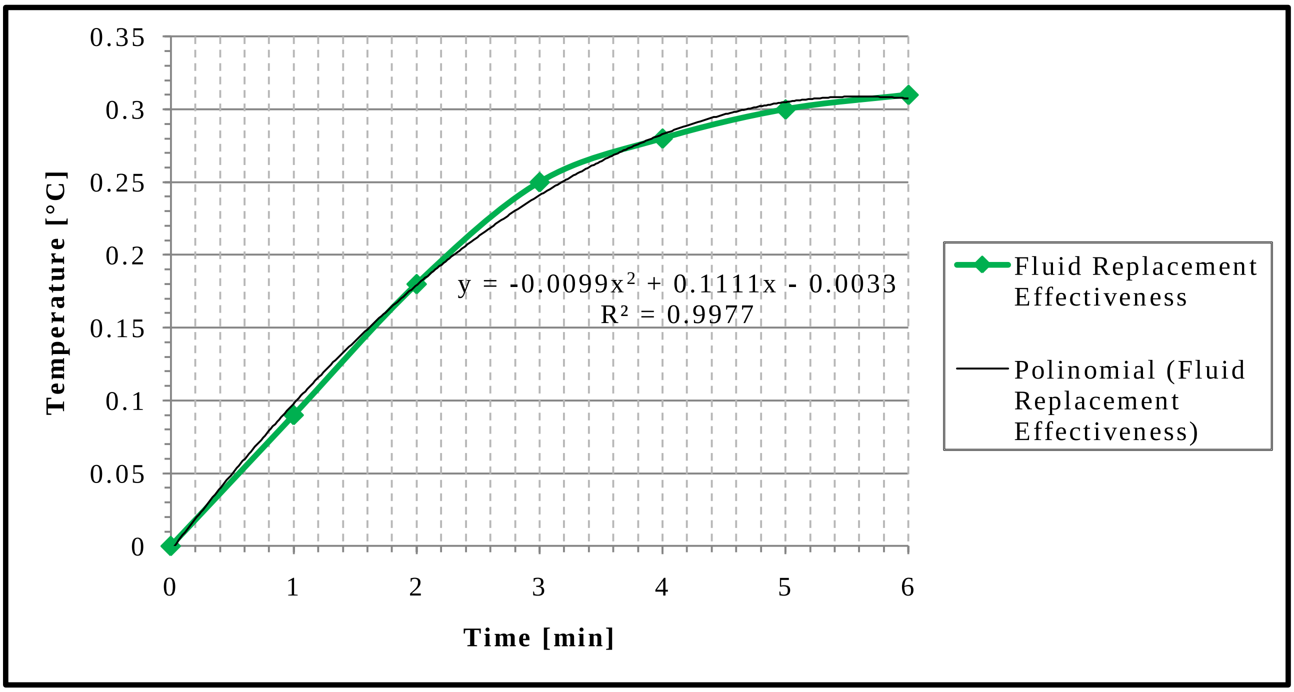

Figure 4.13 – Effectiveness of fluid replacement after work.

where effectiveness is described as

$$\text{Effectiveness}_i = \sum_{i=0}^{6} (T_{NFi_i} - T_{FiAW_i}) \tag{4.3}$$

where,

- T_{NFi_i} - No fluid ingestion core temperature, at i instant [°C];
- T_{FiAW_i} - Fluid ingestion after work core temperature, at i instant [°C];

Assessing the impact of the amount of fluid intaked

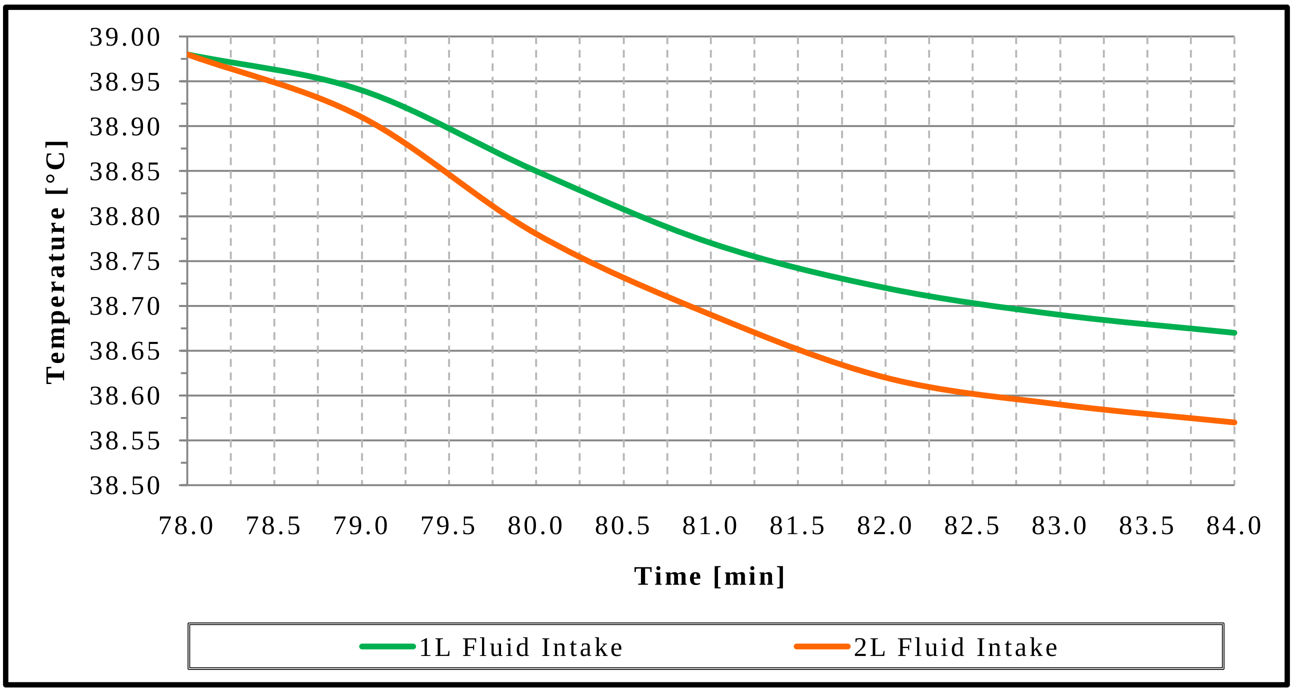

Figure 4.14 – Impact of different amounts of fluid intaked (hypothalamus temperature).

The efficiency of diferent amounts of fluid intaked are,

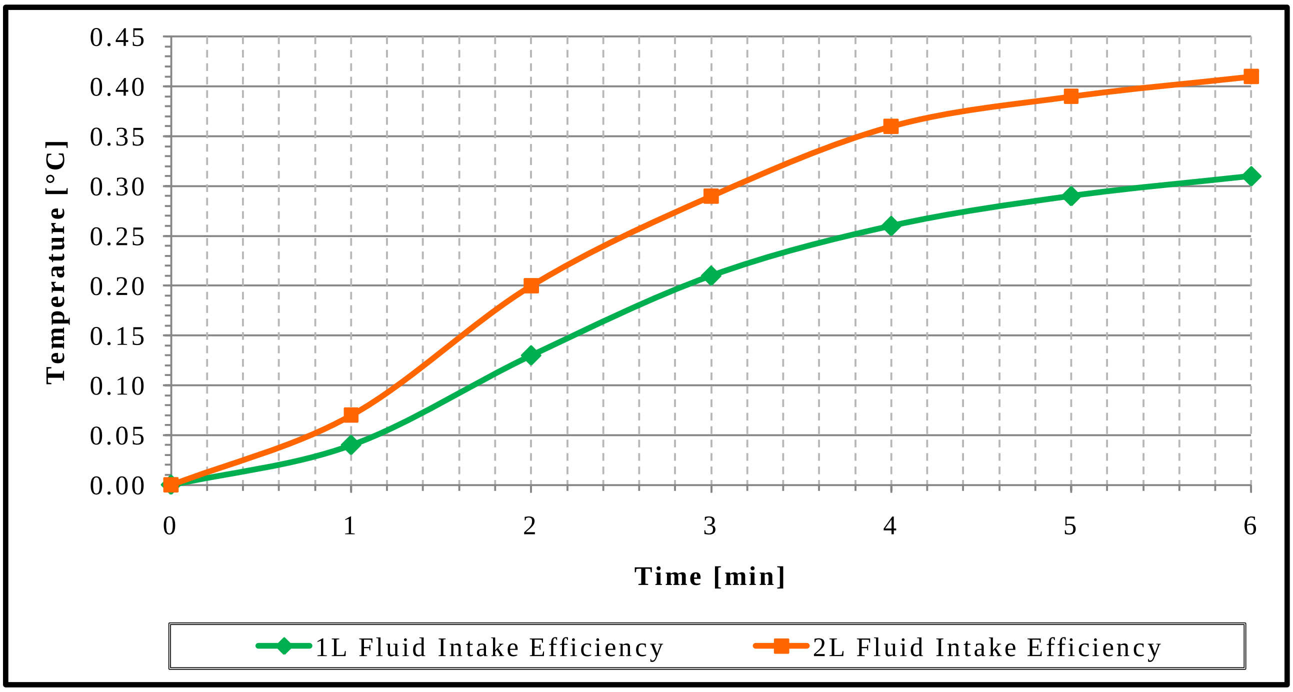

Figure 4.15 – Efficiencies of different amounts of fluid intaked.

where,

$$\mathrm{Efficiency_i} = \sum_{i=0}^{6} (T_0 - T_i) \qquad (4.4)$$

Fluid replacement during work in the heat is critical for two reasons (Figure 4.10); first, to maintain sweat rates to promote evaporative cooling; and second, to maintain blood volume such that the heart can continue to send warm blood to the skin to assist the transfer of body heat to the environment. In addition, Fluid replacement following work in the heat is critical to restore body fluid levels to normal such that the individual does not begin a subsequent exposure in the heat in a dehydrated state (McLellan & Selkirk, 2006).

Once again, reporting to the results obtained after the simulation process; those were according to what has been said. Fluid replacement has a positive impact on the subject thermoregulatory system. The study above design consisted in two different methodologies of fluid replacement, but those can’t be compared.

The methodology that refers to only fluid ingestion after work seems to be the best alternative to apply due to the thermal gradient associated (Figure 4.12). The difference of temperatures between fluid and core temperature at the final of the bout are superior then the difference of temperatures between the fluid and core temperatures at the beginning of the bout, so fluid replacement has more impact on the final stage were core temperature is higher. Also, as tested after, the amount of fluid intake has influence on the decreased temperature (Figure 4.14), so that’s why this fluid ingestion schedules cannot be compared. The message here is that any amount of fluid ingestion is better than none (Figure 4.11).

In spite of what have been said until now it is important to refer that the amount of fluid that a subject should ingest can be determined based on the sweat lost during the trial. Based on other studies 2/3 of fluid replacement determined from the sweat rates seems to be the best solution, because when full fluid replacement was provided subjects reported gastric discomfort and most were unable to consume the equivalent of the full-fluid replacement aliquots. Recommended volumes will be then proportionally higher or lower depending on individual body mass (McLellan & Selkirk, 2006).

4.5. Effective Cooling Strategies

There are two categories of “effective cooling strategies”, namely active cooling strategies and passive recovery strategies. In the present report both cooling strategies were studied and compared.

Indeed, strategies for rapidly reducing the physiological strain related with the strenuous activity associated to firefighters is a major issue. Firefighters may be required to re-enter in fires following short recovery periods. Thus, this strategies must be quick, easy and efficient in reducing thermal heat strain (Barr et al, 2009).

In the subsequent study, passive recovery strategie was consisted on the firefighter leave from fire front to a shady and fresh ambient, it was also considerated that firefighter would take of his helmet, gloves and part of his protective clothing.

It’s a fact that Active cooling strategies, are composed by passive recovery strategies as well as active recovery strategies, which in this particular study were set to be hands and forearms immerssion at the first trial, in the second feet and legs and in the last one all body except head. Time trial was set as a constant for both tested trials, and it was settled to last 20 min. For the first and second trial, the water temperature was set as $15℃$, on the other trial the defined temperature was $\sim 25.5℃$.

Following the same line of thought as in the other trials referred above, firefighters were set to a initial neutral phase, then a pre-fire phase and then an actual fire followed by a supposed cooling strategy. For a more comprehensive understanding external conditions settled on the first three phases (Table 4.11) will be set apart for the last phase, the cooling phase (Table 4.12). Thus,

Table 4.11 – External conditions description.

	External Conditions		
Phase Name	**Neutral**	**Pre-Fire**	**Fire**
Time Duration [min]	20.000	40.000	18.000
Metabolism Rate Level [met]	**1.200**	**2.200**	**3.200**
Evolving Fluid	Air	Air	Air
Beginning of the Phase:			
Posture:	Sitting	Standing	Standing
Orientation:	Turned to North	Turned to North	Turned to North
Static Dry Clothing Insulation [clo]	0.047	0.969	2.930
Average Cloth Vapour Permeability	0.616	0.406	0.224
Average Skin or Cloth External Emissivity	0.924	0.903	0.884
Fluid Temperature [℃]	29.000	35.000	35.000
Relative Humidity (RH) [%]	50.000	40.000	40.000
Fluid Velocity [m/s]	0.100	5.000	5.000
External Dry Convection Coefficient $[\mathrm{W/m^2.℃}]$	5.200	5.200	5.200
Mean Radiant Temperatures [℃]	29.000	30.000	30.000
External Dry Radiation Coefficient $[\mathrm{W/m^2.℃}]$	4.700	4.700	4.700
Extra Radiative Flux Density $[\mathrm{W/m^2}]$:			
From North:	0	0	**2500.000**
From South:	0	0	**50.000**
From East:	0	0	**1000.000**
From West:	0	0	**1000.000**
From Top:	0	0	**100.000**
From Bottom:	0	0	**50.000**

Effective cooling methodologies were set as,

Table 4.12 – Cooling strategies description.

	Passive Recovery	Active Recovery		
	-	Hands & Forearms	Feet & Legs	All Body
Time Duration [min]	20.000	20.000	20.000	20.000
Metabolism Rate Level [met]	1.200	1.200	1.200	1.200
Beginning of the Phase:				
Posture:	Standing	Standing	Standing	Standing
Orientation:	Turned to North	Turned to North	Turned to North	Turned to North
Sections Inside Water:	-	Left and Right Forearm; Left and Right Hand	Left and Right Leg; Left and Right Foot	All Body except Head
Fluid Temperature [°C]	**35.000**	**15.000**	**15.000**	**25.500**
Relative Humidity (RH) [%]	40.000	60.000	60.000	60.000
Fluid Velocity [m/s]	5.000	0.100	0.100	0.100

Comparing both methodologies,

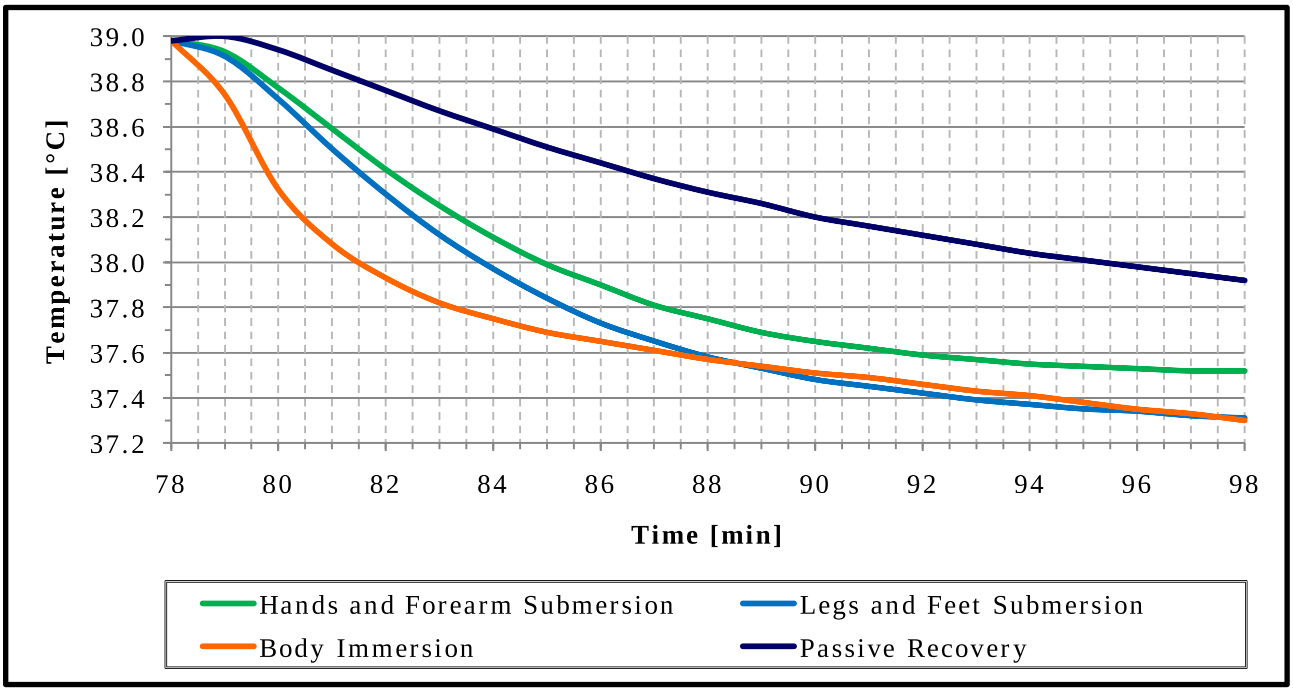

Figure 4.16 – Active cooling VS passive cooling (hypothalamus temperature).

Thus, active cooling effectiveness can be described as,

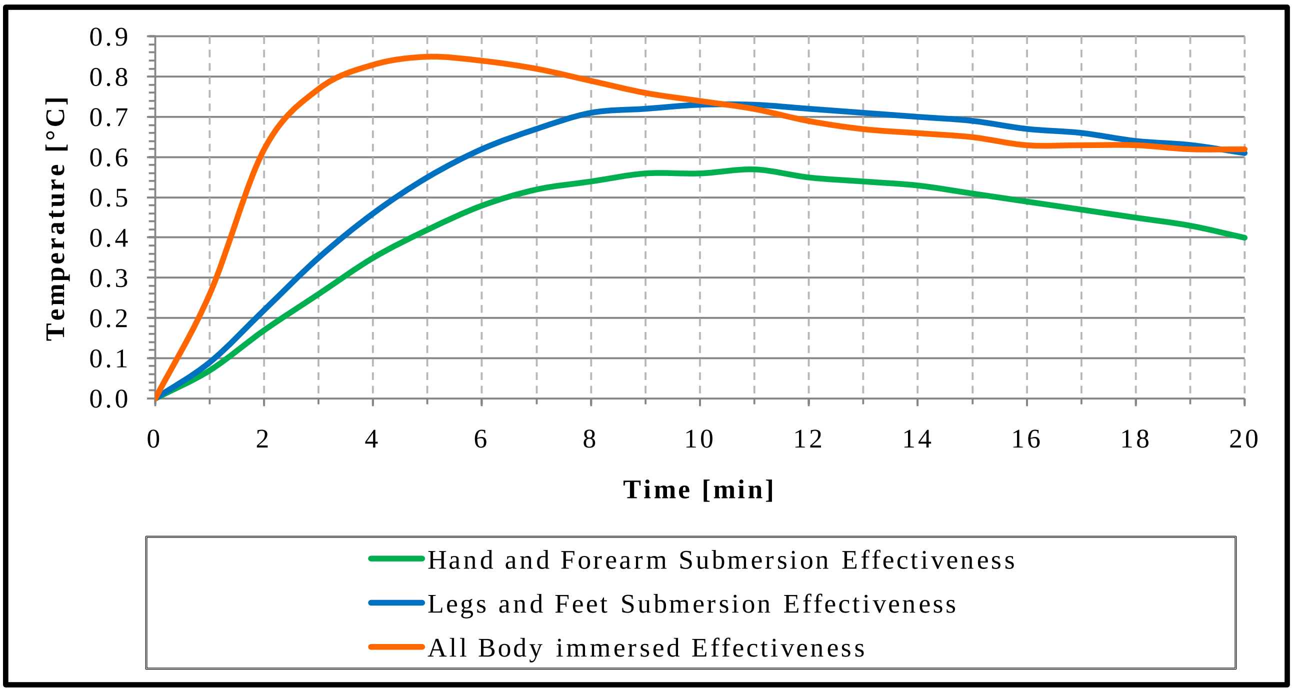

Figure 4.17 – Active cooling effectiveness.

where,

$$\begin{cases} \text{Effectiveness}_{\text{H\&}FA_i} = \sum_{i=0}^{20} (T_{PR_i} - T_{\text{H\&}FA_i}) \\ \text{Effectiveness}_{\text{L\&}F_i} = \sum_{i=0}^{20} (T_{PR_i} - T_{\text{L\&}F_i}) \\ \text{Effectiveness}_{AB_i} = \sum_{i=0}^{20} (T_{PR_i} - T_{AB_i}) \end{cases} \quad (4.5)$$

where,

- T_{PR_i} - Passive recovery core temperature, at i instant [°C];
- $T_{H\&FA_i}$ – Core temperature, at i instant and after Hands and forearms immersion [°C];
- $T_{L\&F_i}$ - Core temperature, at i instant and after Legs and Feet immersion [°C];
- T_{AB_i} - Core temperature, at i instant and after all body immersion, except head [°C];

Still, efficiency of each method was assessed and can be described as

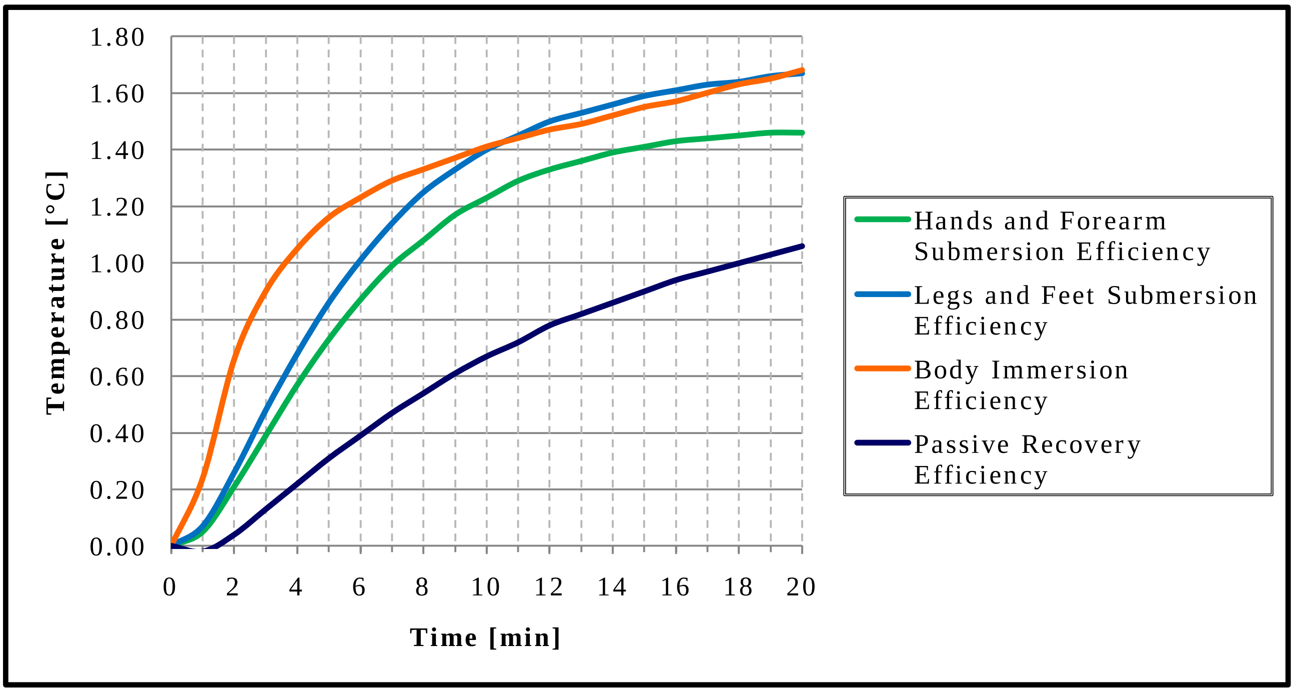

Figure 4.18 – Efficiency of each cooling method.

where,

$$\begin{cases} \text{Efficiency}_{\text{H\&}FA_\text{i}} = \sum_{\text{i}=0}^{20} (\text{T}_0 - \text{T}_\text{i}) \\ \text{Efficiency}_{\text{L\&}F_\text{i}} = \sum_{\text{i}=0}^{20} (\text{T}_0 - \text{T}_\text{i}) \\ \text{Efficiency}_{\text{AB}_\text{i}} = \sum_{\text{i}=0}^{20} (\text{T}_0 - \text{T}_\text{i}) \end{cases} \tag{4.6}$$

The purpose of a cooling strategy following heat exposure during firefighting is to restore the body to physiological equilibrium in as quick a time as possible, both for the health and safety of the individual and in preparation for any subsequent operation that may occur.

Several known methods vary in their effectiveness and practicality and have included a supposed passive recovery period.

In the present dissertation, the tested methodologies of active cooling were hand and forearm immersion as well as leg and foot immersion and all body immersion except head (Figure 4.16).

Passive recovery consisted in a temporary leave from the fire front and sitting in a shaded and fresh area where possible. This is an inexpensive and practical method. Although, through data analyzing we apprehend that passive recovery isn't the best alternative to implement (Figure 4.18). This finding suggests that such strategies employed by firefighters are ineffective in accelerating the physiological recovery following bouts of strenuous firefighting activity. Still, core temperature continued to increase in the first minute and a half of recovery. This rise is likely due to continued circulation and the increased return of warm blood to the core following the cessation of exercise.

On the other hand, active cooling methodologies consist as well leaving from the fire front and set to a shaded and fresh atmosphere and then apply the supposed active cooling method. That's why it's said above that active cooling strategies contemplate passive cooling recovery. In the first two trials the subjects immersed his hands and forearms also his legs and feet in cool water, in about $15°C$ during 20 minutes. The results are the published and as it shown apparently foot and leg immersion has a major impact on decreasing core temperature, this might be due to the exposed area which is higher on the second trial (Table 4.13).

Table 4.13 – Comparison between body areas.

	Hands and Forearms	Feet and Legs	All Body
Area [m^2]	0.226	0.346	1.870
Area [%]	12.086	18.503	100.000

In spite of that it is important to refer that all body immersion except head was the best response in reducing thermal heat strain (Figure 4.17). The subject were immersed in water at $\sim 25°C$ for 20 min, this technique as results show is much efficient in beginning of the phase, when thermal gradient is higher, thus, at the end of the phase core temperature didn't ranged much. In fact, feet and legs immersion had the same impact at the final of the trial which mean that this strategy isn't the best to apply in terms of logistics and effectiveness.

Typically hand and forearm (Figure 3) submersion is the most used technique, due to its easy and simplicity way to perform. Indeed there are other forms of active cooling strategies, although those cannot be simulated with the present thermoregulatory model. One usual method that is recurrently used is blow cold air onto the body through the use of fans (Figure 4).

Due to the lack of values, the 89th node model test couldn't be accomplished. Indeed, as Figure 9 suggests, the core temperature of the individuals, present a similar comportment comparing with the trials already simulated. Black squares represent core temperature of an individual set to passive recovery during his recovery period and the white squares an active cooling methodology. Thus, in a superficial approach, both data (experimental trial and simulated) has a similar comportment (Figure 9 and Figure 4.16), which is an omen that the simulated data are truthful.

The present study also aimed to alert firefighters and other professionals that are exposed to similar environments, to the risk they face while suppressing a fire. Due to space restrictions this is presented on a graphical basis in Appendice V.

5. CONCLUSIONS

The aims of the present study were twofold: (1) Investigate the potential factors that would lead to a state of hyperthermia; (2) Compare cooling strategies that firefighters could easily apply to reduce thermal strain, while the effectiveness of each strategies was also studied.

As intensively reported above, firefighting is a physically demanding occupation that places a significant demanding on cardiopulmonary fitness (Cheung et al., 2010). Strategies for rapidly reducing the physiological strain associated with occupational activity may therefore have important implications for health and safety of firefighters since elevations in body temperature hinder both physical and mental performance (Barr et al., 2009).

In the present dissertation several parameters were studied, namely firefighter physiology, protective clothing, implementation of schedules, fluid ingestion and effective cooling methodologies. In all those parameters cited early the author tries to quantify and qualify an inappropriate behavior that firefighters may follow. Still, all the parameters referred affect the human thermoregulatory system, therefore a proper conduct are required.

Firefighter's physiologies are as shown, a decisive variable while performing such activities that firefighters are exposed to (Figure 4.1). The excess of body fat reduce the body capacity to expel heat overload, limiting in this way the effectiveness of the firefighter while suppressing a fire (Figure 4.1).

Protective clothing is one of the most significant avenues that could lead firefighters to heat strain phenomenon. The reduced escape of metabolic heat produced is the major responsible for this to occur (Figure 4.4). One of the conclusions that could be taken is that protective clothing should be applied taking into account the surrounding environment as well as work rate level that is needed to be performed (Figure 4.2 and Figure 4.3).

Rotating duties are an easy and quick manner to attenuate firefighter's thermal heat strain. In spite of the slight accuracy in short periods of time, and knowing that most of the time firefighters can work periodically, commanders should apply this methodology in order to prevent undesired consequences (Figure 4.8 and Figure 4.9).

Fluid replacement, on the opposite of all other referred parameters has always a positive effect on the human body. The conclusions that we can take from the developed study are that any amount of fluid ingestion is better than none (Figure 4.12), still, the more the better (Figure 4.15). Typically the amount of fluid intake should be set as $\sim 70\%$ of sweat lost during the exercise.

At last, relating to effective cooling methods it's notorious that active cooling has a better performance then passive recovery (Figure 4.16). Comparing all the active cooling methods studied, feet and legs immersion are the best alternative in terms of efficiency and logistics in reducing thermal heat strain (Figure 4.17). However, comparing this technique with hands and forearms submersion, the difference between efficiencies aren't so high (Figure 4.18), and for instance hands and forearms submersion are a more easy trial to perform. The difference between the obtained results in these two techniques could be due to differences of external exposure on the recovery site. In other words, firefighters during feet and legs immersion take off their pants, boots and socks and on the other trial don't, just upper sector protective ensemble.

Lastly, it is also important to refer that a good conduct during fire exposures may avoid heat illness (Table 4.1) and some others fatalities. As reported early the main cause of death of many firefighters is heart attack caused by stress on the fire ground. It is also important to refer that most of the deaths that occur are related to volunteer's firefighters, those appear to be less tolerant to exercise under heat stress, due to their poor preparation.

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APPENDICES

I - General

Figure 1 - Wildland Fire (National Geographic).

Figure 2 - Personal Clothing Ensemble (Carter et al., 2008).

Figure 3 - Hands and Forearms Submersion (McLellan & Selkirk, 2006).

Figure 4 - Cold air blow, through the use of fans (McLellan & Selkirk, 2006).

II - Heat Stress

Figure 5 - Equipment to assess WBGT index (Ross and Barker, 2005).

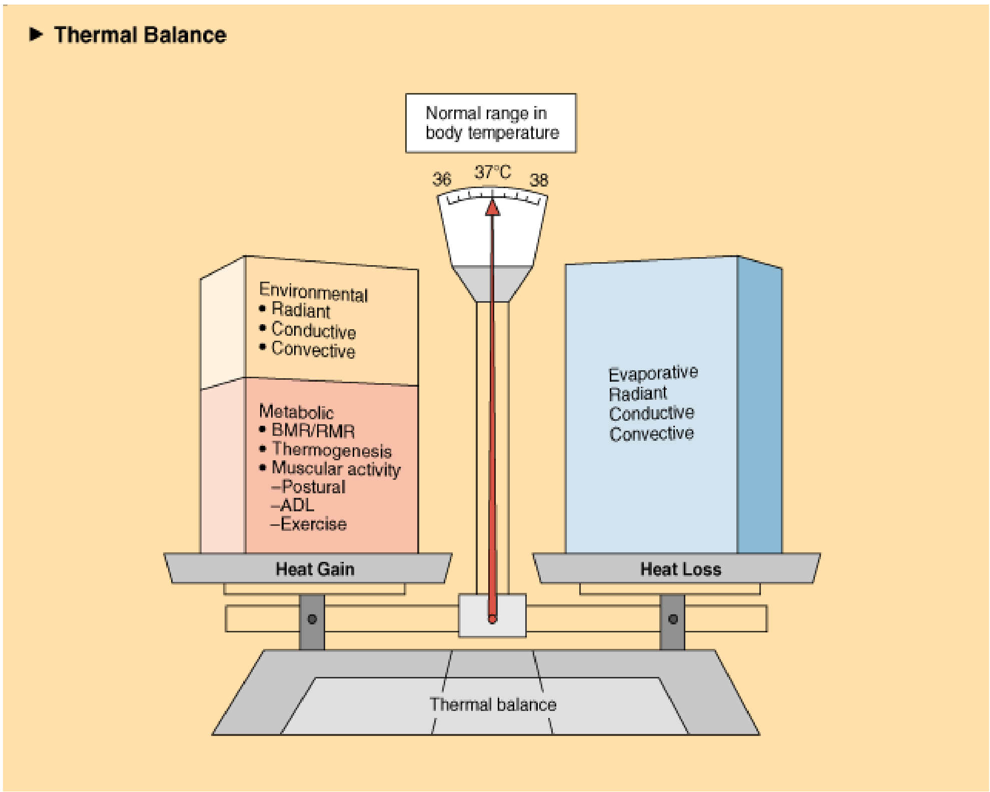


Figure 6 - Thermal balance between heat loss and heat gain (Robinson, 2009).

III - Huthereg

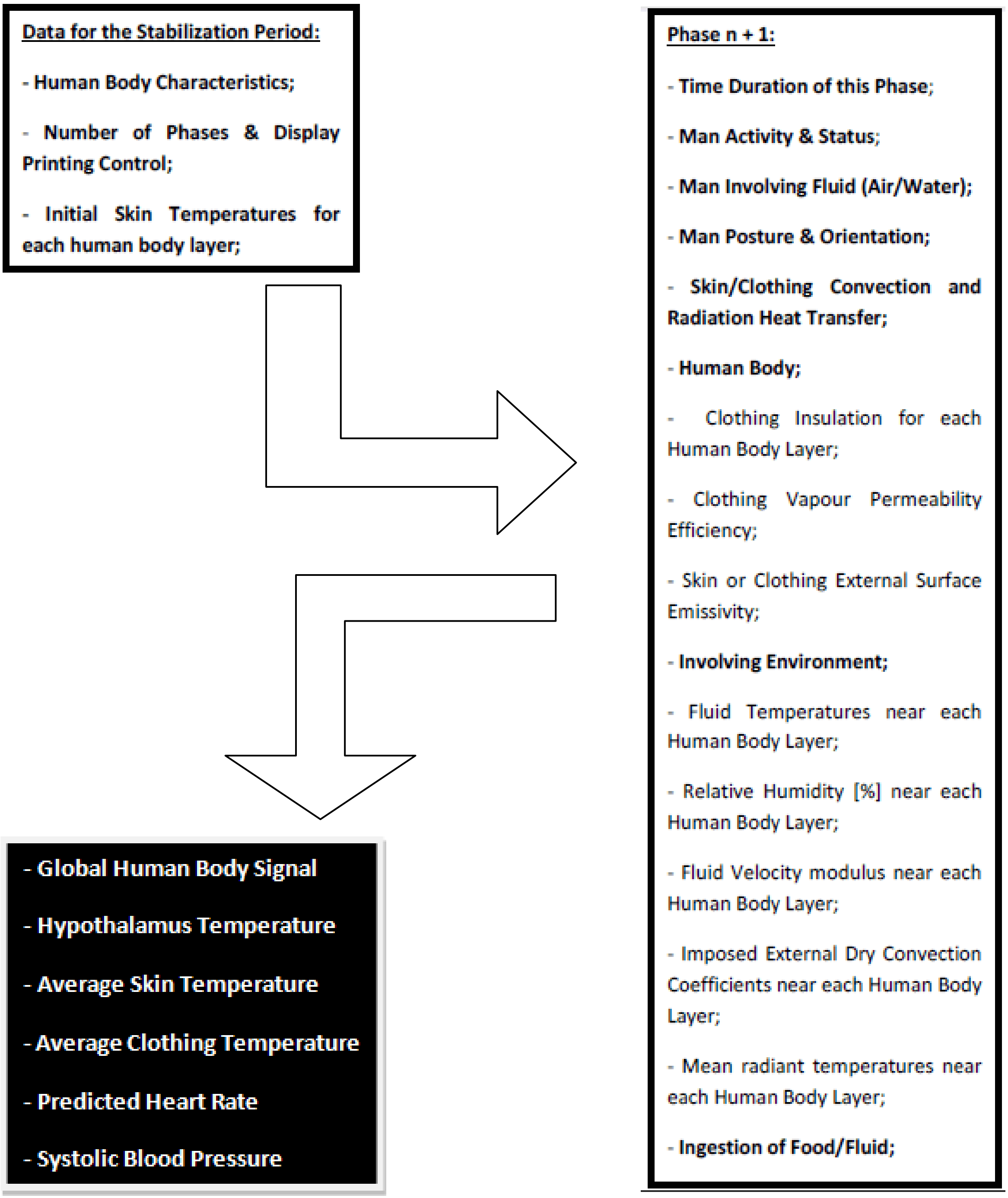
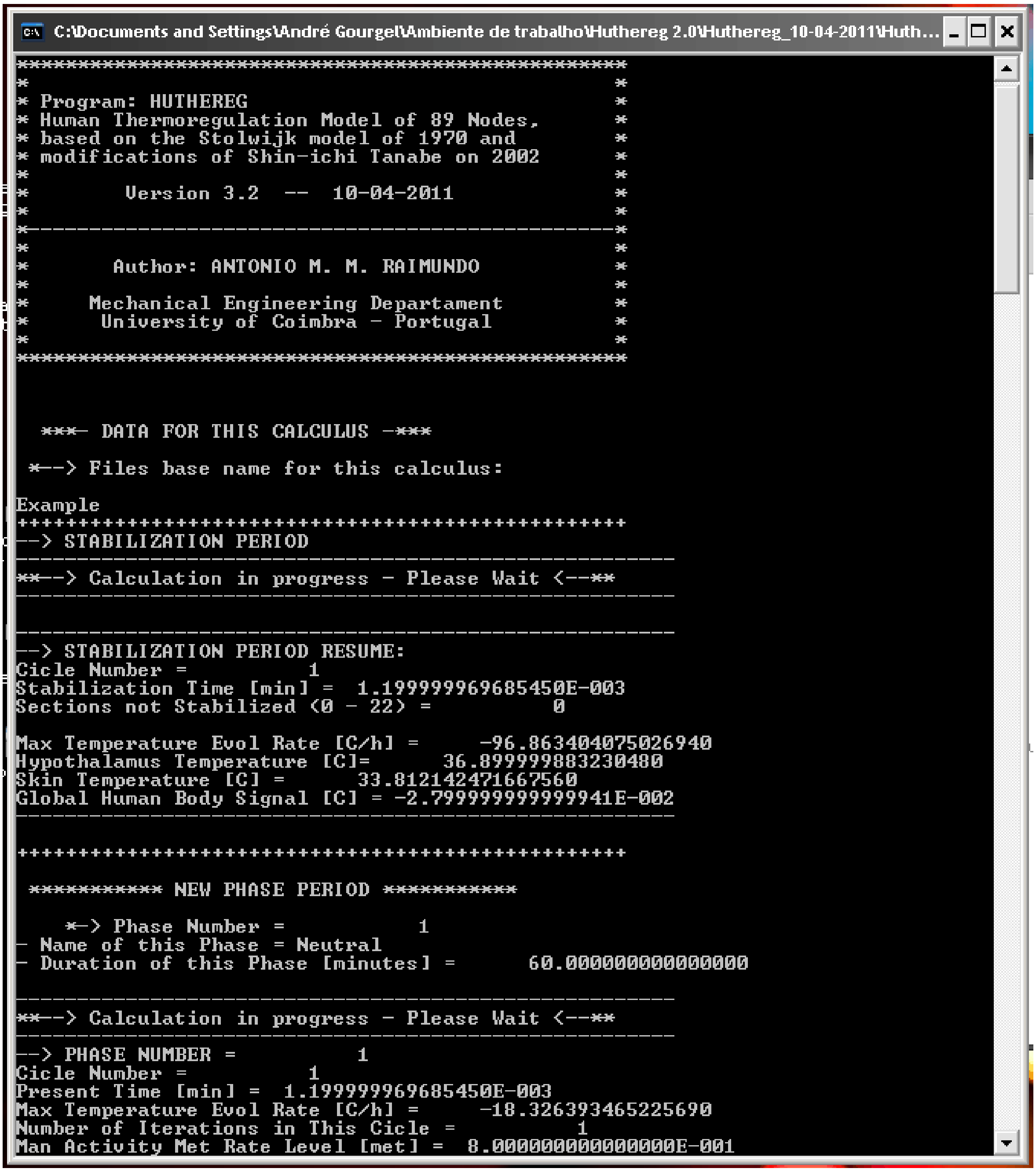


Figure 7 - Required inputs and obtained outputs of 89th node thermoregulatory model.



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**************************************************
*                                                *
* Program: HUTHEREG                              *
* Human Thermoregulation Model of 89 Nodes,      *
* based on the Stolwijk model of 1970 and        *
* modifications of Shin-ichi Tanabe on 2002      *
*                                                *
*        Version 3.2   --   10-04-2011           *
*                                                *
*------------------------------------------------*
*                                                *
*       Author: ANTONIO M. M. RAIMUNDO           *
*                                                *
*     Mechanical Engineering Departament         *
*      University of Coimbra - Portugal          *
*                                                *
**************************************************



  ***- DATA FOR THIS CALCULUS -***

 *--> Files base name for this calculus:

Example
++++++++++++++++++++++++++++++++++++++++++++++++++
--> STABILIZATION PERIOD
------------------------------------------------------
**--> Calculation in progress - Please Wait <--**
------------------------------------------------------

------------------------------------------------------
--> STABILIZATION PERIOD RESUME:
Cicle Number =           1
Stabilization Time [min] =  1.199999969685450E-003
Sections not Stabilized (0 - 22) =           0

Max Temperature Evol Rate [C/h] =     -96.863404075026940
Hypothalamus Temperature [C]=      36.899999883230480
Skin Temperature [C] =      33.812142471667560
Global Human Body Signal [C] = -2.799999999999941E-002
------------------------------------------------------

++++++++++++++++++++++++++++++++++++++++++++++++++

 *********** NEW PHASE PERIOD ***********

    *-> Phase Number =           1
- Name of this Phase = Neutral
- Duration of this Phase [minutes] =      60.000000000000000

------------------------------------------------------
**--> Calculation in progress - Please Wait <--**
------------------------------------------------------
--> PHASE NUMBER =           1
Cicle Number =           1
Present Time [min] =  1.199999969685450E-003
Max Temperature Evol Rate [C/h] =     -18.326393465225690
Number of Iterations in This Cicle =           1
Man Activity Met Rate Level [met] =  8.000000000000000E-001
```

Figure 8 - General aspect of huthereg program.

IV - Experimental Trial

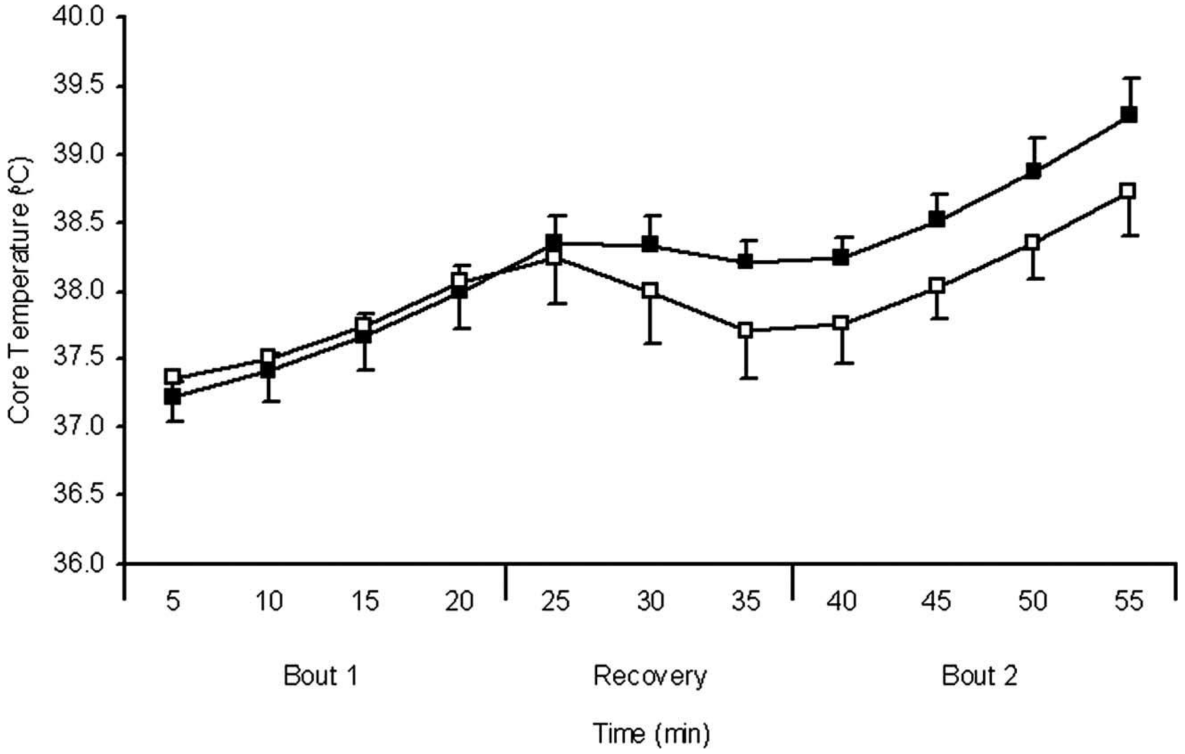

Figure 9 - Experimental results (Barr et al., 2009).

V - Facts

Many Firefighters die on-duty (Figure 10), due to a few causes.

Regarding the name of this appendice, facts, here the author will expose some recently published facts (Robinson, 2009) related with U.S. firefighters, in particular the number of deaths in the past years (1998 – 2008), and the cause (Figure 12 and Figure 13) and nature (Figure 14) of them. So once again the author tries to alert all firefighters the dangers they could face while working on a fire front.

This appendice came with the purpose to illustrate all that have been said until now. In other words, in the next figures are shown the consequences of performing in a wildland fire careless and set aside from what had been said in the past chapters, which was ways to avoid this terminal state (Figure 10).

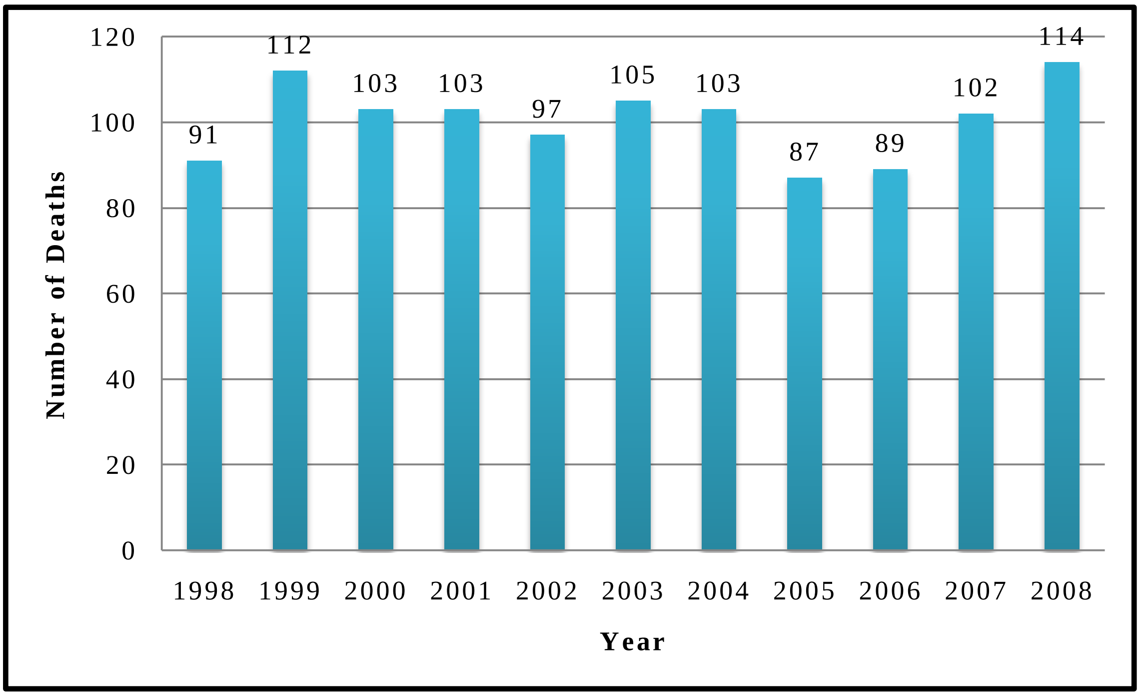

Figure 10 - On-Duty U.S. Firefighters Deaths, not including 9/11/01 WTC deaths (Robinson, 2009).

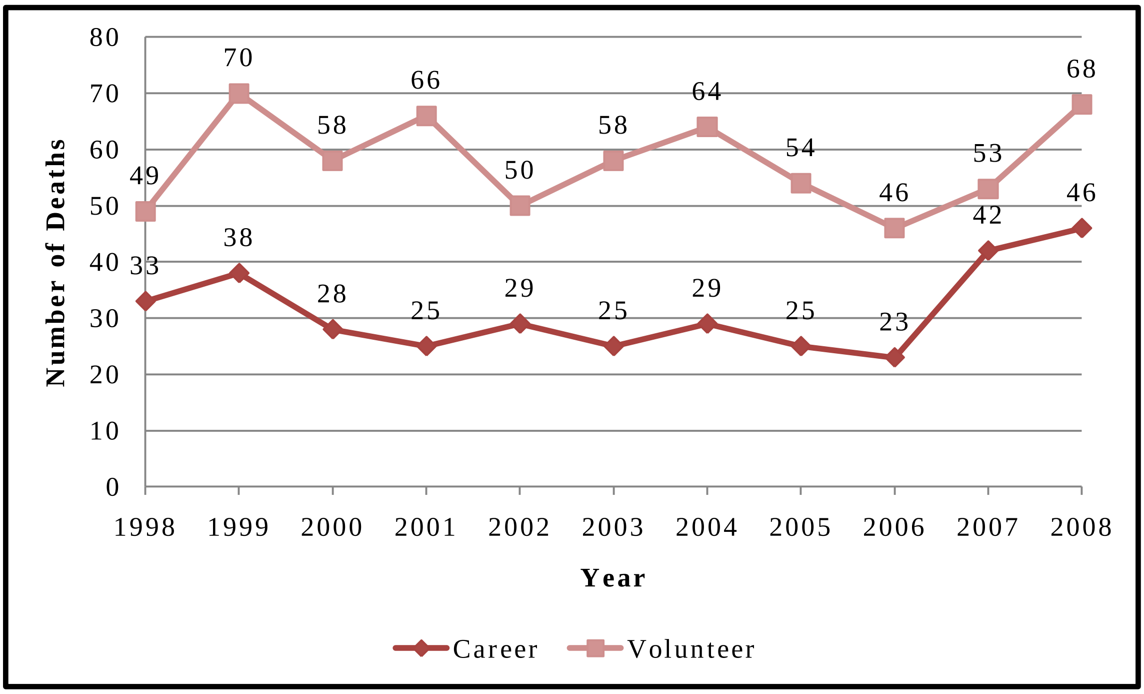

Figure 11 - U.S. Firefighters deaths, career VS volunteer not including 9/11/01 WTC deaths (Robinson, 2009).

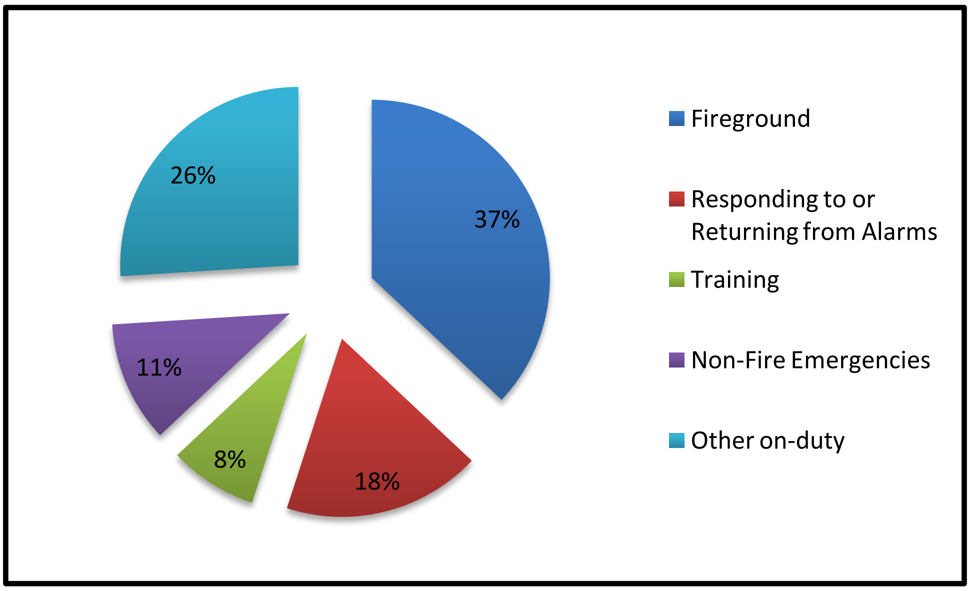

Figure 12 - U.S. Firefighters deaths by type of duty, 2008 (Robinson, 2009).

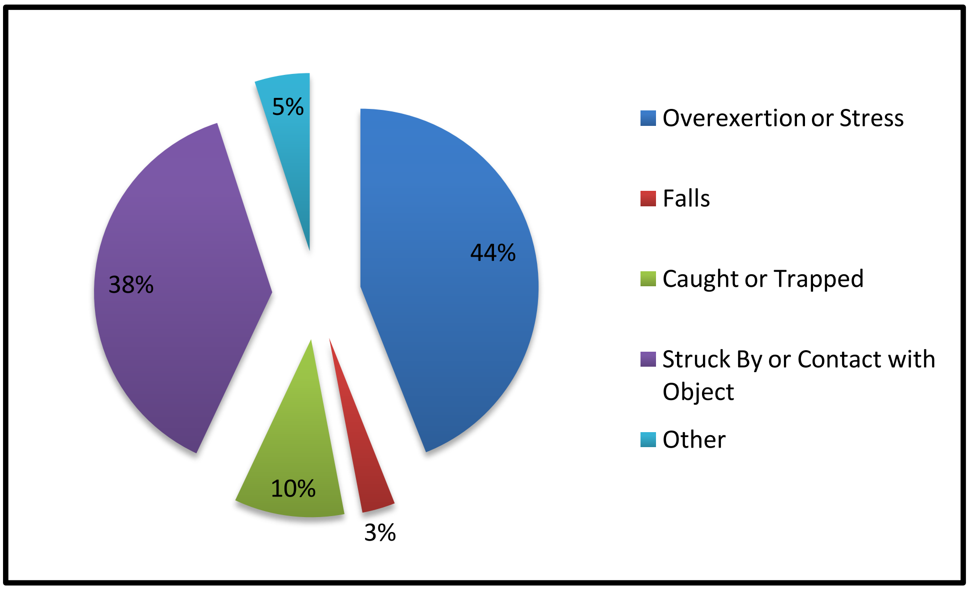

Figure 13 - U.S. Firefighters deaths by type of injury, 2008 (Robinson, 2009).

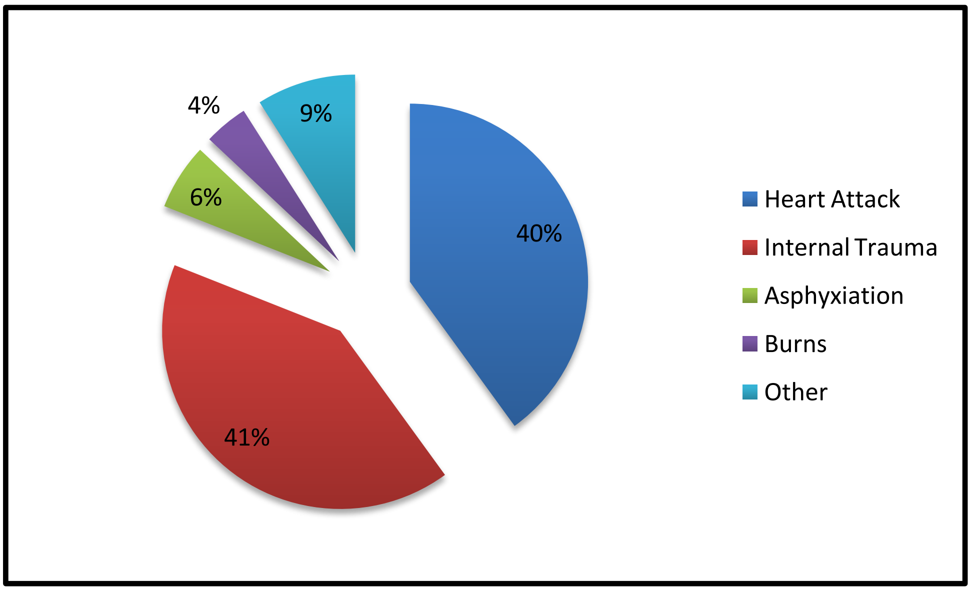

Figure 14 - U.S. Firefighters deaths by nature of injury, 2008 (Robinson, 2009).

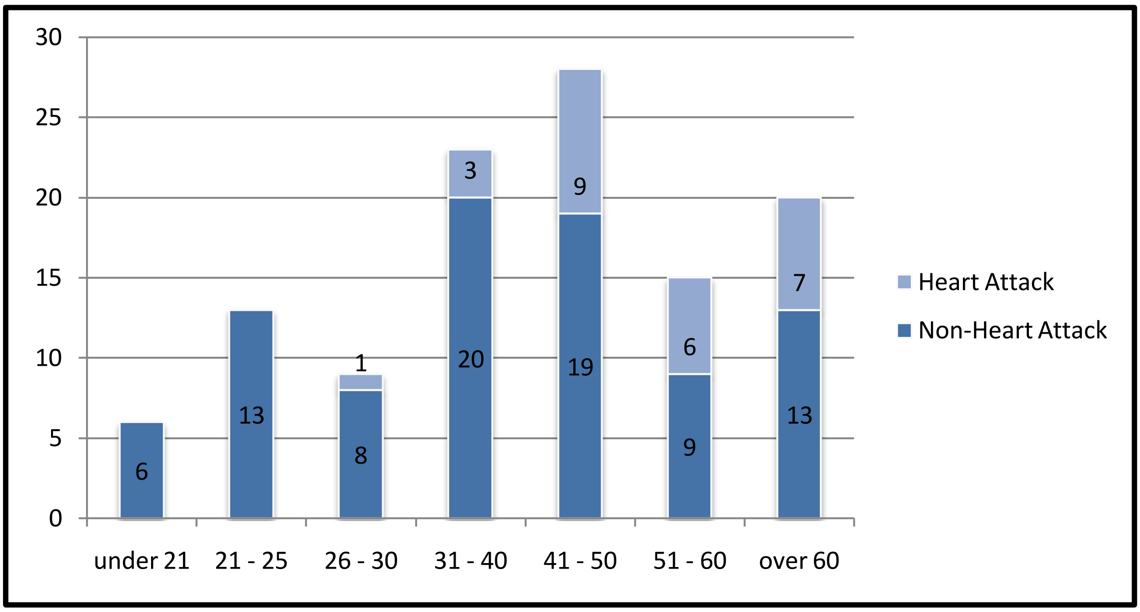

Figure 15 - U.S. Firefighters deaths by age and cause of death, 2008 (Robinson, 2009).