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Human trials to evaluate thermal performance specifications for private bushfire shelters

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HUMAN TRIALS TO EVALUATE THERMAL PERFORMANCE
SPECIFICATIONS FOR PRIVATE BUSHFIRE SHELTERS

A thesis submitted in (partial) fulfilment of
the requirements for the award of the degree

Master of Science (Research)

from

University of Wollongong

by

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CERTIFICATION

I, Benjamin John Haberley, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Masters of Science (Research) in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

______________________________________ Date:_____________________  
Benjamin John Haberley
HUMAN TRIALS TO EVALUATE THERMAL PERFORMANCE SPECIFICATIONS
FOR PRIVATE BUSHFIRE SHELTERS

Abstract

Australia is one of the most bushfire prone regions in the world. Regular bushfires pose a threat to the Australian population and in particular those located on the Eastern seaboard, and in the 2007 Victorian bushfires 173 lives were documented to be lost (Royal Victorian Bushfire Commission, 2009). As a result of these loses, it was deemed that a building standard for bushfire shelters was necessary. This project sought to test the thermal standard for bushfire shelters, which was determined by the Australian Building Codes Board (2010) to be 39° Modified Discomfort Index. A series of three experiments were undertaken to determine if this standard would support life for the expected occupancy period. The first experiment was a preliminary study to determine if the standard of 39° Modified Discomfort Index would provide an environment in which core temperature could be maintained. The second experiment determined the influence of an air-tight simulator on the thermal standard, as an air-tight shelter would cause changes in gas concentrations and also the micro-climate of the shelter. This experiment helped to identify a possible worst-case thermal profile for the bushfire shelter throughout a 60-min exposure. With this and keeping in mind that it has been found that dehydration is associated with a faster rise in core temperature (Montain and Coyle, 1992) and occupants may find themselves seeking shelter in a somewhat dehydrated state. Therefore, the third investigation focussed on the influence of dehydration on the thermal profile identified in experiment two. It can be concluded that from this study that the thermal standard for bushfire shelters would provide a safe environment for healthy individuals.
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1.1 INTRODUCTION

1.1.1 Conceptual Introduction

The Eastern seaboard is home to most Australians, with the South-Eastern corner being predisposed to the most frequent and severe bushfires in the world. In 2009, Victoria suffered a severe summer and experienced several of its worst bushfires. This series of bushfires was a turning point in fire safety procedures, after 173 lives were lost in the fires and damages of $4 billion were exceeded. The primary reasons for the loss of lives and property were attributed to a slow response time and poorly constructed personal shelters. The Royal Victorian Bushfire Commission (2009) deemed that the construction of bushfire a shelter, that satisfied appropriate building codes was required for bushfire-prone areas. The Australian Building Codes Board (ABCB) undertook the development of these standards, and this required the provision of a tenable environment during the most dangerous period of a bushfire. However, since no standards specifically for bushfires were found to exist in any country, these needed to be developed on the basis of first principles of science and engineering.

It was estimated that people may be required to occupy a bushfire shelter for about 60-min during an emergency. This time includes a 10-min period prior to the arrival of the fire front, a 40-min period during which external conditions may be untenable, and finally a 10-min safety margin following the passaging of the fire (Australian Building Codes Board, 2010). This standard requires the internal temperature of the shelter be maintained at maximum mean Modified Discomfort Index (MDI) of 39° for 60-min. It was expected that
this thermal condition would prevent the core temperature of any occupant from increasing by more than 2°C and, therefore, would provide a survivable environment during the most dangerous phase of a bushfire. However, no experimental data existed to support this standard.

The Modified Discomfort Index of 39° represented part of the advice on tenable and habitable conditions provided to the Australian Building Codes Board by the Defence Science and Technology Organisation (Melbourne), through the Land Engineering Agency (Ludovici et al., 2010). In theory, this standard should provide an environment in which critical core temperature is not exceeded (42°C; Ludovici et al, 2010). However, the Modified Discomfort Index is a derivation of the effective temperature scale (Houghten and Yagloglou, 1923), which is actually a sensation index, and was never designed to predict either physiological responses or survival probabilities. Instead, this scale was designed to define thermal comfort limits for people within air-conditioned (office) spaces, by identifying combinations of air temperature, air motion and relative humidity that would elicit equivalent thermal comfort.

Once inside the sealed chamber, occupants would be hot and sweaty, having just been engaged in vigorous activity in most stressful and unpleasant of circumstances. Known problems associated with the Modified Discomfort Index are its insensitivity to sweating changes and the evaporative power of the environment (Budd, 2008). For example, under humid and still conditions, the evaporation of sweat may be restricted by high water vapour pressures or by restricted air movement across the skin surface. Whilst the external environment during a bushfire will be very hot and dry (e.g. 41.4°C, 10% relative
humidity: Wallan (Victoria) at 1500 hours, Saturday February 7th, 2009 [Ludovici et al., 2010]), and conditions within a sealed shelter will initially be identical, these will soon change. Indeed, within such a microclimate, the water vapour pressure will rapidly rise, and there will be limited air movement. Under these conditions, the limitations of the Modified Discomfort Index can introduce errors when attempting to identify untenable conditions and defining building standards. Taking this into consideration, it was necessary to perform a series of experiments to determine the survivability of occupants exposed to a Modified Discomfort Index of 39° across different combinations of temperature and humidity. Furthermore, the standard of 39° Modified Discomfort Index can be achieved across an array of conditions, and variations of 10°C in air temperature and 40% in relative humidity can still equate to the same Modified Discomfort Index value. The question must therefore be asked whether these extreme conditions are still tenable across the entire range.

1.1.2 Gender considerations

It has long been established that morphological and physiological differences between the genders in heat exchange are markedly different ( Wyndham et al., 1965; Weinman et al., 1967; Shapiro et al., 1980). These come from three mechanisms, those being different body surface area to mass ratios, differences in the sweating response and the hormonal influences. Considering a bushfire shelter must provide a tenable environment for both males and females, it is important to be cognisant of these influences, and this dictated that males and females are equally represented in this study.

Firstly, a larger body surface area to mass ratio, on average, occurs in females (Robinson,
Heat transfer of any object occurs through the surface exposed to the stimulus, therefore a larger surface area facilitates a faster rate of heat exchange (Burton, 1933). This can both be a help and a hindrance in maintaining core temperature. In conditions of $39^\circ$ Modified Discomfort Index, the air temperature exceeds body temperature and this becomes a hindrance leading to an increase the rate of heat gained.

The sweating responses between the genders exhibit two main differences. Firstly, females have a less powerful sweating response when exposed to the same conditions (Hertig et al., 1963; Burse, 1979; Shapiro et al., 1980; Mehnert et al., 2002; Gagnon and Kenney, 2012). Secondly, the onset of sweating occurs at a higher body core temperature in women (Fox et al., 1969; Bittel and Henane, 1975; Anderson et al., 1995). However, when males and females are compared in environments with a reduced evaporative power, females better are able to regulate body temperature (Shapiro et al., 1980).

The monthly hormonal changes of women, alters thermoregulatory responses and the ability of individuals to maintain body temperature (Kawahata, 1960; Grucza et al., 1993). The changing thermoregulatory response is a result of fluxing levels of progesterone and oestrogen that occurs during the different stages of the menstrual cycle (Kawahata, 1960; Bittel and Henane, 1975). During periods of peak progesterone secretion, a marked increase in the thermoregulatory threshold compared to men is noted (Grucza et al., 1993; Stratchenfeld et al., 2000, Kaciuba-Uscilko and Grucza, 2001), and this occurs during the luteal phase of menstruation. The increased thermoregulatory threshold experienced during the luteal phase is minimised during ovulation, when oestrogen levels peak, a lowering of the body temperature that the onset of sweating and vasodilation occurs is found.
Not only does the menstrual cycle influence the primary physiological reactions used to cool core temperature, it also influences resting core temperature. Fluctuations of up to 0.05°C can occur in women dependent on the stage of the menstrual cycle the individual is in (Kaciuba-Uscilko and Grucza, 2001). During the luteal phase an increased core temperature is found and this is attributed to the influence of progesterone.

As a result of these differences, women will experience greater physiological strain during heat exposure, and this means that all experiments should involve women.

1.1.3 Physiological consequences of an air-tight shelter

To provide a tenable environment, a bushfire shelter must be air-tight to prevent noxious gases from entering. Thus a need for the structure to be air-tight causes physiological strain through the changing gas concentrations inside the shelter, which would result from respiration. The primary gas changes which need to be considered are declining oxygen and increasing carbon dioxide concentrations. Metabolic rate will be elevated above resting due to hyperthermia (Consolazio et al., 1963; Consolazio, 1964; Gaudio and Abramson, 1968). Not only will gas concentrations change within the shelter from occupation, but so to will the humidity and temperature of the air.

A finite volume of air inside the shelter means that carbon dioxide concentration will rise, as the product of respiration. An accumulation of carbon dioxide in the bloodstream induces a physiological state called hypercapnia, which alters normal thermoregulation by increasing an individuals sweating response (Stokes et al., 1948; Bullard, 1964; Wood,
Excessive sweating in a sealed environment will raise the total water vapour content of the air, lowering the evaporative power of the environment and ultimately impairing the occupant’s ability to maintain core temperature via evaporation. Not only will a rising carbon dioxide induce hypercapnia, but it can also cause safety concerns as at concentrations of 7% a loss of consciousness has been observed (Flury and Zernik, 1931). In fact, the National Institute for Occupational Safety and Health (U.S.A.) deem a concentration of 4% to be “immediately dangerous to life or health”.

Hypoxia, or a deficiency of oxygen, will also influence the sweating response. The oxygen content of the shelter will, through the respiration of the occupants, decline. The exact manner in which hypoxia alters sweating is debatable, with conflicting results being observed, dependent on the method which hypoxia is induced. For example, in response to a normobaric, hypoxic stimulus (13.5% oxygen concentration) during exercise, an elevation in sweat secretion has been noted (Kacin et al., 2007). In contrast to this, a decrease in sweat secretion has been observed during hypobaric hypoxia (Kolka et al., 1987). Whichever may be the case, both have the ability to alter thermoregulatory responses. The recommended minimal concentration of oxygen is 19.5% (Occupational Safety and Health Administration (U.S.A.)), however, it is not until oxygen concentration falls to 10% that a loss of consciousness is estimated. These changes meant that trials must be performed in conditions where temperature, relative humidity, oxygen and carbon dioxide concentration will change, as they would in a bushfire shelter.

1.1.4 Shelter history

Shelters to provide protection from external stresses is not a new concept. In 1881, the
United States War Department (1881) issued a report indicating that Fort Moultrie in Charlestown had such a shelter to protect individuals. The construction and occupancy of confined shelters peaked during and after World War Two, in an attempt to provide shelter for individuals from blasts associated with wars (Leutz, 1965). During World War Two protective shelters were aimed at protecting occupants from the impact of high explosive bombs, and so these shelters required a relatively short occupation period (3-10 hours: Degenkolb, 1965). However, since the development of nuclear war and its associated radiation, protective shelter occupancy duration has increased from hours to weeks (Yaglou, 1960). Three main shelter types were used historically, they included the bunker shelter which was a reinforced concrete construction, the trench or tunnel shelter which were dug into a hill and finally cellar shelters were also utilised (Degenkolb, 1965).

All protective shelters have a common issue maintaining a constant internal environment due to metabolic processes of human occupants, which occur through the consumption of oxygen, production of carbon dioxide and production of metabolic heat (Johnson and Ramskill, 1965). These issues remain consistent in a bushfire shelter, however due to the shorter occupancy period in a bushfire of 1 hour (Australian Building Codes Board, 2010) in comparison to a nuclear strike (<2 weeks), factors such as carbon dioxide build up from smoking and respiration and a depleting oxygen level would be a provide less of a risk (Charanian, 1960; Johnson and Ramskill, 1965). In a bushfire shelter there are added issues such as the external noxious gases and the associated heat of the fire. Thus, the internal temperature must be maintained at a level which will facilitate survival, albeit with some discomfort.
1.2 AIMS OF THIS PROJECT

This project was designed to determine whether or not the standard for bushfire shelters recommended by the Australian Building Codes Board provided a tenable environment for occupants. There is extensive knowledge and research into individuals' tolerance to severe heat exposure and the physiological responses of such an exposure (Bladgen, 1775a; 1775b). With this knowledge in mind, three different investigations were performed. The first was to determine if the standard (39° Modified Discomfort Index) would facilitate an environment in which core temperature would not elevate more than 2°C in 60 min, or rise to 42°C. The second study was aimed at quantifying the impact of a pre-heated (38.0°C) individual upon an air-tight bushfire shelter adhering to the Australian Building Codes Board standard (2010), and to quantify the physiological strain experienced by the occupant. This would define the worst-case thermal profile for a bushfire shelter. Thirdly, the role of dehydration on the rate of core temperature increase must be assessed, because by the nature of the events leading to entry to the bushfire shelter, occupants may find themselves mildly dehydrated. This will give an indication of the viability of the current standard for bushfire shelters and provide an evaluation of the expected physiological strain which can be expected during exposure to a shelter adhering to the Australian Building Codes Board standards (2010).

Thus, the aims of this research were three-fold, and these defined three separate investigations for this project:

(I) Experiment one (Chapter two): The aim of this experiment was to determine the physical impact of a constant Modified Discomfort Index of 39°. This was investigated under three
different thermal conditions\(^1\).

It was hypothesised that:

- The exposure to a Modified Discomfort Index of 39\(^n\) for 60-min would not elicit a rise in core temperature 39.5\(^\circ\)C.

(ii) Experiment two (Chapter three): The aim of this experiment was to quantify and evaluate the impact of changes in air temperature, water vapour pressure, oxygen and carbon-dioxide concentration within an air-tight shelter simulator.

It was hypothesised that:

- Neither the concentration of oxygen nor carbon dioxide would rise to dangerous levels during a 60 min exposure.
- Air temperature and humidity would both increase from the presence of a pre-heated, sweating individual. However, these change would not lead to a rise in core temperature above 39.5\(^\circ\)C.

(iii) Experiment three (Chapter four): The aim of this final experiment was to determine the impact of changes in air temperature and water vapour pressure on hyperthermic men and women.

It was hypothesised that:

- Core temperature would increase throughout these exposures. However, if

\(^1\) Condition one: 40\(^\circ\)C and 70%. Condition two: 45\(^\circ\)C and 50%. Condition three: 50\(^\circ\)C and 30%.
termination occurs at the ethical criterion (39.5°C) prediction equations will show that a core temperature of 42°C will not occur within a 60-min exposure.
1.3 REFERENCES


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CHAPTER TWO: THE PHYSICAL IMPACT OF A CONSTANT MODIFIED DISCOMFORT INDEX OF 39°

2.1 INTRODUCTION

2.1.1 Background information

The eastern seaboard of Australia is one of the most bushfire prevalent regions of the world, particularly the densely populated south-east coast. The bushfires on Saturday the 7th of February 2009, now known as Black Saturday, were some of the worst in Australia’s history and became a turning point in bushfire safety procedures, after 173 lives were lost and in excess of $4 billion of structural damage was accrued. A tighter regulation on the standard for bushfire shelters was deemed necessary. The development of a standard for the bushfire shelters was initiated, (Royal Victorian Bushfire Commission, 2009) since it was found that many lives that were lost, occurred when people stayed to defend their homes. The Royal Victorian Bushfire Commission (2009) stated that the priority for bushfire safety must be the protection of life and the safety of communities, and the development of this standard was undertaken by the Australian Building Codes Board (ABCB). The standard refers to the tenable internal environment which must protect occupants from the direct and indirect actions of a bushfire. However, since such a standard does not exist anywhere else in the world, it had to be developed on the basis of first principles.

The anticipated time of occupancy has been estimated to be 60 min, and this includes 10

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min before the fire front reaches a dwelling, 40 min when the external environment is untenable and a 10 min safety margin after the fire has passed (Australian Building Codes Board, 2010). The thermal requirement of the standard states that the internal temperature of the shelter must be maintained at a maximum mean Modified Discomfort Index (MDI) of 39° for 60 min. It was expected that this standard would suffice to prevent a rise in core temperature of more than 2°C, or an actual temperature of 42°C, thereby providing a survivable environment during a bushfire. The impact of heat exposure on human physiology is not new to the field of thermal physiology (Blagden, 1775a; 1775b). However, no experimental data exists to support this standard, and the research within this thesis is directed at evaluating the suitability of this recommendation.

Once inside the sealed chamber, it is anticipated that occupants will be hot and sweaty, having just been engaged in vigorous activity in the most stressful and unpleasant of circumstances. The Modified Discomfort Index temperature, although reported in degrees, does not quantify air temperature (°C). Instead, it was developed from stress indices designed to equate thermal comfort. Air temperature is certainly part of the index, but it is not the only component. For this reason one can obtain a wide range of air temperatures that have the same Modified Discomfort Index temperature. For instance, variations of 10°C and 40% relative humidity can still exist across conditions that equate to the same Modified Discomfort Index value³. The question must therefore be asked whether conditions are tenable across the entire range of a Modified Discomfort Index of 39°. Therefore it is necessary to perform a series of experiments to determine the survivability of occupants

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³ Condition one: 40°C and 70%. Condition two: 45°C and 50%. Condition three: 50°C and 30%.
exposed to a Modified Discomfort Index of 39° across different combinations of temperature and humidity, and such tests need to be performed on males and females.

2.1.2 Modified Discomfort Index (MDI)

The existing thermal performance specification for private bushfire shelters are based upon the Modified Discomfort Index (MDI). This index is an effective thermal index, meaning it was developed using meteorological parameters (e.g. temperature, humidity, wind speed etc.). The basis of such scales were to determine the comfort of an individual in varying environmental conditions, therefore it is not really appropriate for predicting physiological strain and the risk of heat illness. The origins and limitations of this index are crucial, as it was primarily developed as an index to equate environmental stress. Accordingly, this brief historical perspective on the Modified Discomfort Index and preceding effective thermal indices is provided, as they are all calculated using similar meteorological parameters and are also all used to determine comfort.

The Modified Discomfort Index is the result of 80 years of thermal scale development, starting with Houghten and Yagloglou (1923) developing the effective temperature scale. This scale was developed as a thermal scale for office workers in air conditioned buildings, and many thermal scales have arisen from this index.

The second and most widely used development is the wet-bulb globe temperature index (WBGT), which is derived from the following calculation for indoor use: 0.7 natural wet-bulb temperature + 0.3 globe temperature [°C] (Yagloglou and Minard, 1957). It was
developed by Yagloglou and Minard (1957) to reduce the incidence of heat illness during military training activities. Indeed, general use of the WBGT-index was recommended by the Occupational Safety and Health Administration (1974), and it has subsequently been adopted by the International Standards Organisation for quantifying thermal stress (ISO 7243:1982), the National Institute for Occupational Safety and Health (1986), and the American College of Sports Medicine (1996). However, this is a stress index and, as such, it does not quantify physiological strain, which refers to the consequence of a stress being applied to the body (Budd, 2008). Therefore, its predictive capacity with regard to survival under conditions outside the comfort zone is limited.

The third development was the Israeli Discomfort Index (DI) of Thom (1959), and its subsequent modification by Tennenbaum et al. (1961). The Discomfort Index, calculated by $0.5 \times \text{natural wet-bulb temperature} + 0.5 \times \text{dry-air temperature} \ [^\circ \text{C}]$, does not include a consideration of radiant heat loading (globe temperature), but relies only upon the wet- and dry-bulb temperatures. However, a greater weighting is given to dry-air temperature in an attempt to offset the absence of globe temperature. This appears effective as data from the Discomfort Index were very strongly correlated with observations made using the WBGT (Epstein and Moran, 2006), and that relationship has been emphasised as part of the justification for its use. Nevertheless, it was considered that this should be further modified by changing the weighting coefficients to more heavily emphasise the wet-bulb temperatures (Moran et al., 1998a, 1998b, 1998c; Moran and Pandolf, 1999), and thus arose its latest development in the form of the collaborative U.S.-Israeli Modified Discomfort Index (MDI). However, it too is an environmental stress, and not a strain index.
This study will not only give a determination of the effectiveness of the 39°C Modified Discomfort Index as a standard for bushfire shelters, but will also evaluate its use with respect to physiological strain.

2.1.3 Gender considerations

The shelter standard must be able to facilitate an environment that can protect from the direct and indirect actions of a bushfire for both genders. However, both genders do not dissipate heat at the same rate. The differences in thermoregulation between men and women in hot environments are well documented (Wyndam et al., 1965; Kamon and Avellini, 1976; Shapiro et al., 1980), with women tending to secrete less sweat than males for the same climatic conditions (Hertig et al., 1963; Weinman et al., 1967; Burse, 1979; Shapiro et al., 1980, Mehnert et al., 2002). Women also have a higher thermoregulatory threshold (Fox et al., 1969; Bittel and Henane, 1975; Anderson et al., 1995), meaning that not only do women sweat less powerfully than men, but the onset of this sweating response occurs at a higher temperature (Fox et al., 1969; Bittel and Henane, 1975). Therefore, when women are exposed to a hot environment a lower evaporative cooling response can cause a greater rise in body temperature compared to males particularly in dry environments.

The skin surface area exposed to a thermal stimulus will influence the rate of heat flux (Burton, 1933). Females have a larger body surface area to mass ratio, meaning that they will be more susceptible to faster heat exchange (Robinson, 1943). Not only does body size influence heat storage but also body fatness. A higher body fat percentage is found to be prevalent among women, leading to greater insulation during heat exposure.
This experiment will determine if the prescribed thermal standard of 39° Modified Discomfort Index will provide an environment in which both males and females can maintain core temperature within a safe limit (below 42°C: Kenney, 2004). Considering males and females have different thermoregulatory capabilities it cannot be assumed that an environment in which males can maintain core temperature will elicit the same response in females. Therefore it is necessary that both genders are represented equally during this experiment.

2.1.4 Aims of this study

The research reported below was aimed at evaluating, through human laboratory trials involving young and healthy adults (males and females), the efficacy of the maximal mean Modified Discomfort Index standard of 39° proposed by the Australian Building Codes Board (2010) for private bushfire shelters. Physiological evidence was sought by the Australian Building Codes Board, under advice from Patterson (2010), pertaining to human survival within shelters constructed in accordance with this building code. This will be determined using six individual trials in which subjects will be exposed to three conditions, each of which equate to a mean Modified Discomfort Index of 38-39°, and the associated physiological strain of these exposures will be measured. Specifically, this research was aimed at answering the following question:

“Can someone tolerate an exposure to an Modified Discomfort Index of 39° without experiencing either a critical core temperature of 42°C or a 2°C core temperature elevation?”
At high body temperatures, muscle cell membrane breaks down causing irreversible liver and kidney damage (Gardner and Kark, 2001). Studies indicate that a critical thermal maximum in body temperature before cell and subsequent organ damage in humans is 42°C (Bynum, et al., 1978; Kenney, 2004). If a bushfire shelter is to be deemed successful it must provide an environment that prevents a rise in core temperature to this level and thereby allowing occupants to maintain a healthy state.

2.2 METHODS

2.2.1 Subjects

Sixteen healthy adults, aged 19-24 years, participated in this research (Table 1), with each person being involved in six different experimental trials. Males and females were equally represented, with subjects from each gender being recruited according to their body size, such that equal numbers of individuals of large (mean: males: 2.06 m², females: 1.83 m²), medium (mean: males: 1.92 m², females: 1.64 m²) and small sizes (mean: males: 1.72 m², females: 1.51 m²) were studied within each gender. These sizes were based upon body surface area, since the exchange of thermal energy between the surrounding hot air and each individual (heat transfer) would occur through this surface and will therefore powerfully influence heat transfer and storage. This heat is then retained or lost from the body mass, thereby determining body temperature. All participants provided written, informed consent, and were screened to eliminate those with a contraindicative history of cardiovascular or thermoregulatory problems. All procedures were approved by the Human Research Ethics Committee (University of Wollongong: HE 11/460).
Table 2.1: Subject characteristics (M = male, F = female).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Surface area (m²)</th>
<th>Surface area to mass (m².kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>M-Small</td>
<td>20</td>
<td>1.681</td>
<td>61.36</td>
<td>1.693</td>
<td>0.028</td>
</tr>
<tr>
<td>S2</td>
<td>M-Small</td>
<td>21</td>
<td>1.654</td>
<td>63.45</td>
<td>1.698</td>
<td>0.027</td>
</tr>
<tr>
<td>S3</td>
<td>M-Small</td>
<td>23</td>
<td>1.723</td>
<td>66.04</td>
<td>1.779</td>
<td>0.027</td>
</tr>
<tr>
<td>S4</td>
<td>M-Medium</td>
<td>20</td>
<td>1.802</td>
<td>74.54</td>
<td>1.934</td>
<td>0.026</td>
</tr>
<tr>
<td>S5</td>
<td>M-Medium</td>
<td>20</td>
<td>1.856</td>
<td>68.26</td>
<td>1.904</td>
<td>0.028</td>
</tr>
<tr>
<td>S6</td>
<td>M-Large</td>
<td>22</td>
<td>1.811</td>
<td>76.34</td>
<td>1.961</td>
<td>0.026</td>
</tr>
<tr>
<td>S7</td>
<td>M-Large</td>
<td>20</td>
<td>1.916</td>
<td>92.12</td>
<td>2.213</td>
<td>0.024</td>
</tr>
<tr>
<td>S8</td>
<td>M-Large</td>
<td>20</td>
<td>1.803</td>
<td>80.80</td>
<td>2.003</td>
<td>0.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean (males) 20.8 1.781 72.86 1.898 0.026</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation 1.2 0.089 10.26 0.174 0.001</td>
</tr>
<tr>
<td>S9</td>
<td>F-Small</td>
<td>21</td>
<td>1.583</td>
<td>52.30</td>
<td>1.515</td>
<td>0.029</td>
</tr>
<tr>
<td>S10</td>
<td>F-Small</td>
<td>20</td>
<td>1.616</td>
<td>49.26</td>
<td>1.499</td>
<td>0.030</td>
</tr>
<tr>
<td>S11</td>
<td>F-Small</td>
<td>23</td>
<td>1.630</td>
<td>49.70</td>
<td>1.514</td>
<td>0.030</td>
</tr>
<tr>
<td>S12</td>
<td>F-Medium</td>
<td>24</td>
<td>1.620</td>
<td>58.32</td>
<td>1.613</td>
<td>0.028</td>
</tr>
<tr>
<td>S13</td>
<td>F-Medium</td>
<td>20</td>
<td>1.610</td>
<td>64.32</td>
<td>1.674</td>
<td>0.026</td>
</tr>
<tr>
<td>S14</td>
<td>F-Large</td>
<td>19</td>
<td>1.791</td>
<td>72.24</td>
<td>1.900</td>
<td>0.026</td>
</tr>
<tr>
<td>S15</td>
<td>F-Large</td>
<td>20</td>
<td>1.733</td>
<td>68.90</td>
<td>1.819</td>
<td>0.026</td>
</tr>
<tr>
<td>S16</td>
<td>F-Large</td>
<td>22</td>
<td>1.698</td>
<td>67.34</td>
<td>1.774</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean (females) 21.1 1.660 60.30 1.664 0.028</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation 1.7 0.073 9.14 0.154 0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Overall mean 20.9 1.720 66.6 1.781 0.027</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard Deviation 1.4 0.10 11.41 0.200 0.002</td>
</tr>
</tbody>
</table>
In this study young and healthy individuals were used as subjects, however it should be noted that this is not an accurate representative of the population at large. Certain populations such as the elderly, young and infirmed could potentially have less efficient thermoregulatory systems and, as such, these individuals would not be represented within these groups. However, it would be unethical to expose population groups such as these to the thermal rigours of this study.

2.2.2 Experimental overview

Subjects were exposed to three different shelter conditions, which ranged from 38-39° Modified Discomfort Index. The three conditions varied by 10°C in air temperature (40-50°C) and 40% relative humidity (30-70%). Trials were randomised between subjects to prevent order bias. Trials were conducted at the same time of day for each subject, with each participant being pre-heated and dehydrated prior to the exposures. This was used to replicate a more realistic state that occupants of a shelter would most likely be in when seeking shelter. To minimise heat acclimation, trials were conducted one week apart (Pandolf, 1998).

The three shelter conditions were achieved within a chamber that can independently regulate air temperature and relative humidity. Drinking and eating were not permitted to exasperate the dehydrated state and better replicate a poorly prepared shelter.

MDI = 0.3 air temperature + 0.75 wet-bulb temperature (equation 1: Moran et al., 1998).

1. Shelter condition one: Hot and humid: 40°C and 70% relative humidity (MDI 38° = 0.7 x 34.72 + 0.3 x 40). This trial provided a test of the physiological
equivalence of the Modified Discomfort Index criterion at a lower air
temperature, but with relatively high humidity.

2. Shelter condition two: Hot and quite humid: 45°C and 50% relative humidity
(MDI 39° = 0.7 x 34.67 + 0.3 x 45).

3. Shelter condition three: Very hot and dry: 50°C and 30% relative humidity
(MDI 39° =0.7 x 32.61 + 0.3 x 50).

Subjects were, based on body mass, dehydrated by 2%. Since partial dehydration is
associated with a faster rise in core temperature (Montain and Coyle, 1992), and considering
it is most likely that individuals taking refuge within a bushfire shelter will, by the nature of
the scenario in which they find themselves, enter the shelter in a somewhat dehydrated state,
then this hot-dehydrated state will more closely approximate reality.

Subjects were also pre-heated to two different thermal states; mildly hyperthermic (37.5°C)
and moderately hyperthermic (38.5°C), this was performed using intermittent, whole-body
hot-water immersion (40-41°C) and light treadmill exercise (6 km.h⁻¹). Whole-body water
immersion can rapidly heat and cool people (Booth et al., 2004; Taylor et al., 2008), and, if
the water is hot enough, it will also induce significant thermal sweating, leading to
progressive dehydration. Each subject was exposed to the three experimental conditions in
each of the two thermal states. Thus, a total of 96 trials were performed.

In reality, core temperatures may be greater than either of these two states, but, for the
purpose of tracking core temperature changes, and projecting these to either a critical core
temperature of 42°C (Kenney et al., 2004) or a 2°C core temperature elevation (Ludovici et al., 2010), then it was essential to commence these exposures with a core temperature that had the capacity to rise at least 1°C before reaching the current ethical criterion for terminating such an experiment (39.5°C). Core elevations beyond this point could accurately be extrapolated.

During the immersion, subjects wore a swimming costume and were seated in a support frame and lowered into, and removed from, the immersion tank using an electronic winch (150 kg lift capacity). A safety belt to prevented accidental immersion of the head in the unlikely situation of a subject being rendered unconscious. Once the desired thermal and dehydration state was obtained, the subject was removed from the water. Alternating immersion and walking periods were then continued until both the target dehydration thermal states were achieved.

The subjects then underwent a 60-min exposure in one of the three separate experimental conditions. During each exposure subjects were seated at rest, wearing only a swimming costume. This acted to demonstrate the typical behaviour for the scenario and to maximise heat dissipation.

2.2.3 Experimental standardisation

Subjects were required to refrain from strenuous exercise and the consumption of alcohol and tobacco during the 12 h prior to each trial. For the night prior to a trial, subjects were instructed to drink 15 mL.kg⁻¹ of additional water before retiring, and to eat an evening
meal and breakfast high in carbohydrate and low in fat. Subjects were also be requested to refrain from using caffeine for 2 h prior to each trial. On arrival at the laboratory, participants were provided with supplementary water (10 mL.kg\(^{-1}\)) if urine specific gravity was >1.029 (Armstrong et al., 1994). Beyond this point, no further liquid or food was provided. Before leaving the laboratory, subjects were rehydrated, consuming an iso-osmotic drink equivalent to 150% of the body mass change (100% in the laboratory and 50% taken away).

2.2.4 Measurements

2.2.4.1 Body tissue measurements

2.2.4.1.1 Auditory canal temperature

The primary core temperature index was taken as auditory canal temperature, which was monitored using an ear-moulded plug with a thermistor protruding 1 cm (Edale instruments Ltd., Cambridge, U.K.) and positioned within the external auditory meatus, and insulated with cotton wool. Data were recorded throughout each trial at 15-s intervals using a 16-channel portable data logger (Grant Instruments Ltd., 1206 Series Squirrel, U.K.), and later downloaded to a computer. This procedure isolates the auditory canal from thermal artefacts, permitting auditory canal temperature to faithfully and rapidly track oesophageal temperature under these conditions (Cotter et al., 1995).

In a pilot trial, four core temperature indices (auditory canal, rectal, oesophageal and gastrointestinal tract) were studied during cold water immersion, followed by 45°C cycle ergometry. Performing this study showed that each of the core temperature measurements
track each other and as such any are an acceptable to be used as an core temperature measurement. These data are shown in Figure 2.1, and show the capacity of rectal and auditory canal temperatures to faithfully track oesophageal temperature.

2.2.4.1.2 Skin temperatures

Skin temperatures were measured from four sites (chest, arm, thigh, leg: Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.), with data recorded throughout each trial at 15-s intervals using a 16-channel portable data logger (Grant Instruments Ltd., 1206 Series Squirrel, U.K.), and later downloaded to a computer. Thermistors were be attached to the skin with a single layer of waterproof tape.

2.2.4.1.3 Mean skin and mean body temperatures

Mean skin temperature was derived using a weighted summation of the four skin temperatures after Ramanathan (1964):

\[
T_{\text{skin}} = 0.3 (T_{\text{chest}} + T_{\text{arm}}) + 0.2 (T_{\text{thigh}} + T_{\text{leg}}) \quad \text{Equation 2}
\]

Mean body temperature was then obtained from the thermal-state specific weighted sum of the auditory canal and mean skin temperatures (Sugenoya and Ogawa, 1985; Vallerand et al., 1992):

\[
T_{\text{body}} = (0.9 * T_{\text{core}}) + (0.1 * T_{\text{skin}}) \quad \text{Equation 3}
\]
Figure 2.1 Unpublished laboratory pilot data of four subjects displaying four different core temperature measurements during 45°C cycling following cold water immersion (N = 4).
2.2.4.1.4 Test of thermodynamics: inanimate objects

A test of thermodynamics was conducted to explain some of the thermal responses that were found in the results. By showing that subjects were behaving similarly to inanimate objects. In order to do this two different sized steel spheres were examined and exposed to the same conditions at the subjects, although these trials were performed in water to increase the speed of these responses. As was the case with subjects of this experiment, the spheres were two different mass to surface area ratios. This was done as surface area to mass ratio will influence the rate of heat transfer. The physical characteristics of the spheres are summarised in Table 2.2.

The two spheres similarly to the human subjects underwent six separate trials with two pre-heating temperatures (37.5°C, 38.5°C), these temperatures were achieved by hot-water immersion. The spheres were then exposed to three different water baths (40°C, 45°C and 50°C) until equilibrium was reached, to simulate the environmental conditions used in the human trials of the experiment.

2.2.4.1.5 Thermistor calibration

Thermistors were calibrated against a certified reference thermometer in a stirred water bath across a range of static and physiologically relevant temperatures (Dobros total immersion, Dobbie Instruments, Sydney, Australia). Linear calibration equations were derived for each thermistor using a recorded thermistor data and known temperatures from the certified thermometer ® > 0.99). Raw thermistor data were corrected using these calibration coefficients.
Table 2.2 Characteristics of steel spheres

<table>
<thead>
<tr>
<th>Size</th>
<th>Small sphere</th>
<th>Large sphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>2.98</td>
<td>6.98</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>0.086</td>
<td>0.121</td>
</tr>
<tr>
<td>Radius (m)</td>
<td>0.043</td>
<td>0.061</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>0.27</td>
<td>0.38</td>
</tr>
<tr>
<td>Surface area (m²)</td>
<td>2.32</td>
<td>4.68</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>3.33</td>
<td>9.51</td>
</tr>
<tr>
<td>Surface area to mass (m².kg)</td>
<td>0.78</td>
<td>0.67</td>
</tr>
</tbody>
</table>
2.2.4.2 Heart rate

Heart rate was obtained for ventricular depolarisation, using a heart rate monitor (Model S610i and S810i, Polar Electro Sport Tester, Kempele, Finland), and later downloaded to a computer. Data were sampled at 15-s intervals.

2.2.4.3 Hydration state and whole-body sweat rate

2.2.4.3.1 Hydration state

Prior to commencing each trial, urine specific gravity was measured for each subject (Clinical Refractometer, Model 140, Shibuya Optical, Tokyo, Japan). This is necessary since it was important to start these trials with subjects in a normally hydrated state. Urine specific gravity was measured again at the conclusion of each heat exposure.

2.2.4.3.2 Sweat rate

Gross mass changes (before and after each trial: ±20 g) were used to determine whole-body sweating (fw-150k, A&D scale, CA, U.S.A.) over the course of each trial. Data were collected prior to entering the chamber, and then at 15-min intervals during each heat exposure.

2.2.4.4 Psychophysical measures

Subjective reports of thermal sensation and thermal discomfort were recorded during a resting thermoneutral (baseline) state, just prior to commencing each heat exposure, and at 15-min intervals throughout each heat exposure. Familiarisation with each of the rating
scales preceded the first trial in a session conducted one week prior to testing, with subjects receiving standardised written instructions, with responses being prompted using the same question within each index.

2.2.4.4.1 Thermal sensation

Thermal sensation was monitored using a modified version of the Gagge scale (Gagge et al., 1967), where the end points were extended to enable a better resolution of thermal sensation. Subjects were asked: “How does the temperature of your body feel?”:

13-point thermal sensation scale
1  Unbearably cold
2  Extremely cold
3  Very cold
4  Cold
5  Cool
6  Slightly cool
7  Neutral
8  Slightly warm
9  Warm
10  Hot
11  Very hot
12  Extremely hot
13  Unbearably hot

2.2.4.4.2 Thermal discomfort

Thermal discomfort was evaluated using another scale (Gagge et al., 1967), and in response to the question: “How comfortable do you feel with the temperature of your body?”
The 5-point thermal discomfort scale
1.0 Comfortable
1.5
2.0 Slightly uncomfortable
2.5
3.0 Uncomfortable
3.5
4.0 Very uncomfortable
4.5
5.0 Extremely uncomfortable

2.2.5 Experimental design and statistical analyses

This project was based upon a repeated-measures experimental design, with subjects acting as their own controls and participating in every trial. Data were first analysed to provide standard descriptive parameters (means, standard errors), with subsequent comparisons performed using paired t-tests. Analysis was also performed using a one-way analyses of variance, Tukeys HSD post hoc procedure used to isolate sources of significant difference. Alpha was set at the 0.05 level for all statistical comparisons.

2.3 RESULTS

2.3.1 Pre-experimental physiological status

2.3.1.1 Thermoneutral physiological baselines

It was essential to first establish that subjects presented themselves in a similar physiological state across all six trials. In Table 2.3 the resting, thermoneutral baselines are presented, and these verify that standardisation procedures enabled consistency across all trials. Moreover,
these baselines are consistent with that which would be expected in healthy, euhydrated and well-rested adults.

2.3.1.2 Pre-exposed thermal status of subjects

Occupants of a bushfire shelter due to the environmental and physical circumstances would most likely be hyperthermic, from having just completed vigorous exercise in a most uncomfortable circumstances. As such, mild and moderate hyperthermia were induced to replicate this using pre-exposure, whole-body hot-water immersions. These pre-treatments were aimed at achieving core temperatures of 37.5°C and 38.5°C. From Table 2.4, a summary of data during the first 15 sec of the experimental exposure, it is evident that the target thermal states were achieved.

It is important to note that the data presented in Table 2.4 are resting values, albeit obtained following an alternating exercising and immersion protocol. However, it is evident that within the first 15 s subjects displayed a significant cardiovascular and thermal strain in all three exposures (Table 2.3). The higher heart rates show evidence of a heat-induced elevation in cutaneous (skin) blow flow that is prevalent during heat exposure in which there is a progressively rising core temperature (Rowell et al., 1970).
Table 2.3: Thermoneutral (baseline) data collected at rest prior to commencing pre-heating and dehydration treatments. Data are means with standard deviations in parenthesis (N=16)

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>USG (N=16)</th>
<th>HR (N=16)</th>
<th>Core temperature (N=16)</th>
<th>Thermal sensation (N=16)</th>
<th>Thermal discomfort (N=16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>1.014 (0.006)</td>
<td>73 (14)</td>
<td>36.5 (0.3)</td>
<td>7.0 (0.0)</td>
<td>1.1 (0.4)</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>1.013 (0.008)</td>
<td>74 (12)</td>
<td>36.7 (0.3)</td>
<td>7.2 (0.4)</td>
<td>1.1 (0.3)</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>1.012 (0.006)</td>
<td>75 (9)</td>
<td>36.7 (0.3)</td>
<td>7.0 (0.6)</td>
<td>1.0 (0.1)</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>1.015 (0.005)</td>
<td>70 (11)</td>
<td>36.5 (0.5)</td>
<td>7.0 (0.4)</td>
<td>1.0 (0.1)</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>1.011 (0.006)</td>
<td>74 (12)</td>
<td>36.5 (0.3)</td>
<td>6.9 (0.3)</td>
<td>1.1 (0.2)</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>1.015 (0.006)</td>
<td>70 (14)</td>
<td>36.6 (0.3)</td>
<td>7.1 (0.4)</td>
<td>1.1 (0.3)</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C); USG = urine specific gravity; HR = heart rate.
Table 2.4: Pre-heated data 15s after entering the climate controlled chamber. Data are means with standard deviations in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal condition</th>
<th>Heart rate (bpm)</th>
<th>Core temperature (°C)</th>
<th>Thermal sensation scale (1-13)</th>
<th>Thermal discomfort scale (1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>116 (17)</td>
<td>37.5 (0.1)</td>
<td>8.8 (0.8)</td>
<td>1.8 (0.5)</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>135 (22)</td>
<td>38.6 (0.1)</td>
<td>9.4 (0.7)</td>
<td>2.5 (0.5)</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>128 (22)</td>
<td>37.5 (0.1)</td>
<td>9.3 (0.8)</td>
<td>2.3 (0.5)</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>138 (22)</td>
<td>38.6 (0.1)</td>
<td>9.8 (0.8)</td>
<td>2.7 (0.6)</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>122 (25)</td>
<td>37.6 (0.1)</td>
<td>9.5 (0.9)</td>
<td>2.3 (0.6)</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>144 (30)</td>
<td>38.7 (0.1)</td>
<td>9.8 (0.8)</td>
<td>2.9 (0.9)</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).
2.3.2 Experimental outcomes

2.3.2.1 Heart rate

Cardiovascular results will give an indication of overall physiological strain placed upon subjects, and will aid in the evaluation of the thermal performance standard for bushfire shelters. The observations are represented graphically in Figure 2.2, and summarised in Table 2.5.

The time series data (Figure 2.2) reveal four clear trends. The first thing to be noticed is that heart rate declined rapidly over the initial minutes of the exposure, moving towards a resting state after the combined hot-water immersion and exercise protocol. Secondly, within each trial, heart rate spikes are evident at 15-min intervals. These correspond with subjects standing for body-mass determinations.

Thirdly, it can also be noted that an obvious upward displacement of heart rate occurred across the three experimental conditions. This occurred even though each condition reflects 39° Modified Discomfort Index. This shows that the Modified Discomfort Index is a poor indicator of thermal strain, as least is reflected within heart rate. Fourthly, within shelter conditions one and three, the heart rates were greater for the moderate hyperthermia pre-treatment trials and the difference was statistically significant (P<0.05).

In each of shelter conditions two and three, the mean heart rates, as well as those recorded during the last 15 s of the heat exposures (Table 2.5), differed significantly between the two levels of pre-experimental hyperthermia (P<0.05), with these between-trial differences
being about 10 beats.min\(^{-1}\). That is, subjects experienced significantly greater cardiovascular strain within these two shelter conditions. It is assumed that these greater sustained heart rates reflected a protracted elevation in cutaneous blood flow under these conditions. In the absence of direct blood flow measures, this interpretation is somewhat speculative, although, it is well supported by the significantly raised mean skin temperatures for each of the moderate hyperthermia trials within each of the three shelter conditions (\(P<0.05\)). No significant difference was evident between the mean heart rate and the final 15 s of exposure in the two different levels of hyperthermia in condition one (\(P=0.13\)).

Maximal and minimal data presented in Table 2.5 serve to illustrate the diversity of these cardiovascular responses. The within-subjects heart rate range (maximal minus minimal) was between 39-55 beats.min\(^{-1}\), with greater ranges being observed when participants were rendered moderately hyperthermic prior each trial: condition one (\(P<0.05\)); condition two (\(P=0.07\)); condition three (\(P=0.05\)). Nevertheless, for this group of individuals, heart rates in excess of 170 beats.min\(^{-1}\) represented approximately 85% of the age-predicted maximal heart rate, and are typically associated with heavy exercise. The maximal values reported in Table 2.5 certainly indicate that some participants experienced heart rates beyond this level. Indeed, whilst this level of tachycardia was not observed under shelter condition one, three subjects exceeded this threshold in shelter condition two (one in the mild hyperthermia trial and two in the moderate trial), with six returning high heart rates in condition three (one in the mild hyperthermia trial and five in the moderate trial).
Figure 2.2: Heart rates during three resting (seated) heat exposures (shelter conditions), with subjects pre-heated to both mild (37.5°C) and moderate (38.5°C) hyperthermia in each condition. Data are mean curves with standard errors of the means at 2.5-min intervals (N=16).
Table 2.5: Experimental heart rates (beats.min⁻¹): descriptive statistical summaries. Data are means with standard error of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Final 15-s Mean</th>
<th>Minimal</th>
<th>Maximal</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>101 (4.48)</td>
<td>98 (3.90)</td>
<td>64</td>
<td>151</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>96 (2.79)</td>
<td>103 (3.14)</td>
<td>63</td>
<td>158</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>108 (3.63)</td>
<td>106 (3.83)</td>
<td>64</td>
<td>186</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>115 (4.67)</td>
<td>116 (4.29)</td>
<td>72</td>
<td>175</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>111 (3.47)</td>
<td>111 (3.77)</td>
<td>67</td>
<td>185</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>119 (5.09)</td>
<td>122 (5.08)</td>
<td>68</td>
<td>180</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).
2.3.2.2 Core temperature

Figure 2.3 shows the average core temperatures across all six trials. It is immediately apparent that the three shelter conditions were tolerated without either core temperature exceeding 42°C or a 2°C elevation in core temperature. It therefore is apparent that, when air temperature and humidity are fixed and regulated to maintain 39° Modified Discomfort Index, and when people are unclothed, the above core temperature elevations are unlikely to occur in young, healthy subjects. These outcomes, at first glance, support the thermal specification proposed by the Australian Building Codes Board (2010) for private bushfire shelters.

 Inspection of Figure 2.3 gives evidence of four trends within these data. Firstly, as with heart rate responses, core temperature declined over the initial minutes of each exposure. Secondly, within each shelter condition, core temperatures seemed to converge upon a common value. It could be said that a thermal equilibrium between the subject and environment was reached. For condition one, convergence occurred around 50-60 min of exposure, whilst extrapolation of core temperature results for conditions two and three reveal that this convergence of core temperatures progressively later: 90 and 110 min (respectively). Thirdly, as with heart rate, there was an upwards displacement of these curves with increments in air temperature, but across equivalent Modified Discomfort Index temperatures. Fourthly, core temperatures were higher for the moderate hyperthermia trials within each shelter condition.
For shelter condition one (Figure 2.3: 40°C), the two core temperature curves decayed to approximately the same level: 37.1°C ($P > 0.05$). In condition two, but not condition three, the final core temperatures were again not significantly different ($P > 0.05$). This tells us that subjects were now regulating their body temperature at a higher level, resulting in significantly higher core temperatures relative to the thermoneutral state ($P < 0.05$). These characteristics are common for an inanimate object. However, it is often overlooked in humans, who can regulate body temperature via skin blood flow. For each of the other shelter conditions, the moderate hyperthermia trials displayed similar cooling trends.

Core temperature observations are summarised within Table 2.7, along with other descriptive parameters. No individual from the current experimental series experienced a core temperature $>39.5$°C, let alone the a rise to the critical threshold of 42°C.

Inspection of the mean core temperature curves (Figure 2.3), gives the impression that all subjects experienced cooling during the exposure. However, data averages can often be misleading and mask variations within individuals. So the possibility that not all individuals followed these trends needed to be explored. Figures 2.4 and 2.5 illustrate time series data with individual core traces allowing within- and between-subject analyses.

The individual traces of Figures 2.4 (males) and 2.5 (females) need to viewed from two perspectives. We will first consider moderate hyperthermia: the right sides of these Figures. It is evident that every subject cooled to some degree during each exposure. The power of evaporation facilitated this loss even though the air temperature exceeded that of core
temperature by 11.5°C in condition three. Evaporative cooling can account for the cooling of core temperature which occurred, as the power of evaporation has been known for many years (Bladgen, 1775a 1775b). The changes in mean body temperature which were seen for these trials averaged -1.2°C (condition one), -0.8°C (condition two) and -0.3°C (condition three). These almost linear changes are inversely related to the linear increments in air temperature (5°C), but are one order of magnitude smaller.

From the data collected, we are able to extrapolate the core temperatures to a point where no net heat exchange occurs, and in doing so predict the air temperature which would cause an increase in body temperature in most people. Using this prediction we are able to determine that the air temperature at which most individuals would start to experience an increase in body temperature is 53°C (Figure 2.6: lower panel). When subjects were mildly hyperthermic (Figure 2.6: upper panel), the corresponding predictions using core temperature (Figure2. 7) yielded inferior predictive capabilities.

Observations of the core temperature patterns of subjects when mildly hyperthermic is also important: the left panels of Figures 2.4 (males) and 2.5 (females). When exposed to shelter condition one, all male subjects showed a typical decrease in core temperature until reaching a steady state (Figure 2.4: top left panel). A similar trend occurred in females (Figure 2.5: top left panel), however six out of eight subjects experienced an elevation beyond the zenith, this typically occurred within the first 10-20 min of the exposure. Regardless, core temperatures did not exceed the entry value (37.5°C).
The male core temperature responses remained below the temperature at which occupants initially entered the shelter in condition two (Figure 2.4: middle left panel). That being said, three individuals did experience a slight rise in core temperature after the initial decline. From the examination of the female data (Figure 2.5: middle left panel), it can be noted all participants experienced an increase in core temperature after the initial decline, with two subjects terminating above the entry value (37.5°C). Whilst the thermal strain was elevated from condition one, it was still well tolerated.

Finally, the third shelter condition must be examined (bottom left panels of Figures 2.4 and 2.5). In the male subjects, a steady state occurred at 10 min, after the initial decline. Observation of the female data shows an elevation past the entry value in all subjects bar one. The exception to this is an individual whose data is almost a mirror image of the other traces. These data cannot be accounted for on the basis of technical errors or equipment failure. This is deemed to be an one-off phenomenon, based on her responses to the other heat exposures being perfectly normal. Also, her average heart rate data during the first five min of exposure was 33 beats.min⁻¹ above the group mean. This is consistent with dysthermia. However, this individual only provided two of the six maximum heart rates presented in Table 2.5. Accordingly, there was not reason to exclude these data.

A convergence of core temperatures was noted in this study, this is a typical physical response occurrence in inanimate objects but is being observed in a physiological setting during this experiment. To evaluate the thermodynamics of an inanimate object for comparison the data found in this experiment, two steel spheres were heated and then
exposed to the same temperature as each shelter conditions. The larger of these spheres could be used to represent the current male subjects. Examination of these results reveals two trends (Figure 2.8).

Firstly, thermal convergence of both of the spheres can be noted, that is they both converge to the same equilibrium temperature at the same time, regardless of the initial starting temperature for both sized spheres. This pattern was seen within both the male and female subjects of this experiment and would suggest that the subjects are behaving like inanimate objects.

The second trend that can be noted is that the smaller of the two spheres heated up at a faster rate than the larger one. This is because it has a larger surface area to mass ratio, and this was seen in the data for the females, who also had a larger surface area to mass ratio (Table 2.1), and were found to be heating at a faster rate than the males. The surface of an object is the site for heat transfers therefore a larger surface area to mass ratio will facilitate a faster rate of heat exchange.

Unlike with the human trials where subjects core temperature decreased throughout the exposure, the spheres increased until their temperature reached the same temperature as the water bath. The ability of humans to regulate temperature through blood vessel diameter changes and sweating accounts for these differences.
Figure 2.3: Core temperature responses during resting (seated) heat exposures (shelter conditions one-three), with subjects pre-heated to both mild (37.5°C) and moderate (38.5°C) hyperthermia in each condition. Data are mean curves with standard errors of the means at 2.5-min intervals (N = 16).
Table 2.6: Experimental core temperatures (°C): descriptive statistical summaries. Data are means with standard error of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Final 15s</th>
<th>Mean</th>
<th>Minimal</th>
<th>Maximal</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>37.1 (0.06)</td>
<td>37.1 (0.04)</td>
<td>36.5</td>
<td>37.7</td>
<td>0.1</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>37.2 (0.04)</td>
<td>37.4 (0.04)</td>
<td>36.8</td>
<td>38.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>37.4 (0.06)</td>
<td>37.2 (0.05)</td>
<td>36.9</td>
<td>37.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>37.5 (0.08)</td>
<td>37.7 (0.06)</td>
<td>36.8</td>
<td>39.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>37.6 (0.06)</td>
<td>37.4 (0.05)</td>
<td>37.0</td>
<td>38.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>37.8 (0.08)</td>
<td>37.9 (0.06)</td>
<td>37.2</td>
<td>38.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).
Figure 2.4: Individual core temperature response curves for male subjects (N=8) during resting (seated) heat exposures (shelter conditions one-three), with subjects pre-heated to both mild (37.5°C: left) and moderate (38.5°C: right) within each condition. Data were collected at 15-s intervals.
Figure 2.5: Individual core temperature response curves for female subjects (N=8) during resting (seated) heat exposures (shelter conditions one-three), with subjects pre-heated to both mild (37.5°C: left) and moderate (38.5°C: right) within each condition. Data were collected at 15-s intervals
Figure 2.6: Predicting mean body temperature changes with increments in air temperature. Symbols represent individual data (N = 16) collected at each of three air temperatures when subjects were mildly (upper panel) and moderately hyperthermic (lower panel).
Figure 2.7: Predicting core temperature changes with increments in air temperature.

Symbols represent individual data (N=16) collected at each of three air temperatures when subjects were mildly (upper panel) and moderately hyperthermic (lower panel)
Figure 2.8 Comparison of core temperatures of two spheres of different sizes, large (left-hand panel) and small (right-hand panel) during hot-water immersion (upper: 40°C, middle: 45°C and lower: 50°C). The vertical line indicates the point of thermal convergence of the spheres.
2.3.2.3 Skin temperatures

Following the trend of the heart rate and core temperature data, skin temperatures were displaced vertically with increments in air temperature (Figure 2.9). That is, they seemed to be more powerfully influenced by air temperature than the Modified Discomfort Index temperature.

While the Modified Discomfort Index remained the same across all three conditions the water vapour pressure was different (Table 2.7). With mean skin temperatures varying by about 1.0°C across conditions, and 0.6°C within conditions, the cutaneous water vapour pressure was less variable (Table 2.7). As such, the water vapour pressure gradient from skin to air temperature, which dictates evaporation, differed more than seven-fold (Table 2.7). Thus, the hottest condition also permitted the greatest sweat evaporation.

The combined influences of skin and water vapour pressure resulted in the mean skin temperatures from both trials within each shelter condition converging to a common, steady-state values (P > 0.05). This was achieved during the first 30 min of exposure to the stimulus. The positive core-skin temperature gradient was maintained within every trial (Figure 2.10), that is skin did not exceed core temperature. This is integral for the blood-borne delivery of heat to the skin for its ultimate dissipation. Within each shelter condition, these gradients overlapped, except during the first 5-10 min, where heat loss from the core was transiently impaired when subjects had been heated in the hotter of the two thermal states. This would account, at least in part, for the very rapid fall in core temperature for each of the mildly hyperthermic trials (Figure 2.3).
Table 2.7: Mean skin temperatures (°C) and water vapour pressures (kPa). Data are means with standard error of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Skin temperature</th>
<th>Skin vapour pressure</th>
<th>Air vapour pressure</th>
<th>Vapour pressure gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>34.6 (0.13)</td>
<td>5.5</td>
<td>5.16</td>
<td>0.34</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>35.0 (0.09)</td>
<td>5.62</td>
<td>5.16</td>
<td>0.46</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>35.7 (0.12)</td>
<td>5.85</td>
<td>4.79</td>
<td>1.06</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>36.0 (0.14)</td>
<td>5.94</td>
<td>4.79</td>
<td>1.15</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>36.4 (0.12)</td>
<td>6.07</td>
<td>3.70</td>
<td>2.37</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>36.8 (0.13)</td>
<td>6.21</td>
<td>3.70</td>
<td>2.51</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).
Figure 2.9: Mean skin temperature curves during resting (seated) heat exposures (shelter conditions one-three), with subjects pre-heated to mild (37.5°C) and moderate (38.5°C) hyperthermia in each condition. Data are mean curves with standard errors of the means at 2.5-min intervals (N = 16).
Figure 2.10: Core-skin temperature gradients during resting (seated) heat exposures (shelter conditions one-three), with subjects pre-heated to mild (37.5°C) and moderate (38.5°C) hyperthermia in each condition (N = 16).
2.3.2.4 Whole-body sweat rate

When air temperature exceeds skin temperature, the only mechanism for heat loss is through the evaporation of secreted sweat from the surface of the skin. Within the hottest of these trials (shelter condition three), evaporative cooling permitted all subjects to lose heat from the body core even those who produced less sweat, such as the females. Indeed, greater pre-heating enhanced heat loss, albeit at a greater absolute temperature. Across all trials, the sweat rate averaged 0.55 L.h\(^{-1}\) (Table 2.8), with males secreting slightly higher rates (0.61 versus 0.48 L.h\(^{-1}\)), although this difference was not considered to be statistically significant (P = 0.9). Regardless, these values are relatively high resting sweat rates, but they are neither excessive nor poorly tolerated.

2.3.2.5 Psychophysical indices

The psychophysical indices are summarised in Table 2.9. These followed unremarkable and entirely predictable response patterns. In each exposure, these subjective evaluations were elevated from the start, no doubt due to the thermal pre-treatments, and they remained stable thereafter across all trials.

However, it was found that both thermal sensation and discomfort were higher with each increment in air temperature even for the same Modified Discomfort Index value. This finding is consistent with the data from other variables, indicating that strain upwardly displacement with air temperature increases.
Table 2.8: Whole-body sweat rates (g.min\(^{-1}\): N=16). Data are means with standard error of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Mean</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>5.84 (0.72)</td>
<td>6.76 (1.30)</td>
<td>5.04 (0.34)</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>6.57 (0.46)</td>
<td>6.50 (0.27)</td>
<td>6.65 (0.38)</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>8.02 (1.17)</td>
<td>7.46 (0.28)</td>
<td>8.58 (2.24)</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>11.03 (1.02)</td>
<td>12.69 (1.25)</td>
<td>9.38 (0.58)</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>11.52 (1.42)</td>
<td>13.25 (1.45)</td>
<td>9.79 (2.00)</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>11.85 (1.34)</td>
<td>14.71 (1.58)</td>
<td>9.00 (1.00)</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).

Table 2.9: Thermal sensation (scale: 1-3) and discomfort votes (scale: 1-5).

Data are means with standard errors of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Sensation</th>
<th>Discomfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>8.6 (0.2)</td>
<td>1.6 (0.4)</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>8.9 (0.6)</td>
<td>2.0 (0.4)</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>9.0 (0.7)</td>
<td>2.1 (0.5)</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>9.4 (0.7)</td>
<td>2.5 (0.6)</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>9.8 (0.8)</td>
<td>2.4 (0.5)</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>9.5 (0.7)</td>
<td>2.6 (0.6)</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).
2.3.3 Gender differences

2.3.3.1 Heart rate

Cardiovascular strain is a good indication of physiological demand placed upon a system. Viewing data from a gender perspective gives insight into the separate influence of the Modified Discomfort Index standard on males and females. Figure 2.11 shows at the relationship between heart rate and gender. Across both genders, heart rate initially declined until reaching a steady state, and it is also noted that across all exposures, the females had, on average, higher heart rates. This was statistically significant (P > 0.05) in all exposures except condition one, when moderately hyperthermic. This gap between the genders becomes more pronounced as the air temperature increased. This would indicate that females are experiencing a greater cardiovascular strain during the heat exposure.

Observation of Table 2.10 indicates a between-gender significant difference (P > 0.05) between the average heart rate of each shelter condition across both levels of hyperthermia occurred. Inspection of the final 15 s of exposure for each gender revealed a significant difference (P > 0.05) for shelter condition two and three when mildly and moderately hyperthermic, however, it was only significant in shelter condition one when mildly hyperthermic (P > 0.05), and not when pre-heated to a moderately hyperthermic state (P = 0.24).

When individual minimum and maximum data are considered, it can be noted that, for every trial the maximum was higher in female subjects. The minimum value also seems to be gender specific with every minimum value being supplied by a female, if the data involving
subjects adopting a supine state is ignored, which results in a lower heart rate (Stewart, 1918). The adoption of the supine state was required for those suffering from hypotension and impending syncope, this phenomenon was only observed in female subjects, who found these exposures to be more stressful.

2.3.3.2 Core temperature

Examination of Figure 2.12 shows some disparities between the two genders in regard to core temperature across all trials. It is immediately apparent that females were more affected by these exposures. This is shown by a slower decrease of core temperature in conditions two and three when moderately hyperthermic, and also in the mildly hyperthermic state females showed a greater increase in core temperature during the exposure, the result of both of these was that the females terminated these trials with a higher core temperature than males. Mild hyperthermia shows the greatest statistical significance at termination, with conditions one and three both showing a significant difference (P < 0.05). However, there appears to be no difference between the males and females during condition one when moderately hyperthermic (P = 0.303). Therefore, it can be deduced that, when exposed to 39° Modified Discomfort Index, females will both gain heat faster when mildly hyperthermic and lose heat at a slower rate when moderately hyperthermic when compared to males exposed to the same stimulus. Nevertheless, the present sample of female subjects was still able to tolerate these exposures without an increase in core temperature.
Figure 2.11: Heart rates during three resting (seated) heat exposures (shelter conditions), with male (blue) and female (pink) subjects pre-heated to both mild (right panel; 37.5°C) and moderate (left panel; 38.5°C) hyperthermia in each condition. Data are mean curves with standard errors of the means at 2.5-min intervals (N = 16).
Table 2.10: Experimental heart rates of males and females (beats/min): descriptive statistical summaries. Data are means with standard error of the means in parenthesis \((N=16)\).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Gender</th>
<th>Final 15s</th>
<th>Mean</th>
<th>Minimal</th>
<th>Maximal</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>M</td>
<td>89 (3.83)</td>
<td>86 (3.17)</td>
<td>64</td>
<td>138</td>
<td>6</td>
</tr>
<tr>
<td>One</td>
<td>Mild</td>
<td>F</td>
<td>114 (1.94)</td>
<td>110 (1.67)</td>
<td>87</td>
<td>151</td>
<td>3</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>M</td>
<td>95 (3.04)</td>
<td>100 (2.74)</td>
<td>80</td>
<td>152</td>
<td>5</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>F</td>
<td>97 (2.68)</td>
<td>106 (3.31)</td>
<td>63*</td>
<td>158</td>
<td>6</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>M</td>
<td>101 (4.01)</td>
<td>99 (3.69)</td>
<td>64</td>
<td>138</td>
<td>7</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>F</td>
<td>116 (2.22)</td>
<td>113 (2.86)</td>
<td>86</td>
<td>186</td>
<td>6</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>M</td>
<td>104 (3.08)</td>
<td>107 (3.54)</td>
<td>72</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>F</td>
<td>126 (4.40)</td>
<td>125 (3.72)</td>
<td>88</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>M</td>
<td>104 (1.78)</td>
<td>101 (2.37)</td>
<td>73</td>
<td>135</td>
<td>5</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>F</td>
<td>118 (3.96)</td>
<td>121 (2.64)</td>
<td>67*</td>
<td>185</td>
<td>5</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>M</td>
<td>105 (3.94)</td>
<td>108 (3.44)</td>
<td>68</td>
<td>169</td>
<td>7</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>F</td>
<td>132 (3.60)</td>
<td>136 (3.16)</td>
<td>78*</td>
<td>180</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).

*Subject experienced hypotension and had to enter a supine state.
Figure 2.12: Core temperature responses during three resting (seated) heat exposures (shelter conditions), with male (blue) and female (pink) subjects pre-heated to both mild (right panel; 37.5°C) and moderate (left panel; 38.5°C) hyperthermia in each condition. Data are mean curves with standard errors of the means at 2.5-min intervals (N = 16).
Table 2.11: Experimental core temperature responses of males and females (°C): descriptive statistical summaries. Data are means with standard error of the means in parenthesis (N = 16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>Thermal state</th>
<th>Gender</th>
<th>Final 15s Mean</th>
<th>Minimal</th>
<th>Maximal</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>Mild</td>
<td>M</td>
<td>37.0 (0.03)</td>
<td>37.0 (0.03)</td>
<td>36.5</td>
<td>37.6</td>
</tr>
<tr>
<td>One</td>
<td>Mild</td>
<td>F</td>
<td>37.3 (0.04)</td>
<td>37.2 (0.04)</td>
<td>36.8</td>
<td>37.6</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>M</td>
<td>37.2 (0.04)</td>
<td>37.4 (0.04)</td>
<td>36.8</td>
<td>38.8</td>
</tr>
<tr>
<td>One</td>
<td>Moderate</td>
<td>F</td>
<td>37.1 (0.05)</td>
<td>37.4 (0.05)</td>
<td>36.9</td>
<td>38.8</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>M</td>
<td>37.3 (0.05)</td>
<td>37.2 (0.04)</td>
<td>36.9</td>
<td>37.6</td>
</tr>
<tr>
<td>Two</td>
<td>Mild</td>
<td>F</td>
<td>37.4 (0.01)</td>
<td>37.2 (0.01)</td>
<td>36.9</td>
<td>37.9</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>M</td>
<td>37.4 (0.06)</td>
<td>37.6 (0.1)</td>
<td>37.1</td>
<td>38.7</td>
</tr>
<tr>
<td>Two</td>
<td>Moderate</td>
<td>F</td>
<td>37.6 (0.08)</td>
<td>37.7 (0.10)</td>
<td>36.8</td>
<td>38.8</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>M</td>
<td>37.5 (0.05)</td>
<td>37.4 (0.04)</td>
<td>37</td>
<td>37.9</td>
</tr>
<tr>
<td>Three</td>
<td>Mild</td>
<td>F</td>
<td>37.7 (0.05)</td>
<td>37.5 (0.05)</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>M</td>
<td>37.6 (0.08)</td>
<td>37.8 (0.10)</td>
<td>37.2</td>
<td>38.9</td>
</tr>
<tr>
<td>Three</td>
<td>Moderate</td>
<td>F</td>
<td>38.0 (0.05)</td>
<td>38.1 (0.04)</td>
<td>37.6</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).
Examination of Table 2.11 reveals that the core temperatures differed between the genders across three of the six exposures; those being shelter condition one when mildly hyperthermic, and shelter condition three for both thermal states. The mean and final 15 s of exposure were both statistically significant ($P > 0.05$).

Inspection of the maximal values does not reveal any significant outcomes as these values in almost every case refer to the temperatures of subjects when they entered the shelter at after the pre-treatment. The exception being in shelter condition three, when subjects were mildly hyperthermic, in this instance females report a higher value by 0.01°C. However, the minimal data shows that for every exposure except one (condition two when moderately hyperthermic), female subjects had a higher minimum core temperature. A slower rate of cooling throughout each exposure can be associated with such higher values.

2.3.4 Modified Discomfort Index as a standard

The ability of the same Modified Discomfort Index value to be achieved over a wide range of air temperature and humidity means that it is possible for different physiological responses to be observed for the same Modified Discomfort Index. Thus, we may anticipate that the Modified Discomfort Index is somewhat a poor indicator of physiological strain, although it was derived from an index that was never intended to be used for this purpose.

The current results support the claim that the Modified Discomfort Index and effective thermal indices which are similar in nature are poor indicators of physiological. These
results indicate that each of the following physiological variables were upwardly displaced with increments in air temperature:

- heart rate (Figure 2.2 and 2.11)
- core temperature (Figures 2.3, 2.4, 2.5 and 2.12)
- mean skin temperature (Figure 2.9)
- whole-body sweat rates (Table 2.7)
- thermal sensation (Table 2.9)
- thermal discomfort (Table 2.9).

The fact that the current participants tolerated a Modified Discomfort Index temperature of 39° without an excessive rise in core temperature or any significant physiological strain does not, in itself, validate this index as a possible predictor of physiological strain. For almost every physiological variable, strain differed significantly between shelter conditions one and three, clearly demonstrating that conditions possessing an equivalent Modified Discomfort Index do not necessarily elicit identical physiological outcomes.
Table 2.12 Experimental descriptive statistical summaries when mildly hyperthermic across three conditions using One-way Analysis of Variance. Data are means with standard error of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Condition one</th>
<th>Condition two</th>
<th>Condition three</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core temperature (°C)</td>
<td>37.1 (0.04)</td>
<td>37.2 (0.05)</td>
<td>37.4 (0.05)</td>
</tr>
<tr>
<td>Skin temperature (°C)</td>
<td>34.6 (0.13)</td>
<td>35.7 (0.11)</td>
<td>36.4 (0.12)</td>
</tr>
<tr>
<td>Body temperature (°C)</td>
<td>37.1 (0.05)</td>
<td>37.4 (0.06)</td>
<td>37.6 (0.05)</td>
</tr>
<tr>
<td>T\textsubscript{core}-T\textsubscript{skin}</td>
<td>2.5 (0.08)</td>
<td>1.6 (0.10)</td>
<td>1.1 (0.06)</td>
</tr>
<tr>
<td>Heart rate (beat.min\textsuperscript{-1})</td>
<td>98 (3.9)</td>
<td>106 (3.76)</td>
<td>111 (3.77)</td>
</tr>
<tr>
<td>Thermal sensation</td>
<td>8.6 (0.20)</td>
<td>9.0 (0.20)</td>
<td>9.6 (0.20)</td>
</tr>
<tr>
<td>Thermal discomfort</td>
<td>1.6 (0.10)</td>
<td>2.1 (0.10)</td>
<td>2.4 (0.20)</td>
</tr>
<tr>
<td>Sweat rate (L.hr\textsuperscript{-1})</td>
<td>0.33 (0.04)</td>
<td>0.48 (0.07)</td>
<td>0.69 (0.08)</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).

* Denotes a significant difference between condition 1 and condition 2.
† Denotes a significant difference between condition 2 and condition 3.
‡ Denotes a significant difference between condition 1 and condition 3.
Table 2.13 Experimental descriptive statistical summaries when moderately hyperthermic across three conditions using One-way Analysis of Variance. Data are means with standard error of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core temperature (°C)</td>
<td>37.4 (0.04)††</td>
<td>37.7 (0.06)†</td>
<td>37.9 (0.06)††</td>
</tr>
<tr>
<td>Skin temperature (°C)</td>
<td>35.0 (0.09)††</td>
<td>36.0 (0.14)†</td>
<td>36.8 (0.13)††</td>
</tr>
<tr>
<td>Body temperature (°C)</td>
<td>37.4 (0.10)‡‡</td>
<td>37.8 (0.06)</td>
<td>37.9 (0.09)‡‡</td>
</tr>
<tr>
<td>T_{core} - T_{skin}</td>
<td>2.4 (0.08)‡‡</td>
<td>1.7 (0.10)†</td>
<td>1.1 (0.09)‡‡</td>
</tr>
<tr>
<td>Heart rate (beats.min⁻¹)</td>
<td>103 (3.14)‡</td>
<td>116 (4.29)</td>
<td>122 (5.08)‡</td>
</tr>
<tr>
<td>Thermal sensation</td>
<td>8.9 (0.20)</td>
<td>9.4 (0.20)</td>
<td>9.5 (0.2)</td>
</tr>
<tr>
<td>Thermal discomfort</td>
<td>2.0 (0.10)‡</td>
<td>2.5 (0.20)</td>
<td>2.6 (0.2)‡</td>
</tr>
<tr>
<td>Sweat rate (L.hr⁻¹)</td>
<td>0.39 (0.01)‡</td>
<td>0.66 (0.05)</td>
<td>0.71 (0.07)‡</td>
</tr>
</tbody>
</table>

Notes: Condition one: 40°C and 70% relative humidity; Condition two: 45°C and 50% relative humidity; Condition three: 50°C and 30% relative humidity; Mild = mild hyperthermia (37.5°C); Moderate = moderate hyperthermia (38.5°C).

* Denotes a significant difference between condition 1 and condition 2.

† Denotes a significant difference between condition 2 and condition 3.

‡ Denotes a significant difference between condition 1 and condition 3.
Experimental measures have been summarised in Table 2.11 and 2.12, which show that there is unequal physiological demand for the three conditions, irrespective of a similar Modified Discomfort Index value. No statistical significance was to be found between heart rate values when subjects were mildly hyperthermic, and also no statistical difference was found for thermal sensation scale when participants were moderately hyperthermic. There was a statistical significance between all three shelter conditions in six variables including skin temperature, body temperature and core-skin gradient when mildly hyperthermic, and heart rate, skin temperature and core-skin temperature when moderately hyperthermic.

2.4 DISCUSSION

This experiment was aimed at evaluating the Modified Discomfort Index as an appropriate thermal standard for private bushfire shelters (Australian Building Codes Board, 2010). The Modified Discomfort Index as a standard can be achieved from a variety of temperature and humidity combinations (a range of 10°C and 40% relative humidity). Therefore it was necessary to test the standard under a range of conditions. The investigations principal consideration was the maintenance of core temperature below 39.5°C. The result of this experiment has shown that core temperature can be maintained within a healthy range across a variety temperature humidity combinations, all equalling 39° Modified Discomfort Index. Considering a bushfire shelter must be air-tight a second experiment must be conducted to determined these influences on physiological function during the occupancy of a bushfire shelter (Experiment Two).
2.4.1 Physiological responses

2.4.1.1 Cardiovascular responses

Previous authors have noted an increase in heart rate during hot environments when compared to cool environments (Rowell et al., 1970; Kamon and Belding, 1971; Neilsen et al., 1993). Even though a resting state was adopted during all exposures, heart rate increased, this increase is a response to maintain blood pressure. In order to dissipate heat from the internal tissues to the surrounding air, cutaneous blood flow must increase (Rowell et al., 1970), causing a decrease in mean arterial and central venous pressures which must be counteracted by an increased heart rate or elevated ventricular contractility.

2.4.1.2 Thermal responses

It has been known for some time that core temperature can be regulated when air temperature is greater than body temperature (Wenzel et al., 1978). During environments where the air temperature exceeds that of skin temperature, as it does in this study, the only avenue for heat loss is through the evaporation of sweat. The ability of sweat evaporation to cool the body has been observed for many years (Bladgen 1775a, 1775b). The application of a 39° Modified Discomfort Index has, from the results, elicited a decrease in core temperature.

The highest average termination temperature recorded was 37.8°C (SEM 0.08), this represents a loss of 0.7°C to the environment via sweating, and again provides evidence of the power of evaporation, even during the hottest shelter condition. This provides evidence that the standard can be tolerated, and it also facilitates heat loss.
Thermal convergence of the body core temperature was seen in this project. This is a well known physical concept that is also seen within a physiological setting. The thermal trajectory of an object is roughly exponential, and is determined by physical characteristics of the object such as shape, dimensions, density, thermal conductivity and the specific heat of the object. Participants of this study acted to some degree in a similar manner to the spheres by reaching equilibrium at about the same time, regardless of the starting temperature. They behaved as if governed by the physical, rather than the physiological exchange of heat (Booth et al., 2004). Newton’s Law of Cooling states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature. Therefore, pre-heating only changes the rate of heat exchange, and not the thermal energy content at the point of thermal equilibrium, or the time to attain the state.

The mass of an object will determine the amount of thermal energy an object can ultimately hold and generate, however, this does not influence the rate of heat transfer. The transfer of heat occurs through the surface of an object, meaning that a larger surface area facilitates a greater rate of thermal energy exchange. This is mathematically apparent when the heat transfer coefficient is examined. It calculates the heat transfer of an object by using heat flow, the temperature gradient and finally surface area. This is why both, the smaller sphere and females both show a faster rate of heat exchange than their counterparts whom have a smaller surface area to mass ratio.
2.4.2 Gender considerations

2.4.4.1 Cardiovascular responses

Previous authors have noted different cardiovascular responses between males and females when exposed to hot environment (Wyndam et al., 1953; Hertig et al., 1965; Buskirk et al., 1965; Shapiro et al., 1980). It has been suggested that women are, on average, less habitually active than men and therefore when working at similar loads have a greater cardiovascular strain (Weinman et al., 1967), but when matched for fitness this difference in cardiovascular strain disappears (Drinkwater et al., 1976; Kamon et al., 1978; Avellini et al., 1980). Therefore on average women typically would naturally have a higher heart rate than men, as regular exercise will increase vagal tone causing heart rate to decrease (Rowell and O’Leary, 1990).

However, these differences fail to account for the higher heart rate experienced by females at rest. Such a higher heart rate could reflect a compensation for a lower arterial oxygen concentration (Astrand et al., 1964) or possibly it could be associated with the lower blood volume that women have compared to men (12%: Astrand, 1952). The elevated heart rate experienced by women is more likely to be explained by the latter, since the heat stimulus induces vasodilation to dissipate heat from the internal tissues to the periphery, and this results in a greater peripheral shift of blood volume in women compared to men (Senay and Fortney, 1975). The results are found to agree with previous authors findings, in that, as humidity increases the gap between the two genders tends to decrease or disappear totally as is seen within the results of this experiment (Shapiro et al., 1980).
Experiences of heat-induced hypotension, possibly leading to syncope, was exclusively female dominated, a greater propensity to orthostatic hypotension as a result from a less efficient venous return mechanism can explain this trend. Heat exposure causes dilatation of the blood vessels as a convective cooling mechanism to maintain homeostasis. However, once orthostatic changes occur (sit to stand) blood pools in the lower extremities due to the vessels already being dilatated, and an inefficient venous return causes the resultant hypotension with syncope to occur in females.

2.4.4.2 Thermal responses

Comparative studies of the thermoregulation of men and women have yielded results indicating differences in their ability to regulate body temperature when exposed to a hot environment (Fox et al., 1969; Bittel and Henane, 1975; Davies, 1979). These differences are the result of both physical, physiological and hormonal differences that occur between the genders.

In general, females have a larger body surface area to mass ratio, and this can be both a hindrance and an asset to thermoregulation. It means that women can both dissipate heat more quickly in mildly hot environments (Robinson, 1942), but conversely women can also gain heat at a faster rate in conditions of extreme heat (Strydom et al., 1971). This pattern was nicely illustrated by the heating responses of the two spheres of different sizes (Figure 2.8).

Women have a less powerful sweating response than men (Wyndham et al., 1965; Weinam
et al., 1967) The current results show this pattern, with a lower production of sweat within the hottest condition (condition three), and a difference between the two genders of 5.71 g.min\(^{-1}\) noted. Considering, air temperature exceeded that of body temperature, evaporative cooling was the only avenue for heat loss. Therefore, the lower sweating response observed in women would limited the rate at which heat was lost.

Hormonal differences between the genders have been shown to influence the thermoregulatory process in women at different stages of the menstrual cycle (Kawahata, 1960; Bittel and Henane, 1975). These changes in thermoregulation are brought about by the actions of oestrogen and progesterone. Progesterone, which peaks during the luteal phase of menstruation, influences thermoregulation in women by increasing the thermoregulatory threshold, meaning that the differences between men and women in the sweating threshold is even more pronounced (Grucza et al., 1993; Stratchenfeld et al., 2000; Kaciuba-Uscilko and Gruzca, 2001). During the peak of ovulation, oestrogen levels are at their highest, which in contrast to progesterone, causes a lowering of the body core temperature and the threshold for which sweating and vasodilation occurs during heat exposure (Tankersley et al., 1992; Stephenson and Kolka, 1999). During this experiment the menstrual cycle was not controlled for, thus, natural variations in the female subjects temperature regulation would of existed, this was part of the design to get as close to realistic scenario as possible.

2.4.3 Modified Discomfort Index as a standard

The Modified Discomfort Index was recommended to be used as a standard for bushfire
shelters (Patterson, 2010). However, Ramanathan and Belding (1973) showed that effective thermal indices such as the Modified Discomfort Index, are poor predictors of physiological strain, with a poor ability to differentiate between dry and humid environments. Although it is correct to suggest that a greater physiological strain will be experienced in more stressful environments, effective thermal indices of the same value within different combinations of parameters can produce different levels of strain (Wyndham et al., 1953; Ramanathan and Belding, 1973; Budd, 2008). This was also developed in the current experiment across most physiological variables. In order to predict physiological responses to an environment with any validity, the integrated effects of all thermal parameters must be taken into account (Büttner, 1938). Many of the effective thermal indices only focus on meteorological influences and not the effector responses of the human body to these meteorological influences.

However, none of the effective indices has the capacity to precisely predict the impact of an environmental stress upon people, and none would represent an appropriate means through which to predict physiological strain. To achieve this, one must use what is known as a rational heat strain scale, and such scales are derived from components defined by the first Law of Thermodynamics (e.g. the heat balance equation for humans). Rational indices take into consideration the capacity of the body to both produce heat (metabolism) and to dissipate heat (dry and evaporative heat loss), and the best known rational method is the Heat Strain Index (Belding and Hatch, 1955).

Budd (2008) has most recently described limitations of another effective thermal index, the
wet-bulb globe-temperature (WBGT) index, relating to sweating and the evaporative power of the environment. For equivalent WBGT values, the evaporation of sweat may be restricted due to high water vapour pressure or restricted air movement at the skin surface, both of which will occur within any sealed microclimate, such as a bushfire shelter. This same evaporative and sweating limitations applies to the Modified Discomfort Index, and it can introduce large errors when attempting to identify untenable conditions for defining building standards, although this did not occur in the current project.

Wyndham et al., (1953) has also shown a non-linear relationship to an increase in the Hill’s Wet Katatherometer and the Effective Temperature Scale, both of which are effective thermal indices which use similar meteorological parameters as the Modified Discomfort Index. A non-linear response makes it difficult to predict physiological strain for particular environmental conditions. For example, one cannot say that body temperature will increase by 0.4°C for every increase in the respective index value.

The results of this study validate these findings with an unequal physiological responses being found across numerous measures between three conditions equating to the same Modified Discomfort Index. It was found that greater physiological strain was apparent as air temperature increased. The problem with using effective thermal indices to determine physiological strain is that they were never developed to be used in such a manner and to be used as such is a misuse of their intended purpose. The applications for the Effective Temperature Scale, as per the developer, are to be to determine comfort in various environmental conditions (Houghten and Yagloglou, 1923). This is the case with many other
effective thermal indices, however they are commonly used as they are based on readily measurable parameters (temperature, humidity and wind speed etc.) and can be calculated easily.

2.5 CONCLUSIONS

The aim of this study was to evaluate the standard of 39°C Modified Discomfort Index for it’s use in bushfire shelter. The success of this was to be determined by the ability of occupants to maintain core temperature below 42°C or prevent a rise of 2°C in hour of exposure. From a thermal perspective, the results support the use of the Modified Discomfort Index of 39°C as a maximal mean temperature for bushfire shelters. However, further information must be obtained on the respiratory influences and the impact that an airtight structure will have upon the regulation of body temperature when exposed to the thermal standard. This will be explored in the next Chapter.
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3.1 INTRODUCTION

3.1.1 Background information

The Australian Building Codes Board was advised that if shelters could restrict thermal stress to a maximal mean Modified Discomfort Index (MDI) of 39° this would prevent a rise in core temperature of <2°C (Ludovici et al., 2010), and would therefore support life during the critical, 60-min occupancy phase. However, the need of this shelter to be air-tight would ultimately alter the internal conditions of the shelter. The standard for a bushfire shelter must be able to protect occupants from both the indirect and direct actions of bushfires. This standard includes providing an environment which is free from the noxious gases, such as smoke, that are associated with a bushfire. As such, the shelter must be constructed air-tight. Concentrations of gases become paramount in any air-tight structure where occupancy is needed. The presence of an occupant will alter gas concentrations through respiration, that is, carbon dioxide concentration will rise whilst oxygen concentration will fall. Not only will gas concentrations change during the exposure but also indeed, the humidity and air temperature will alter throughout the 60-min occupancy.

The first series of experiments supported the use of 39° Modified Discomfort Index as the thermal standard for bushfire shelters. However, this series was undertaken in conditions which were stable with respect to all initial characteristics of the internal environment of a
shelter. This state does not accurately reflect the changes in micro-climate that will occur inside the air-tight shelter. This Chapter will delve in to the impact of these influences on the maintenance of core temperature.

3.1.2 Gas concentration changes

A bushfire shelter needs to be able to protect the occupants not only from the thermal influences of a fire, but also its associated toxic gas production. Therefore, respiratory exchange process must be analysed for those using a bushfire shelter. Respiration will cause changes in the gas concentrations inside the shelter, with oxygen being consumed and carbon dioxide expelled. Over a 60-min exposure, the fractional oxygen must not decrease, and the carbon dioxide increase to intolerable levels.

Prior to commencing trials, a theoretical safety confirmation of the suggested volume of an air-tight shelter was conducted. To calculate the oxygen consumption, an exaggerated resting oxygen consumption of 1 L.min\(^{-1}\) was assumed (i.e. about four times greater than normal). Within 60 min such a resting individual would consume 60 L of oxygen. Considering room oxygen is approximately 21%, the final oxygen content remaining should remain greater than 15% in a room that conformed to the ABCB standard (2010:1.2 m\(^3\)). To determined the corresponding carbon dioxide production, a respiratory exchange ratio of 0.83 was assumed (valid for resting individuals), and the corresponding carbon dioxide production will be 0.83 L.min\(^{-1}\) (also four times greater than normal). The carbon dioxide concentration of this exhaled air will be 4-5% (room air is typically 0.03%). Thus, this person would produce 50 L of carbon dioxide, and so the final carbon dioxide concentration
of the room would be expected to increase to about 4.8%. The decrease in oxygen would induce mild hypoxia and increases in carbon dioxide will cause mild hypercapnia, both of which have been shown to influence thermoregulation (Wright and Boulant, 2007).

Hypercapnia, which is the build of carbon dioxide in the blood, has been shown to increase sweating (Stokes et al., 1948; Bullard, 1964; Wood, 1991). In a sealed environment this will cause changes to the micro-climate by raising the water vapour content of the air, impairing evaporative cooling and raising the thermal strain placed on the occupants.

Not only will hypercapnia influence the occupants ability to regulate temperature, but the falling oxygen content inside the simulator, leading to hypoxia, will also alter thermoregulation (Wood, 1991). The exact method which these changes occur is debatable, and dependent upon the method which hypoxia occurs. For instances Kacin et al. (2007) have shown that a normobaric, hypoxic stimulus (13.5% oxygen) during exercise will elevate sweat secretion, although during hypobaric hypoxia, a decrease in the secretion of sweat has been noted (Kolka et al., 1987). Both scenarios will alter the regulation of body temperature, and must be considered.

3.1.3 Changing thermal profile

The presence of an occupant will influence the thermal profile of a bushfire shelter by changing the micro-climate. Moisture is constantly lost, through the skin as well as respiratory surfaces (Benedict and Benedict, 1927). Before a sweating response even occurs some water is lost to the environment and water vapour pressure increases. As mentioned
above, hypercapnia will increase the rate of sweating which will, in turn, cause even greater increases in the humidity.

Occupants of a bushfire shelter will continue to produce heat via metabolism. Considering 80% of energy is lost to the environment as heat, it can be assumed that this alone will cause changes in the initial environment of the shelter. As a consequence, the air temperature rise.

A bushfire shelter must provide an environment which can support life. Not only does this mean protecting from the thermal stress associated with a bushfire but also providing an environment in which basic human processes such as respiration can occur unhindered. As such, through processes such as respiration and sweating it can be expected that the microclimate inside the shelter will alter, causing greater thermal strain than a stable $39^\circ$ Modified Discomfort Index would provide.

### 3.1.4 Aims of this study

Occupants enclosed within an air-tight and insulated shelter will have several stresses that will simultaneously influence physiological function and heat tolerance. These include changes in air temperature, relative humidity, and the fractional concentrations of both carbon dioxide and oxygen. In this, the second experiment from this series, an answer to the following question was sought (Patterson, 2010):

“In an enclosed, air-tight room, what is the rate of increase in relative humidity [water vapour pressure] and ambient [air] temperature due to human
The changes in air temperature a relative humidity found during this experiment will provide a thermal profile for a potential worst-case bushfire shelter. This thermal profile will be used in Experiment Three to determine the influence of dehydration on the occupants of a bushfire shelter, as dehydration is associated with a faster rise in core temperature (Montain and Coyle, 1992).

To answer this research question, 16 human exposures within an air-tight and insulated shelter simulator were undertaken. This simulator was constructed to conform with the Australian Building Codes Board (2010) performance standard for bushfire shelters with respect to its internal volume per occupant (Figure 1: 1.2 m\(^3\)). It was made from insulated sandwich panels constructed with an external skin of steel, laminated to a core of expanded polystyrene insulation (75-mm wall thickness; thermal resistance 1.92 m\(^2\).K.W\(^{-1}\)). The simulator was then housed within an existing climate-controlled chamber (Figure 1) and, as such, its internal air volume could be thermally isolated from that of the outer chamber. However, to ensure the necessary response characteristics (sensitivity), the simulator was designed to hold only one individual (1.2 m\(^3\)). For each of these trials, the outer chamber was regulated to remain stable at an air temperature of 45\(^\circ\)C and a relative humidity of 50% (Modified Discomfort Index standard of 39\(^\circ\)). However, once each subject entered this simulator, an air-tight door was closed, and whilst the conditions of the outer, climate-controlled chamber remained stable, those of the sealed simulator changed due to the presence of the experimental subject. In addition, all subjects completed this trial in a pre-
heated state (core temperature 38.0°C), but hydration was sustained at its basal level, both before, and after entering the simulator. This ensured that the hydration state of each individual remained normal, and that sweating would not be impaired by progressive dehydration over the 60-min exposure. These states were designed to approximate worst-case conditions with respect to changes in the internal (physical) state of the simulator, and so provide a more rigorous evaluation of how fast the internal conditions of this chamber would change. In each trial, the resultant physiological strain was quantified, with the primary physiological variable being the body core temperature.

Figure 3.1: The air-tight and insulated simulator constructed to conform with the Australian Building Codes Board (2010) performance standard for bushfire shelters with respect to its internal volume per occupant (1.2 m³).
3.2 METHODS

3.2.1 Subjects

Participants were 16 healthy, young males (Table 3.1), each of whom was screened to eliminate those with a contraindicative history of cardiovascular or thermoregulatory problems. All procedures were approved by the Human Research Ethics Committee (University of Wollongong: HE 12/022). In this study young and healthy individuals were used as subjects, however as mentioned in Chapter two, this is not a representation of the population at large. Certain population groups would not be accurately represented in this study (aged, infirm and young).

Figure 3.2: Left: Pre-heating, hot-water immersion (39°C). Right: Subject positioned within the air-tight simulator prior to commencing a resting exposure (door open, showing rehydration fluid on the table (900 mL)).
Table 3.1: Subject characteristics.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>27</td>
<td>1.81</td>
<td>70.10</td>
</tr>
<tr>
<td>S2</td>
<td>21</td>
<td>1.80</td>
<td>72.30</td>
</tr>
<tr>
<td>S3</td>
<td>21</td>
<td>1.87</td>
<td>82.06</td>
</tr>
<tr>
<td>S4</td>
<td>22</td>
<td>1.85</td>
<td>94.34</td>
</tr>
<tr>
<td>S5</td>
<td>21</td>
<td>1.92</td>
<td>93.58</td>
</tr>
<tr>
<td>S6</td>
<td>20</td>
<td>1.78</td>
<td>80.64</td>
</tr>
<tr>
<td>S7</td>
<td>26</td>
<td>1.87</td>
<td>74.20</td>
</tr>
<tr>
<td>S8</td>
<td>40</td>
<td>1.78</td>
<td>73.26</td>
</tr>
<tr>
<td>S9</td>
<td>21</td>
<td>1.71</td>
<td>65.64</td>
</tr>
<tr>
<td>S10</td>
<td>19</td>
<td>1.75</td>
<td>70.02</td>
</tr>
<tr>
<td>S11</td>
<td>24</td>
<td>1.77</td>
<td>87.06</td>
</tr>
<tr>
<td>S12</td>
<td>23</td>
<td>1.71</td>
<td>64.92</td>
</tr>
<tr>
<td>S13</td>
<td>22</td>
<td>1.80</td>
<td>74.26</td>
</tr>
<tr>
<td>S14</td>
<td>21</td>
<td>1.66</td>
<td>63.62</td>
</tr>
<tr>
<td>S15</td>
<td>22</td>
<td>1.87</td>
<td>91.94</td>
</tr>
<tr>
<td>S16</td>
<td>19</td>
<td>1.75</td>
<td>94.94</td>
</tr>
<tr>
<td>Mean</td>
<td>23.1</td>
<td>1.80</td>
<td>78.31</td>
</tr>
<tr>
<td>S.D.</td>
<td>5.0</td>
<td>0.07</td>
<td>11.06</td>
</tr>
</tbody>
</table>
3.2.2 Experimental conditions and procedures

All testing was conducted at the same time of day, with subjects presenting in a well-hydrated state. Subjects completed only one heat exposure, and this occurred within an air-tight and insulated shelter simulator (Figure 3.1), and under conditions designed to simulate a Modified Discomfort Index of 39°C: air temperature of 45°C and 50% relative humidity. This thermal state matched shelter condition two from Experiment One. The simulator was first equilibrated to the surrounding thermal conditions (>30 min). However, once each subject entered the inner chamber and the air-tight door was closed, the conditions within the simulator would change due to the presence of the experimental subject, whilst those of the outer, climate-controlled chamber were regulated and stable.

Within each trial, subjects were seated at rest for 60 min (Figure 3.2). Drinking was controlled to sustain euhydration, with each subject provided with 900 mL of an isotonic fluid during the exposure. This was served at room temperature, and in five 180-mL portions. These were consumed at 10-min intervals, starting at time zero. The total volume was derived using the mean sweat rate of male subjects, plus one standard deviation, observed within shelter condition three of Experiment One. This ensured sweating would not be impaired by progressive dehydration during the exposure, and thereby permitted an approximation of worst-case conditions with respect to changes in the internal (physical) state of the simulator.

Prior to each exposure, participants were heated to induce moderate hyperthermia. A pre-exposure core temperature of 38.0°C was induced by a combination of hot-water immersion (39°C; Figure 3.2) and exercise (treadmill: 6-8 km.h⁻¹) in an air-conditioned laboratory, whilst
wearing a long-sleeved shirt and long trousers. This pre-heated state was designed to replicate
the thermal status of individuals seeking shelter from a bushfire. In reality, core temperatures
may be greater, but, for the purpose of tracking core temperature changes, and projecting
these to either a critical core of temperature 42°C (Kenney et al., 2004) or a 2°C core
temperature elevation (Ludovici et al., 2010), then it was essential to commence these
exposures with a core temperature that had the capacity to rise at least 1°C before reaching the
current core temperature criterion for terminating such an experiment (39.5°C).

During the immersion phase, participants wore swimming costumes only, but donned a
long-sleeved shirt and long trousers for walking. However, dehydration during this pre-
exposure was prevented by the progressive replacement of the mass with an approximately
equivalent mass of water. Once the target core temperature had been attained, the resting
thermal exposure commenced, and subjects removed clothing back to their swimming
costumes, and adopted a seated resting posture within the air-tight (inner) chamber. In this
unclothed state, the evaporation of sweat was maximised, ensuring that water vapour pressure
changes within this chamber (shelter simulator) would more closely approximated those of a
worst-case scenario.

For reasons of subject safety, the following design features were incorporated into this shelter
simulator:

- the door was designed to be easily opened from both sides,
- a window permitted continuous visual contact with the test subject,
- there was a communication port to facilitate communication between the subject
and experimenters,

- monitoring equipment provided the researchers with continuous feedback concerning the physiological status of each subject, and
- continuous monitoring of shelter air temperature, humidity and gas composition was undertaken.

In addition to the standard safety procedures and trial termination criteria used within the current laboratory, additional trial termination criteria were set for this experiment, and these were dictated by changes in the gas concentration of the air within the shelter simulator. Thus, the following criteria were used:

- core temperature reaching 39.5°C,
- heart rate reaching 95% of the age-predicted cardiac reserve,
- signs of heat distress,
- the fractional concentration of carbon dioxide within the simulator rising to 5% or more for 15 min,
- signs of carbon dioxide distress,
- an oxygen concentration falling to 13% or less for 15 min,
- signs of hypoxic distress, or
- the subject wishing to terminate the trial for any reason.

3.2.3 Experimental standardisation

Subjects were required to refrain from strenuous exercise and the consumption of alcohol and tobacco during the 12 h prior to each trial. For the night prior to each trial, subjects were
instructed to drink 15 mL.kg\(^{-1}\) of additional water before retiring, and to eat an evening meal and breakfast high in carbohydrate and low in fat. Subjects also refrained from using caffeine for 2 h prior to a trial. On arrival at the laboratory, subjects were provided with supplementary water (10 mL.kg\(^{-1}\)) if urine specific gravity was >1.029, and this ensured that each trial commenced with every participant in a euhydrated state (Armstrong et al., 1994). Before leaving the laboratory, subjects were rehydrated, consuming an iso-osmotic drink equivalent to 150% of the heat-induced body mass change.

3.2.4 Experimental measurements

Physiological, psychophysical and psychological measures included: body core temperature, skin temperature, heart rate, sweat rate, hydration status, psychophysical responses and changes in anxiety status. In addition, air temperature, relative humidity and the fractional concentrations of carbon dioxide and oxygen within the air-tight simulator were monitored continuously.

3.2.4.1 Body tissue temperatures

3.2.4.1.1 Auditory canal temperature

Auditory canal temperature was monitored using an ear-moulded plug with a thermistor protruding 1 cm (Edale instruments Ltd., Cambridge, U.K.) and positioned within the external auditory meatus, and insulated with cotton wool. These data are shown in Figure 2.1, and show the capacity of auditory canal to track oesophageal. Data were recorded throughout each trial at 15-s intervals using a 16-channel portable data logger (Grant Instruments Ltd., 1206 Series Squirrel, U.K.), and later downloaded to a computer. This procedure isolates the
auditory canal from thermal artefacts, permitting auditory canal temperature to faithfully and rapidly track oesophageal temperature under these conditions (Cotter et al., 1995). In a pilot trial, four core temperature indices (auditory canal, rectal, oesophageal and GI) were studied during cold water immersion, followed by 45°C cycle ergometry. Performing this study showed that each of the core temperature measurements track each other and as such any are an acceptable to be used as a core temperature measurement. These data are shown in Figure 2.1 in Experiment One.

3.2.4.1.2 Skin temperatures

Skin temperatures were measured from four sites (chest, arm, thigh, leg: Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.), with data recorded throughout each trial at 15-s intervals (Grant Instruments Ltd., 1206 Series Squirrel, U.K.). Thermistors were attached to the skin with a single layer of waterproof tape.

3.2.4.1.3 Mean skin and mean body temperatures

Mean skin temperature was derived using a weighted summation of the four skin temperatures (after Ramanathan, 1964):

\[
T_{\text{skin}} = 0.3 (T_{\text{chest}} + T_{\text{arm}}) + 0.2 (T_{\text{thigh}} + T_{\text{leg}}) \quad \text{Equation 2}
\]

Mean body temperature was then obtained from the weighted sum of the auditory canal and mean skin temperatures (Sugenoya and Ogawa, 1985; Vallerand et al., 1992):

\[
T_{\text{body}} = (0.9 * T_{\text{core}}) + (0.1 * T_{\text{skin}}) \quad \text{Equation 3}
\]
3.2.4.1.4 Thermistor calibration

Thermistors were calibrated against a certified reference thermometer in a stirred water bath across a range of static and physiologically relevant temperatures (Dobros total immersion, Dobbie Instruments, Sydney, Australia).

3.2.4.2 Heart rate

Heart rate was monitored continuously (15-s intervals) from ventricular depolarisation (Vantage NV, Polar Electro Sport Tester, Kempele, Finland).

3.2.4.3 Hydration state and whole-body sweat rate

3.2.4.3.1 Hydration state

Prior to commencing each trial, urine specific gravity was measured for each subject (Clinical Refractometer, Model 140, Shibuya Optical, Tokyo, Japan). It was necessary as it was important to start these trials with subjects in a normally hydrated state. Urine specific gravity was measured again at the conclusion of each heat exposure.

3.2.4.3.2 Sweat rate

Gross mass changes (before and after each trial: ±20 g) were used to determine changes in whole-body sweating (fw-150k, A&D scale, CA, U.S.A.) over the course of each trial. Data were collected prior to entering, and immediately after leaving the simulator.
3.2.4.4 Psychophysical measures

Subjective reports of thermal sensation and thermal discomfort were recorded during a resting thermoneutral (baseline) state, just prior to commencing each heat exposure, and at 15-min intervals throughout each heat exposure. Familiarisation with each of the rating scales preceded the first trial, with subjects receiving standardised written instructions, with responses being prompted using the same question for each index.

3.2.4.4.1 Thermal sensation

Thermal sensation was monitored using a modified version of the Gagge scale (Gagge et al., 1967), where the end points were extended to enable a better resolution of thermal sensation.

Subjects were asked: “How does the temperature of your body feel?”:

<table>
<thead>
<tr>
<th>13-point thermal sensation scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Unbearably cold</td>
</tr>
<tr>
<td>2  Extremely cold</td>
</tr>
<tr>
<td>3  Very cold</td>
</tr>
<tr>
<td>4  Cold</td>
</tr>
<tr>
<td>5  Cool</td>
</tr>
<tr>
<td>6  Slightly cool</td>
</tr>
<tr>
<td>7  Neutral</td>
</tr>
<tr>
<td>8  Slightly warm</td>
</tr>
<tr>
<td>9  Warm</td>
</tr>
<tr>
<td>10 Hot</td>
</tr>
<tr>
<td>11 Very hot</td>
</tr>
<tr>
<td>12 Extremely hot</td>
</tr>
<tr>
<td>13 Unbearably hot</td>
</tr>
</tbody>
</table>
3.2.4.5 Psychological Responses

2.2.4.5.1 State anxiety

State anxiety was evaluated using the Spielberger State Anxiety Inventory (Spielberger et al., 1970), where subjects were asked to respond to 20 questions (Figure 3.3). Scores on the 20 items are summed (items 1, 2, 5, 8, 10, 11, 15, 16, 19 and 20 are reverse scored), with higher scores representing greater levels of anxiety.

3.2.4.6 Changes in the characteristics of the air within the shelter simulator

The fractional concentrations of both oxygen and carbon dioxide within the bushfire shelter simulator were sampled at 60-s intervals (MacLab ML206 Gas Analyser) during each trial. In addition, the air temperature (Edale Instruments Ltd, U.K.) and relative humidity (Vaisala hygrometer) of this air-tight chamber were recorded at 15-s intervals using a portable data logger (Grant Instruments Ltd., 1206 Series Squirrel, U.K.).
DIRECTIONS

A number of statements which people have used to describe themselves are given below. Read each statement and then select the appropriate response to the right of the statement to indicate how you feel right now, that is, at this moment. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

1. I feel calm
2. I feel secure
3. I am tense
4. I feel strained
5. I feel at ease
6. I feel upset
7. I am presently worrying over possible misfortunes
8. I feel satisfied
9. I feel frightened
10. I feel comfortable
11. I feel self-confident
12. I feel nervous
13. I am jitters
14. I feel indecisive
15. I am relaxed
16. I feel content
17. I am worried
18. I feel confused
19. I feel steady
20. I feel pleasant

Figure 3.3: Spielberger state anxiety index
3.2.5 Design and analyses

This experiment used a single-trial design, the purpose of which was primarily to provide an evaluation of changes within the thermal characteristics and gas composition of the air within the air-tight simulator. In addition, changes in physiological responses were tracked during these trials. Data were first analysed to provide standard descriptive parameters (e.g. means, standard errors), with simple modelling used to describe the time course of changes within the simulator (least-squares, best-fit polynomials (regression analysis)). Data are reported as means with standard errors of the means (±) and standard deviations (SD).

3.3 RESULTS

3.3.1 Pre-experimental state

It is important to determine that all subjects presented in a well-rested and adequately hydrated state. Table 2 contains the resting, thermoneutral baseline data, which verify that the standardisation procedures resulted in these trials being conducted on euhydrated, healthy and well-rested individuals.

3.3.2 Pre-exposure thermal status of subjects

Only one level of pre-exposure (mild) hyperthermia was induced (38.0°C). Data collected immediately upon entering the simulator are contained within Table 3.3, from which it is evident that the desired thermal state was successfully achieved. Observation of the heart rate data indicate a significant cardiovascular strain as observed in Experiment One.
Table 3.2: Thermoneutral (baseline) data prior to commencing the pre-heating treatment. Data are means with standard deviations in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Urine specific gravity</th>
<th>Heart rate (beats.min(^{-1}))</th>
<th>Core temperature (°C)</th>
<th>Thermal sensation (1-13)</th>
<th>Thermal discomfort (1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.012 (0.006)</td>
<td>69 (9)</td>
<td>36.6 (0.2)</td>
<td>7.1 (0.6)</td>
<td>1.0 (0.1)</td>
</tr>
</tbody>
</table>

Table 3.3: Pre-heated physiological data collected 15 s after entering the simulator. Data are means with standard deviations in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Heart rate (beats.min(^{-1}))</th>
<th>Core temperature (°C)</th>
<th>Skin temperature (°C)</th>
<th>Thermal sensation (1-13)</th>
<th>Thermal discomfort (1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102 (17)</td>
<td>38.1 (0.1)</td>
<td>35.8 (0.3)</td>
<td>9.5 (0.7)</td>
<td>2.2 (0.5)</td>
</tr>
</tbody>
</table>

Table 3.4: Shelter simulator data collected 15 s after subjects had entered the simulator. Data are means with standard deviations in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Air temperature (°C)</th>
<th>Relative humidity (%)</th>
<th>Oxygen concentration (%)</th>
<th>Carbon dioxide concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.7 (1.1)</td>
<td>42.3 (6.8)</td>
<td>20.8 (0.1)</td>
<td>0.040 (0.008)</td>
</tr>
</tbody>
</table>
3.3.3 Experimental outcomes: physical status of the simulator

3.3.3.1 Pre-experimental status of the simulator

Prior to the subjects entering the simulator, it was equilibrated (>30 min) to the conditions within the regulated outer chamber (air temperature 45°C, 50% relative humidity). This status is shown in Table 3.4, from which it is seen that the desired thermal status of the simulator was closely approximated prior to subject entry, and that the air composition closely resembled typical room-air conditions.

3.3.3.2 Shelter air temperature

Time series data for the changes in the temperature of the air within the shelter simulator are illustrated in Figure 3.4. The temperature and humidity of the simulator were only regulated up until the point where the subject entered the simulator. Beyond this point, the temperature and humidity were free to vary according to the exchanges between the pre-heated occupant and the simulator over the 60-min occupancy.

The air temperature within the shelter declined in a curvilinear manner across all trials. At the end of the 60-min exposure, the air temperature averaged 40.5°C (SD 0.5), indicating a 3.2°C reduction. The decrease temperature means that a net loss in thermal energy inside the simulator must have occurred. It is most likely that subjects gained thermal energy from the air, considering subjects entered the shelter at a temperature on average 5.8°C cooler than the average air temperature of the simulator (Table 3.3), the shelter simulator represented a closed system contained within a well-regulated outer chamber.
The vertical lines on Figure 3.4 show 10-min temperature changes. These will be used in the final experiment of this series to set the thermal profile for a bushfire shelter, in which the following reductions in air temperature will occur: 10 min: -1.0°C; 20 min: -0.6°C; 30 min: -0.3°C; 40 min: -0.2°C; 50 min: -0.3°C.

3.3.3.3 Shelter humidity

Humidity rose in an exponential manner within the shelter over the 60-min exposure (Figure 3.5), with termination occurring, on average, at 90.1% (SD 2.1). The shape of this curve conforms with that seen within any closed (insulated) system in which the properties of its air are perturbed by the presence of air possessing different characteristics. In this instance, the boundary layer of air next to each participant was relatively still, being influenced only by the natural convective flow of air over the body surface and intermittent movement of each. Thus, since each subject was heated and sweating prior to entering the shelter simulator, then this boundary layer of air would approximate saturation, thereby creating a vapour pressure gradient from this layer to the air within the simulator. This gradient would cause water molecules to be continually added to the shelter air, with such molecular movements being proportional to the size of the vapour pressure gradient. However, as time progressed, this gradient gradually became smaller, due to the ever increasing number of water molecules accumulating within the simulator air. This progressively reduced the rate at which the relative humidity of the simulator increased, forcing this change to resemble an exponential function.
Figure 3.4: Air temperature changes within the bushfire shelter simulator (1.2 m³) initially equilibrated to a Modified Discomfort Index of 39°C (shelter condition two: air temperature 45°C, 50% relative humidity). Pre-heated subjects (core temperature 38.0°C) rested (seated) within the simulator (60 min), during which air temperature and humidity were free to vary. Data are means with standard errors of the means at 2.5-min intervals (N = 16). Also shown is a third-order polynomial prediction of relative humidity (red curve) with 99% prediction intervals (blue dashed lines).
Figure 3.5: Relative humidity changes within the bushfire shelter simulator (1.2 m$^3$) initially equilibrated to a Modified Discomfort Index of 39°C (shelter condition two: air temperature 45°C, 50% relative humidity). Pre-heated subjects (core temperature 38.0°C) rested (seated) within the simulator (60 min), during which air temperature and humidity were free to vary. Data are means with standard errors of the means at 2.5-min intervals (N=16). Also shown is a third-order polynomial prediction of relative humidity (red curve) with 99% prediction intervals (blue dashed lines).
Initial air temperature of the simulator was 43.7°C and relative humidity was 42.3%, upon entry (Table 3.4). This is equal to a water vapour pressure of 3.78 kPa (Santee and Gonzalez, 1988). However, upon termination of the experiments the air temperature fell to 40.5°C and humidity rose to 90.1%, this is equates to a water vapour pressure of 6.82 kPa. This 3.05 kPa change occurred due to the increases in humidity (113.3%), since the change in air temperature was in the opposite direction and minimal (7.3%). The high humidity represented nearly completely saturated air, which would allow for minimal evaporation of sweat.

The vertical lines on Figure 3.5 mark 10-min increments in relative humidity. These data will be used in the final experiment of this series, in which there will be a gradual elevation in relative humidity: 10 min: 60%; 20 min: 70%; 30 min: 80%; 40 min: 84%; 50 min: 86%.

3.3.3.4 Simulator oxygen concentration

The fractional concentration of oxygen within the shelter air decreased linearly over time (Figure 3.6), and this relationship was very strong (\( r^2 = 0.994 \)), with the terminal oxygen concentrations averaging 16.7% (SD 0.8). From this relationship, one can predict changes in oxygen concentration within an air-tight space constructed to these specifications, heated to the current experimental conditions and occupied by a pre-heated individual:

\[
\text{Oxygen conc. (\%) at time } t \text{ (min)} = 20.47 - 0.06 \times t \quad [r^2 = 0.994]
\]

Equation 4

Table 3.5 contains prediction times to reach concentrations of 19.5%, 13% and 10%.

Since the simulator would approximate a closed system, then it was possible to calculate the resting oxygen consumption for these enclosed individuals on a first-principles basis. Known
variables were the fractional concentrations of oxygen at the start and end of each exposure, and the internal volume of the simulator before the subject entered minus the air volume displaced by objects within the simulator (chair, table, computer, drinks, data logger). Unknown was the total body volume of each individual, but this was approximated using the algorithm developed by Sendroy and Collison (1966). Thus, one could derive the volume of oxygen contained within the air space surrounding the subject at the start and the conclusion of each trial, and thereby compute oxygen consumption (L.min\(^{-1}\)). The average resting rate of oxygen consumption of the occupants was 0.67 L.min\(^{-1}\) (SD 0.20). This value is considered high for a resting individual, however, hyperthermia will cause an increase in resting metabolic rate (Consolazio et al., 1963; Consolazio, 1964, Gaudio and Abramson, 1968), and this is a result of the direct thermal influence upon chemical reactions (Q10 effect), and also due to an increased physiological demand (e.g. heart rate and sweat production). Thus, this first-principles approximation was not too unrealistic.

3.3.3.5 Simulator carbon dioxide concentration

As each exposure progressed, the fractional concentration of carbon dioxide increased linearly (Figure 3.7; \(r^2 = 0.997\)), with the concentration averaging 3.94\% (SD 0.72) at the termination of these trials. This too was expected, permitting a prediction of the carbon dioxide concentration changes within an air-tight shelter constructed to these specifications. Thus, Table 3.5 contains prediction times to reach concentrations of 4\%, 5\% and 7\%.

Carbon dioxide conc. (%) at time t (min) = 0.129 + 0.063 \* t \[r^2 = 0.997\] Equation 5
Figure 3.6: Changes in the fractional concentration of oxygen within a bushfire shelter simulator (1.2 m³) during 60 min rest (pre-heated subjects). Data are means with standard errors of the means (N = 16) and linear predictions (red curve) with 99% prediction intervals (blue dashed lines).
Figure 3.7: Changes in the carbon dioxide fractional concentration within a bushfire shelter simulator (1.2 m³) during 60 min rest (pre-heated subjects). Data are means with standard errors of the means (N = 16) and linear predictions (red curve) with 99% prediction intervals (blue dashed lines).
Table 3.5: Predictions of times to reach different oxygen and carbon dioxide concentrations within an occupied, single-person bushfire shelter (1.2 m$^3$).

<table>
<thead>
<tr>
<th>Oxygen</th>
<th>Time (min:sec)</th>
<th>Carbon dioxide</th>
<th>Time (min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.5%</td>
<td>15:49</td>
<td>4.0%</td>
<td>61:26</td>
</tr>
<tr>
<td>13.0%</td>
<td>121:35</td>
<td>5.0%</td>
<td>77:19</td>
</tr>
<tr>
<td>10%</td>
<td>170:24</td>
<td>7.0%</td>
<td>109:04</td>
</tr>
</tbody>
</table>

Notes: Critical concentrations appear within the red cells. (1) Oxygen concentrations: (a) 19.5%: Recommended minimal composition of breathing air (Occupational Safety and Health Administration (U.S.A.)); (b) 13%: Safety limit imposed by current investigators; © 10%: Estimated concentration for loss of consciousness. (2) Carbon dioxide concentrations: (a) 7%: Concentration for loss of consciousness (Flury and Zernik, 1931); (b) 5%: Safety limit imposed by current investigators; © 4%: Concentration deemed to be “immediately dangerous to life or health” (National Institute for Occupational Safety and Health (U.S.A.)).
3.3.4 Physiological responses

3.3.4.1 Heart rate

Unlike Experiment One, where the temperature of the shelter was regulated, in this series of experiments, air temperature was altered during shelter occupancy. As a result, the cardiac strain was different between the two experiments. During Experiment One, heart rate declined until it reached a new steady-state after 10 min of exposure. Whilst in contrast, in this series of trials heart rate declined during the first 10 min of exposure and then a gradual increase was observed (Figure 3.8A). This shows a progressive elevation in physiological strain. This relationship was also most powerful:

\[
\text{Heart rate (beats.min}^{-1}\text{) at time } t \text{ (min)} = 96.51 + 0.72 * t \quad [r^2 = 0.960] \quad \text{Equation 6}
\]

This prediction equation was determined after 10 min exposure, since in almost every subject, a reduction in core temperature was experienced until this point.

3.3.4.2 Core temperature

Core temperature showed an obvious elevation beyond 10 min (Figure 3.9A). On average (Table 3.6) core temperature rose at a rate of 0.3°C min\(^{-1}\), terminating at 39.3°C (SD 0.2), and a strong relationship between time and core temperature \((r^2 = 0.989; \text{Figure 3.9B})\) was found. This enabled a prediction to the point core temperature would reach 42°C, and after starting with a core temperature of 38.0°C, it would experience a 2°C elevation. A core temperature of 42°C would be predicted to occur after 145 min of exposure, and a 2°C elevation in core temperature would be experienced after 80 min of exposure on average.

\[
\text{Core temperature (°C) at time } t \text{ (min)} = 37.53 + 0.03 * t \quad [r^2 = 0.989] \quad \text{Equation 7}
\]

The prediction equation was determined after 10 min exposure considering in every subject a
reduction in core temperature was experienced until this point.

Using only mean data from these regression analyses ignores both the within- and between-subject variability, and it will lower the precision. In order to eliminate this inaccuracy, individual core temperature data were separately modelled beyond 10 min (linear regression analyses: Table 3.6). Data were then averaged to provide a prediction equation, which can predict both within- and between-subject variability. The two prediction equations were found to be near identical.

\[
\text{Core temperature (°C) at time t (min) = 37.45 + 0.03 \times t \quad [r^2 = 0.990]} \quad \text{Equation 8}
\]

Using prediction Equation 8 we are able to recalculate the times which a core temperature of 42°C would occur, and also when an elevation of 2°C would occur. These were calculated to be 132 min and 74 min respectively. Both of these values fall outside the specified duration of occupancy according to the standard (Australian Building Codes Board, 2010), with the former being over twice that value.

In Experiment One, under the same conditions, core temperature was shown to decrease. The change being seen in this series of trials can be associated with the decreased evaporative power of the simulator as relative humidity increases. From approximately the fifth minute, the simulator experienced an exponential rise in water vapour pressure (Figure 3.10), with the air becoming more saturated. Considering this saturation minimised heat loss for the occupant, core temperature was found to increase. In addition, each subject gained thermal energy from the air within the simulator (Figure 3.9A).
Figure 3.8: A: Heart rate response during a resting (seated) heat exposure within a shelter simulator equilibrated to a Modified Discomfort Index of 39°C (shelter condition two: air temperature 45°C, 50% relative humidity). Subjects were pre-heated to a mild-moderate hyperthermic state (38.0°C). Data are means with standard errors of the means at 2.5-min intervals (N=16). B: Same data presented from 10 min onwards, and with a first-order polynomial prediction of heart rate (red curve) with 99% prediction intervals indicated (blue dashed lines).
Figure 3.9: A: Core temperature changes during a resting (seated) heat exposure within a shelter simulator equilibrated to a Modified Discomfort Index of 39°C (shelter condition two: air temperature 45°C, 50% relative humidity). Subjects were pre-heated to a mild-moderate hyperthermic state (38.0°C). Data are means with standard errors of the means at 2.5-min intervals (N=16). B: Same data presented from 10 min onwards, and with a first-order polynomial prediction of core temperature (red curve) with 99% prediction intervals indicated (blue dashed lines).
Table 3.6: Linear regression parameters for changes in core temperature, with rates of core temperature change also presented.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Correlation coefficient</th>
<th>Intercept</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.998</td>
<td>37.69</td>
<td>0.054</td>
</tr>
<tr>
<td>S2</td>
<td>0.997</td>
<td>37.56</td>
<td>0.034</td>
</tr>
<tr>
<td>S3</td>
<td>0.998</td>
<td>37.40</td>
<td>0.038</td>
</tr>
<tr>
<td>S4</td>
<td>0.984</td>
<td>37.48</td>
<td>0.031</td>
</tr>
<tr>
<td>S5</td>
<td>0.993</td>
<td>37.32</td>
<td>0.027</td>
</tr>
<tr>
<td>S6</td>
<td>0.997</td>
<td>37.44</td>
<td>0.028</td>
</tr>
<tr>
<td>S7</td>
<td>0.995</td>
<td>37.42</td>
<td>0.031</td>
</tr>
<tr>
<td>S8</td>
<td>0.999</td>
<td>37.61</td>
<td>0.035</td>
</tr>
<tr>
<td>S9</td>
<td>0.994</td>
<td>37.46</td>
<td>0.034</td>
</tr>
<tr>
<td>S10</td>
<td>0.990</td>
<td>37.50</td>
<td>0.033</td>
</tr>
<tr>
<td>S11</td>
<td>0.999</td>
<td>37.32</td>
<td>0.028</td>
</tr>
<tr>
<td>S12</td>
<td>0.998</td>
<td>37.57</td>
<td>0.033</td>
</tr>
<tr>
<td>S13</td>
<td>0.999</td>
<td>37.52</td>
<td>0.037</td>
</tr>
<tr>
<td>S14</td>
<td>0.996</td>
<td>37.33</td>
<td>0.036</td>
</tr>
<tr>
<td>S15</td>
<td>0.996</td>
<td>37.21</td>
<td>0.039</td>
</tr>
<tr>
<td>S16</td>
<td>0.995</td>
<td>37.43</td>
<td>0.034</td>
</tr>
<tr>
<td>Mean</td>
<td>0.995</td>
<td>37.45</td>
<td>0.034</td>
</tr>
<tr>
<td>SD</td>
<td>0.004</td>
<td>0.12</td>
<td>0.006</td>
</tr>
</tbody>
</table>
3.3.4.3 Skin temperature

An increase in skin temperature was found, and this was also in contrast to Experiment One where skin temperature was found to decreases throughout the exposure. Skin temperature changes are as a result of the thermal gradient that was found between the air temperature and skin temperature. Thermal energy moves from a high gradient (air temperature) to a low gradient (skin temperature), thus an increase in the low gradient occurs. The air-to-skin thermal gradient averaged 7.9°C (43.7-35.8°C) at the start of these exposures.

Another and more important factor which contributed to the difference in skin temperature was water vapour pressure progressively rising throughout the exposure. From the examination of Figure 3.11 and Table 3.7 it can be seen that rising skin temperature tracks changes in the evaporative capacity of the environment ($r^2 = 0.968$). The declining evaporative capacity of the environment facilitated the high skin temperatures found at the termination of these trials.

However, at no point did these skin temperatures exceed core temperature (Figure 3.12), and this is important because if skin temperature exceeds core, thermal energy will be transferred from the skin to the core by the thermal gradient increasing the core temperature.
Figure 3.10: Core temperature change and the accompanying elevation in the water vapour pressure (blue curve) of the surrounding air during a resting (seated) heat exposure within a shelter simulator equilibrated to a Modified Discomfort Index of 39°C (shelter condition two: air temperature 45°C, 50% relative humidity). Subjects were pre-heated to a mild-moderate hyperthermic state (38.0°C). Data are means with standard errors of the means provided for the core temperature data at 2.5-min intervals (N=16).
Figure 3.11: Skin temperature change and the accompanying elevation in the water vapour pressure (blue curve) of the surrounding air during a resting (seated) heat exposure within a shelter simulator equilibrated to a Modified Discomfort Index of 39°C (shelter condition two: air temperature 45°C, 50% relative humidity). Subjects were pre-heated to a mild-moderate hyperthermic state (38.0°C). Data are means with standard errors of the means provided for the skin temperature data at 2.5-min intervals (N=16).
Table 3.7: Mean skin temperature, skin and air water vapour pressures, and the corresponding water vapour pressure gradients. Data are means with standard errors of the means in parenthesis (N = 16).

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Skin temperature (°C)</th>
<th>Skin vapour pressure (kPa)</th>
<th>Air vapour pressure (kPa)</th>
<th>Vapour pressure gradient (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>37 (0.08)</td>
<td>6.261</td>
<td>5.676</td>
<td>0.841</td>
</tr>
<tr>
<td>25</td>
<td>38.1 (0.07)</td>
<td>6.663</td>
<td>6.213</td>
<td>0.45</td>
</tr>
<tr>
<td>35</td>
<td>38.4 (0.05)</td>
<td>6.76</td>
<td>6.376</td>
<td>0.383</td>
</tr>
<tr>
<td>45</td>
<td>38.6 (0.06)</td>
<td>6.859</td>
<td>6.547</td>
<td>0.312</td>
</tr>
<tr>
<td>55</td>
<td>38.8 (0.05)</td>
<td>6.904</td>
<td>6.725</td>
<td>0.179</td>
</tr>
</tbody>
</table>

Figure 3.12: Skin and core temperature (red curve) changes during a resting (seated) heat exposure. Subjects were pre-heated to a mild-moderate hyperthermic state (38.0°C). Data are means with standard errors of the means provided for the skin temperature data at 2.5-min intervals (N = 16).
3.3.4.4 Whole-body sweat rate

In this series of trials, the air temperature constantly exceed core and skin temperatures. This means that the only avenue for heat loss was through the evaporation of sweat but as the humidity within the simulator climbed (Figure 3.4) and the water vapour pressure gradient fell (Table 3.7), this avenue became ineffective leading to an increase in core and skin temperatures (Figure 3.12). These increases provided a powerful stimuli for the production of sweat.

The average sweat rate for this series of trials was 0.71 L.hr\(^{-1}\) (SD 0.29). This high level of sweating was maintained by subjects ingesting 180 mL of isotonic fluid at 10-min intervals. The fluid was administered to maintain sweating by preventing dehydration, enabling an evaluation of the influences of occupancy on the internal status of a sealed, bushfire shelter. Since there was no significant difference in the mean body masses of these subjects before and after these exposures (\(P > 0.05\)), this objective was deemed to have been satisfied.

3.3.4.5 Psychophysical indices

The psychophysical indices followed unremarkable, and predictable responses (Table 3.8). These subjective evaluations of thermal sensation and discomfort were elevated from the start of the exposure, and this was no doubt due to the thermal pre-treatments. However, in this experiment, both of these indices gradually increased during the heat exposure, with thermal discomfort attaining maximal values in five of the 16 subjects at the last point of measurement. An accumulation of moisture on the skin surface, would occur in humid conditions, have been associated with high levels of discomfort (Boutcher et al., 1993).
Table 3.8: Thermal sensation (scale: 1-13) and discomfort votes (scale: 1-5). Data are means with standard errors of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Trial stage</th>
<th>Sensation</th>
<th>Discomfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>7.1 (0.22)</td>
<td>1.0 (&lt;0.1)</td>
</tr>
<tr>
<td>0 min</td>
<td>9.5 (0.18)</td>
<td>2.2 (0.14)</td>
</tr>
<tr>
<td>15 min</td>
<td>10.3 (0.20)</td>
<td>3.0 (0.16)</td>
</tr>
<tr>
<td>30 min</td>
<td>11.3 (0.25)</td>
<td>3.7 (0.20)</td>
</tr>
<tr>
<td>45 min</td>
<td>11.8 (0.20)</td>
<td>4.2 (0.17)</td>
</tr>
<tr>
<td>60 min</td>
<td>12.3 (0.13)</td>
<td>4.5 (0.11)</td>
</tr>
</tbody>
</table>

Table 3.9 Speilberger State Anxiety Inventory scores (scale: 20-80). Data are means with standard errors of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Trial stage</th>
<th>State anxiety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>36 (1.7)</td>
</tr>
<tr>
<td>0 min</td>
<td>43 (2.2)</td>
</tr>
<tr>
<td>15 min</td>
<td>50 (1.9)</td>
</tr>
<tr>
<td>30 min</td>
<td>59 (2.0)</td>
</tr>
<tr>
<td>45 min</td>
<td>68 (2.6)</td>
</tr>
<tr>
<td>60 min</td>
<td>71 (2.3)</td>
</tr>
</tbody>
</table>
3.3.4.6 State anxiety

The results found which are based on the Speilberger State Anxiety Inventory are quite typical in individuals in environments of increasing discomfort, as this was determined to be based on the thermal discomfort responses of the occupants (Table 3.8). A rising anxiety occurred throughout the exposure (Table 3.9), with increasing values indicating an increasing level of anxiety (Speilberger et al., 1983). These results follow the same trend as the thermal discomfort, so it can be said that occupants became more anxious as they became uncomfortable (White, 2009).

3.4. DISCUSSION

This study was aimed at quantifying the influence of human occupancy of an air-tight simulator for 60 min, equilibrated initially at 39° Modified Discomfort Index and conforming to the minimum volume set out by the Australian Building Codes Board (2010: 1.2 m³). Similar studies have been conducted to determine the influence of human occupancy on air-tight structures such as bomb shelters, however, the period of occupancy for such structures is significantly longer. For reason this experiment was conducted, in order to determine a thermal profile which would represent a worst-case scenario found in a bushfire shelter that adhered to the minimum structural requirements (Australian Building Codes Board, 2010). This experiment has two principal considerations. Firstly, it was necessary to ensure that the changing internal climate of the simulator could be tolerated by occupants and secondly, we needed to quantify the changes in the internal climate of a bushfire simulator to determine the likely thermal profile for bushfire shelters during occupancy. The results from these trials have determined the expected changes in the shelter micro-climate due to human occupancy.
In addition, it was found that these changes can be tolerated without a significant increase in core temperature, and that the gas concentrations did not alter enough to pose a significant health risk. Obtaining the thermal profile of such a shelter during occupancy enabled further investigation into the influence of dehydration in this changing environment (Experiment Three).

3.4.1 Physiological responses to an air-tight simulator

3.4.1.1 Gas concentrations

On the basis of the gas concentration results, it was found that neither oxygen nor carbon dioxide concentration reached levels which provided a significant health risk to the occupant (National Institute of Occupational Safety and Health (U.S.A.)) during the 60 min exposure.

Moreover, hypercapnia has been shown to cause increases in respiration, this increase can be noted during thermoneutral conditions and becomes more pronounced with the addition of hyperthermia (Stokes et al., 1948). An increase in respiration is stimulated via both central and peripheral chemoreceptors, which detect an increased carbon dioxide and lower pH (Cunningham and O’Riordan, 1957). An increased respiration is an adverse response, as an increase in respiration results in a greater production of carbon dioxide in a closed system.

In response to the resulting hypercapnia peripheral vasodilation occurs (Stupfel, 1974). Increasing blood flow to the periphery allows a more rapid exchange of heat with the environment, which in this case is hotter than the individual and therefore allows for more heat to be gained by the individual. Evaporative heat loss is increased during hypercapnia as
the sweating response is more powerful (Stokes et al., 1948), however, in a closed environment this can become ineffective as it causes the simulator humidity to increase. The decreasing evaporative ability of the environment minimises the amount of heat that can be lost through sweating, and sweating becomes wasteful, leading to dehydration.

3.4.1.2 Cardiovascular responses

Cardiovascular responses are a good overall predictor of physiological strain. Previous authors have found an increase in heart rate when people are exposed to a hot environment (Fox et al., 1963; Rowell et al., 1970; Neilsen et al., 1993). This is a typical response to any heat exposure, and is consistent with results from this series of experiments which yielded a high cardiovascular strain indicated by an elevated heart rate, with eight of the subjects recording a peak heart above 140 beats.min\(^{-1}\). This value is equivalent to 70\% of the age-predicted maximum for this group of subjects. However, a high level of cardiovascular strain was an expected homeostatic response that occurred as a result of blood flow shifting to the periphery. In order to facilitate heat loss via blood bourne convection, cutaneous (skin) blood flow is increased in hot environments.

A rising core temperature results in a need to dissipate heat to the environment to in order to attempt to decrease the thermal load on an individual. This occurs by dilating the peripheral blood vessels, causing an increased skin blood (Wyss et al., 1975), allowing for a faster thermal exchange between the individual and the environment. However central venous pressure drops when blood flow shifts to the periphery (Crandell et al., 1999). Central venous pressure is an indicator of venous return (Gelman, 2008) and as per the Frank-Starling Law
states that the stroke volume of the heart is proportional to the amount of blood returning to the heart. Therefore, a decreasing central venous pressure also results in a lower stroke volume. Stroke volume is a one of the components which determines cardiac output, and as such cardiac output can be expected to decline. A decrease in pulse pressure from a smaller stroke volume lowers mean arterial pressure by 5-10 mmHg (Rowell et al., 1970) causing a decrease in baroreceptor firing rate and the resulting baroreflex response will result in an increased heart rate (Fu et al., 2009).

There are various other influences which can alter the heart rate response. For example, psychological and emotional state influence heart rate disproportionally to metabolic demand by altering sympathetic drive (Carroll et al., 1986; Levenson, 1992). An enhanced sympathetic drive causes a release of adrenaline from the adrenal glands, leading to an elevated heart rate by binding to the beta-1 adrenergic receptor (Daul et al., 1995). During the course of these trials a progressively increasing anxiety index was recorded, terminating at a Speilberger State Anxiety Inventory value of 71 which is indicative of an altered psychological state.

3.4.1.3 Thermal responses

Many authors note that in an environment with high humidity and temperature, thermoregulation fails and core temperature begins to rise (Herrington et al., 1937; McArdle et al., 1947). The initial thermal conditions used in this investigation have been shown to facilitate heat gain (Herrington et al., 1937) and considering that the relative humidity was increasing throughout the exposure, it is no surprise that sweating becomes ineffective and as
The increasing core temperature is the function of two mechanisms. Firstly, air temperature exceeding body temperature and secondly, decreased water vapour pressure between the skin and air. In both instances a gradient is the primary influence.

In the first mechanism, when air temperature exceeds body temperature, the thermal gradient between the air and body causes heat gain to occur to the internal body tissues from the air. This would also explain the decrease in air temperature as heat was transferred to the occupant causing core temperature to rise. As this was a closed system, no thermal energy was lost or gained from the simulator it was merely transferred to the occupant. The increased skin blood flow occurs in an attempt to dissipate heat to the environment (Rowell et al., 1970), although the air temperature prevented this. Had air temperature been lower than body temperature, then heat would have been dissipated to the environment causing air temperature to increase.

In the second instance, humidity was increased primarily due to the evaporation of the occupants sweat, and this caused evaporation to become progressively ineffective. As the air becomes saturated with water vapour from sweat, the ability to cool from evaporation diminished. In periods of high humidity, evaporation often becomes wasteful, and causes an insulating layer of sweat to develop on the skin (Steadman, 1979). However, considering the exposure duration was limited to 60 min (Australian Building Codes Board, 2010), an elevation of core temperature to a dangerous level did not occur.
The conditions inside the simulator remained tenable for the entire exposure. However, if the duration of exposure were to increase, strategies would need to be implemented to maintain the internal environment. Similar studies have been conducted on bomb shelters, which are similarly air-tight (Charanian et al., 1963; Allen, 1960), although occupancy is typical two weeks or longer (Yaglou, 1961). According to equation 5 carbon dioxide concentration would pose a health risk first, but this would not occur until 109 min of exposure. If the duration of bushfire shelters needed to be extended such similar methods to those applied to bomb shelters, to regulate temperature, humidity, carbon dioxide and oxygen concentration may be considered (Charanian et al., 1963). However, the concern of such shelters is the ultimately survivability of the occupants and not their comfort during occupancy. Thus, the cost of including such measures outweighs the benefits.

3.5. CONCLUSION

This experiment evaluated the effect of a pre-heated and euhydrated individual on the micro-climate of a bushfire simulator adhering to the thermal standard (39° Modified Discomfort Index) and structural standard (1.2m³) for bushfire shelters (Australian Building Codes Board, 2010). The results of this study also provided evidence that the changing micro-climate did not cause core temperature to elevate to 42°C or by more than 2°C over a 60-min exposure (Australilan Building Codes Board, 2010), providing that the structural integrity of the shelter remains intact.

A prediction equation (equation 8) was developed to derive the time at which core temperature would reach 42°C, and when a core temperature elevation of 2°C would occur. After 132 min,
of exposure a core temperature of 42°C was predicted, and an elevation of 2°C in core temperature would occur after 74 min of exposure. Both of these values fall outside the 60-min occupancy period outlined by the Australian Building Codes Board (2010). It was therefore concluded that the conditions inside shelter would provide a tenable environment for healthy occupants.

Gas concentrations inside the air-tight shelter changed linearly throughout the exposure as the simulator provided a closed system. However, neither oxygen nor carbon dioxide concentrations posed a significant health risk for a 60-min exposure. Prediction equations were derived for estimating these gas concentrations during more extended exposures (equations 4 and 5). These enabled prediction of the time for the oxygen and carbon dioxide concentrations to reach values which would pose significant health risks (Occupational Safety and Health Administration (U.S.A.)). From these predictions, an oxygen concentration of 10% would occur at 170 min and a 7% concentration of carbon dioxide would occur at 109 min, both of which are well outside the predicted 60 min (Australian Building Codes Board, 2010). It was therefore concluded that oxygen and carbon dioxide concentrations would remain within a safe limit throughout the occupancy of a bushfire shelter.

A thermal profile for bushfire shelters was derived using the relative humidity and air temperature changes recorded during these trials. These profiles (Table 3.9) will be used in the next experiment. Although during this experiment, core temperature was maintained without a significant health risk, dehydration will cause a faster rise in core temperature (Montain and Coyle, 1992). Dehydration could be anticipated in the scenario occupants find themselves in
prior to the bushfire. Thus, the next experiment was designed using this thermal profile and dehydrated individuals.

Table 3.10: Temperature and relative humidity profiles for Experiment Three.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Shelter condition one</th>
<th>Shelter condition two</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air temperature (°C)</td>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>10</td>
<td>39</td>
<td>70</td>
</tr>
<tr>
<td>20</td>
<td>38.4</td>
<td>70</td>
</tr>
<tr>
<td>30</td>
<td>38.1</td>
<td>80</td>
</tr>
<tr>
<td>40</td>
<td>37.9</td>
<td>84</td>
</tr>
<tr>
<td>50</td>
<td>37.6</td>
<td>86</td>
</tr>
</tbody>
</table>
3.6. REFERENCES


National Institute for Occupational Safety and Health (U.S.A.).
http://www.cdc.gov/niosh/idlh/124389.html


4.1. INTRODUCTION

4.1.1 Background information

The final experiment of this study was conducted to determine whether the dehydration will influence the rate of thermoregulation in occupants of a bushfire shelter. The need for the shelter to be air-tight to prevent asphyxiation from smoke inhalation causes changes in air temperature, relative humidity, carbon dioxide concentration and oxygen concentration. In well-hydrated individuals, these did not pose a threat as was discovered in Experiment Two but considering the nature of the scenario occupants may find themselves seeking the shelter in a dehydrated state. Dehydration will influence the thermoregulatory and cardiovascular response during heat exposure (Montain and Coyle, 1992), as such must be investigated.

4.1.2 Research background

4.1.2.1 Experiment one

In experiment one, a preliminary evaluation of thermal strain and heat tolerance during the 60-min exposure of sixteen individuals to three different thermal states (shelter conditions) was performed. Each of these conditions satisfied the Modified Discomfort Index standard of 39°. These exposures were conducted within a thermally regulated climate chamber, and with air temperature and relative humidity remaining constant. These conditions covered a 10°C range in air temperature (40-50°C) and a 40% range in relative humidity (30-70%):

- Shelter condition one: Hot and humid: 40°C, 70% relative humidity.
- Shelter condition two: Hot and quite humid: 45°C, 50% relative humidity.
- Shelter condition three: Very hot and dry: 50°C, 30% relative humidity.

From a first-principles understanding, it was known that variations in air temperature would represent the most challenging element of these conditions. However, since each shelter condition had an air temperature greater than the body temperature of the experimental participants, then the only way for heat to be lost was through the evaporation of sweat (evaporative cooling). This is a very powerful mechanism for heat dissipation (Bladgen, 1775). Thus, changes in water vapour pressure would interact with air temperature and, in so doing, provide an unequal thermal strain and heat tolerance.

Since, to the best of the researchers knowledge, this interaction had not previously been investigated within a population sample that included men and women, this necessitated controlled, human experimentation. Physiological evidence was sought pertaining to human survival within shelters constructed in accordance with this performance standard, and an answer to the following question was sought (Patterson, 2010):

“Can someone tolerate an exposure to a Modified Discomfort Index of 39° without experiencing either a critical core temperature of 42°C or a 2°C core temperature elevation?”

To perform this evaluation, 96 separate trials were undertaken. Equal numbers of healthy large, medium and small males (N=8) and females (N=8) were exposed to the three shelter
conditions (seated rest in swimwear). Each exposure was completed in two pre-heated and slightly dehydrated states (2%): mild (core temperature 37.5°C) and moderate hyperthermia (core temperature 38.5°C). This permitted a superior representation of the thermal status of people taking shelter from a bushfire. Thus, each subject acted as his/her own control, and was involved in six experimental trials, during which physiological strain was quantified from changes in heart rate, and body core and skin temperatures.

Subjects experienced significantly greater cardiovascular strain within shelter conditions two and three when moderately hyperthermic. Indeed, three subjects had resting heart rates in excess of 170 beats.min⁻¹ in shelter condition two, with six returning such high values in condition three. Whilst this level of cardiovascular strain was significant, it is well tolerated within healthy, asymptomatic individuals. Nevertheless, less healthy individuals will be challenged under such conditions, particularly those with a history of cardiovascular disease, the frail and the aged, and this may precipitate serious and life-threatening cardiovascular complications.

On average, and across all three shelter conditions, the Modified Discomfort Index of 39° was tolerated without either a core temperature of 42°C being obtained, or a 2°C core temperature elevation being experienced. It therefore appeared that, when air temperature and relative humidity were regulated to achieve a stable Modified Discomfort Index of 39°, excessive hyperthermia in resting, semi-clothed young adults would be unlikely to occur.

Thus, Experiment One provided preliminary support for the specification of bushfire shelters
to keep the internal conditions to a maximal mean Modified Discomfort Index of 39° for 60 min. What remained uncertain was whether or not the stable states used during this research provided a faithful simulation of the conditions that would actually exist within an occupied shelter. Indeed, the air temperature, relative humidity, and the oxygen and carbon dioxide concentrations would change throughout the 60-min occupancy of a sealed (air-tight) shelter, and these changes, along with their physiological impact, were emphasised during the second experiment from this series.

4.1.2.2 Experiment two

When people are enclosed within an air-tight and insulated shelter, the status of the trapped air will not remain stable, and this creates added stresses that simultaneously influence physiological function and heat tolerance. These include changes in air temperature, relative humidity, and the fractional concentrations of both carbon dioxide and oxygen.

Thus, the first aim of the second study from this series was to characterise changes in the trapped air within an air-tight chamber build to the specifications of the Australian Building Codes Board. These trials answered the following question:

“In an enclosed, air-tight room, what is the rate of increase in relative humidity [water vapour pressure] and ambient [air] temperature due to human [occupancy] thermoregulation?”

Sixteen heat exposures were performed within a customised and air-tight bushfire shelter simulator (1.2 m³) housed within a climate-controlled chamber. Sixteen young, healthy adults
(19-40 years) were exposed to a single shelter (thermal) condition which had an initial Modified Discomfort Index of 39° (air temperature 45°C, relative humidity 50%). Immediately following shelter entry, an air-tight door isolated the subject and the surrounding air from the outer chamber. This permitted the temperature, water vapour pressure and gas composition of this air space to change independently of the regulated external conditions. Every subject completed this trial in a pre-heated (core temperature 38.0°C) but normally hydrated state. This latter consideration, along with using male subjects and a rigid fluid replacement regimen (five, 180-mL isotonic drinks), was designed to ensure the maintenance of greater sweat rates during the period of shelter occupancy. This was aimed at providing a better simulation of the worst-case changes within the thermal status of the air enclosed within the shelter simulator. During these trials, physiological strain was quantified, with the primary physiological variables being heart rate and body core temperature. In addition, air temperature, relative humidity and the fractional concentrations of carbon dioxide and oxygen were monitored continuously.

The temperature of the air within this simulator did not rise, but slowly declined during each occupancy, presumably due to thermal energy being transferred to each occupant. The fractional concentrations of oxygen and carbon dioxide changed proportionately over time, but neither reached levels associated with significant health risks (16.7% and 3.94%, respectively). The average changes were modelled using first-order (linear) polynomials: Oxygen conc. (%) at time t (min) = 20.47 - 0.06 * t \[r^2 = 0.994\] Equation 4
Carbon dioxide conc. (%) at time t (min) = 0.129 + 0.063 * t \[r^2 = 0.997\] Equation 5
In addition, the water vapour content (humidity) of the air within the shelter simulator gradually rose, terminating with a relative humidity of approximately 90%.
The increasing humidity of the trapped air progressively reduced evaporative cooling, and led to an inexorable rise in core temperature (0.03 °C.min⁻¹). Using data from every subject beyond the first 10 min of exposure, an equation was derived for predicting these core temperature changes:

\[
\text{Core temperature (°C) at time } t \text{ (min)} = 37.45 + 0.03 \times t \quad [r^2 = 0.990]
\]

Equation 8

However, assuming an initial core temperature of 38.0°C, neither a 2°C core temperature elevation nor a core temperature of 42°C would be anticipated to occur within 60 min of entering a bushfire shelter.

From these trials, it was concluded that an appropriately insulated shelter, that was also isolated from the surrounding conditions and retained its integrity during a bushfire, would not experience a dangerous elevation in air temperature. Furthermore, the changes in oxygen and carbon dioxide concentration that accompany an enclosed occupancy would not reach levels associated with significant health risks. However, the humidity of this air would gradually rise, suppressing the evaporation of sweat, and producing in a linear elevation in core temperature beyond the first 10 min of exposure. Nevertheless, this rise did not appear to approach either a 2°C increase or a value of 42°C during a 60-min exposure. Thus, it again appeared that the current specifications (Australian Building Codes Board, 2010) were conducive to human survival.

4.1.2.3 Remaining unknowns

It has been shown that exposure to a constant Modified Discomfort Index of 39° for 60 min in healthy, heated and mildly dehydrated individuals is not associated with intolerable thermal
strain. Through the exposure of healthy and heated, but well hydrated individuals to an initial Modified Discomfort Index of 39° within an air-tight chamber (60 min), the worst-case status of the air within such a shelter has been identified. Under these conditions, well-hydrated subjects able to tolerate enclosure, albeit now with significant physiological strain. The remaining uncertainty is whether heated and mildly dehydrated men and women can also tolerate these conditions, since these are characteristics of the people most likely to be taking shelter from a bushfire.

4.1.3 Aims of this study

Accordingly, now that the thermal profile of the bushfire shelter has been identified, these conditions need to be investigated using men and women who have been pre-heated and dehydrated (2%), since these physiological states can degrade subsequent thermal tolerance (Montain and Coyle, 1992). In this, the third experiment from this series, an answer to the following question was sought (Patterson, 2010):

“What is the rise in body core temperature during a 1-hour exposure in an enclosed room that has an increasing temperature and relative humidity?”

4.2. METHODS

4.2.1 Subjects

Sixteen healthy adults, aged 19-26 years, participated in this study (Table 4.1), with each person being involved in two trials. Males and females were equally represented in the experiment, with subjects being recruited according to their body size, such that equal numbers
of individuals of large (mean: males: 2.01 m², females: 1.85 m²), medium (mean: males: 1.96 m², females: 1.67 m²) and small sizes (mean: males: 1.68 m², females: 1.51 m²) were studied within each gender. These sizes were based upon body surface area, since the exchange of thermal energy between the surrounding hot air and each individual (heat transfer) would occur through this surface. This heat is then retained or lost from the body mass, thereby determining body temperature. All participants provided written, informed consent, and were screened to eliminate those with a contraindicative history of cardiovascular or thermoregulatory problems. All procedures were approved by the Human Research Ethics Committee (University of Wollongong: HE 12/022). As with the previous experiments, young and healthy individuals were used in this experiment. This is not an accurate representation of the entire population. Groups such as the aged, young an infirm, may have different thermoregulatory capacities and such would not be represented within this study.

4.2.2 Experimental conditions and procedures

Subjects completed two experimental trials, each of which initially commenced at a Modified Discomfort Index of 38-39°. All testing was conducted at the same time of day, with subjects presenting in a well-hydrated and rested state. These trials matched the shelter conditions one and two found in Experiment One, and each state was achieved within a climate-controlled chamber that could independently regulate air temperature and relative humidity.

- Shelter condition one: Hot and humid: 40°C, 70% relative humidity.
- Shelter condition two: Hot and quite humid: 45°C, 50% relative humidity
Table 4.1: Subject characteristics (M = male, F = female).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group</th>
<th>Age (y)</th>
<th>Height (m)</th>
<th>Mass (kg)</th>
<th>Surface area (m²)</th>
<th>Surface area to mass (m².kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>M-Small</td>
<td>21</td>
<td>1.681</td>
<td>59.48</td>
<td>1.671</td>
<td>0.028</td>
</tr>
<tr>
<td>S2</td>
<td>M-Medium</td>
<td>26</td>
<td>1.85</td>
<td>74.06</td>
<td>1.966</td>
<td>0.027</td>
</tr>
<tr>
<td>S3</td>
<td>M-Large</td>
<td>19</td>
<td>1.75</td>
<td>94.7</td>
<td>2.097</td>
<td>0.022</td>
</tr>
<tr>
<td>S4</td>
<td>M-Medium</td>
<td>22</td>
<td>1.796</td>
<td>74.2</td>
<td>1.926</td>
<td>0.026</td>
</tr>
<tr>
<td>S5</td>
<td>M-Large</td>
<td>21</td>
<td>1.921</td>
<td>93.88</td>
<td>2.235</td>
<td>0.024</td>
</tr>
<tr>
<td>S6</td>
<td>M-Medium</td>
<td>20</td>
<td>1.781</td>
<td>82.1</td>
<td>1.998</td>
<td>0.024</td>
</tr>
<tr>
<td>S7</td>
<td>M-Small</td>
<td>21</td>
<td>1.655</td>
<td>63.24</td>
<td>1.696</td>
<td>0.027</td>
</tr>
<tr>
<td>S8</td>
<td>M-Large</td>
<td>22</td>
<td>1.874</td>
<td>93.52</td>
<td>2.192</td>
<td>0.023</td>
</tr>
<tr>
<td>S9</td>
<td>F-Small</td>
<td>20</td>
<td>1.561</td>
<td>54.06</td>
<td>1.521</td>
<td>0.028</td>
</tr>
<tr>
<td>S10</td>
<td>F-Large</td>
<td>20</td>
<td>1.791</td>
<td>72.1</td>
<td>1.899</td>
<td>0.026</td>
</tr>
<tr>
<td>S11</td>
<td>F-Small</td>
<td>23</td>
<td>1.563</td>
<td>51.24</td>
<td>1.488</td>
<td>0.029</td>
</tr>
<tr>
<td>S12</td>
<td>F-Medium</td>
<td>21</td>
<td>1.61</td>
<td>61.18</td>
<td>1.639</td>
<td>0.027</td>
</tr>
<tr>
<td>S13</td>
<td>F-Medium</td>
<td>20</td>
<td>1.683</td>
<td>61.14</td>
<td>1.692</td>
<td>0.028</td>
</tr>
<tr>
<td>S14</td>
<td>F-Large</td>
<td>24</td>
<td>1.756</td>
<td>71.52</td>
<td>1.865</td>
<td>0.026</td>
</tr>
<tr>
<td>S15</td>
<td>F-Small</td>
<td>22</td>
<td>1.582</td>
<td>52.22</td>
<td>1.513</td>
<td>0.029</td>
</tr>
<tr>
<td>S16</td>
<td>F-Large</td>
<td>23</td>
<td>1.698</td>
<td>68.02</td>
<td>1.782</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Table 4.2: Temperature and relative humidity profiles.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Shelter condition one</th>
<th>Shelter condition two</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air temperature (°C)</td>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>10</td>
<td>39</td>
<td>70</td>
</tr>
<tr>
<td>20</td>
<td>38.4</td>
<td>70</td>
</tr>
<tr>
<td>30</td>
<td>38.1</td>
<td>80</td>
</tr>
<tr>
<td>40</td>
<td>37.9</td>
<td>84</td>
</tr>
<tr>
<td>50</td>
<td>37.6</td>
<td>86</td>
</tr>
</tbody>
</table>
However, air temperature and relative humidity were changed at 10-min intervals (Table 4.2). These changes replicated those observed when well-hydrated and profusely sweating individuals were sealed within a heated, air-tight shelter (Experiment Two).

Since partial dehydration is associated with a faster rise in core temperature (Montain and Coyle, 1992), and since it is most likely that individuals taking refuge within a bushfire shelter will, by the nature of the scenario in which they find themselves, enter the shelter in a somewhat dehydrated state, then this hot-dehydrated state will more closely approximate reality. Indeed, it will also be closer to the worst-case scenario. To pre-heat each subject, a combination of water immersion (40°C: swimming costume) and exercise (treadmill walking: 6 km.h⁻¹: long-sleeved shirt and long trousers) was used. Whole-body water immersion can rapidly heat and cool people (Booth et al., 2004), and, if the water is hot enough, it will also induce significant thermal sweating, leading to progressive dehydration. Every subject experienced these two heat exposures in a moderately hyperthermic state (core temperature of 38.0°C) and with a dehydration level equivalent to a 2% loss in body mass.

In reality, core temperatures may be greater than either of these two states, but, for the purpose of tracking core temperature changes, and projecting these to either a critical core temperature of 42°C (Kenney et al., 2004) or a 2°C core temperature elevation (Ludovici et al., 2010), then it was essential to commence these exposures with a core temperature that had the capacity to rise at least 1°C before reaching the current ethical criterion for terminating such an experiment (39.5°C).
During the immersion phase, participants wore swimming costumes and sat within a stainless-steel seat and support frame that was lowered into, and removed from, the immersion tank using an electronic winch (150-kg lift capacity). A safety belt secured the subject to this frame to counter buoyancy affects, whilst also ensuring subject safety. Once the desired thermal state was obtained, the subject was removed from the water, and donned a long-sleeved shirt and long trousers for walking. This replicated typical clothing for this scenario. Alternating immersion and walking periods were then continued until both the target dehydration state (2% body mass reduction) and the thermal state were achieved.

Once these pre-experimental states had been attained, the resting thermal exposure commenced. Subjects removed clothing back to their swimming costumes and adopted a seated resting posture within the pre-heated, climate-controlled chamber. This was aimed at replicating typical behaviour for this scenario, and it also maximises heat dissipation.

4.2.3 Experimental standardisation

Subjects were required to refrain from strenuous exercise and the consumption of alcohol and tobacco during the 12 h prior to each trial. For the night prior to each trial, subjects were instructed to drink 15 mL.kg\(^{-1}\) of additional water before retiring, and to eat an evening meal and breakfast high in carbohydrate and low in fat. Subjects also refrained from using caffeine for 2 h prior to a trial. On arrival at the laboratory, subjects were provided with supplementary water (10 mL.kg\(^{-1}\)) if urine specific gravity was >1.029, and this ensured that each trial commenced with every participant in a euhydrated state (Armstrong et al., 1994). Before leaving the laboratory, subjects were rehydrated, consuming an iso-osmotic drink equivalent to 150% of the heat-induced body mass change.
4.2.4 Experimental measurements

Physiological, psychophysical and psychological measures included: body core temperature, skin temperature, heart rate, sweat rate, hydration status, psychophysical responses and psychological status.

4.2.4.1 Body tissue temperatures

4.2.4.1.1 Auditory canal temperature

Auditory canal temperature was monitored using an ear-moulded plug with a thermistor protruding 1 cm (Edale instruments Ltd., Cambridge, U.K.) and positioned within the external auditory meatus, and insulated with cotton wool. These data are shown in Figure 2.1, and show the capacity of auditory canal to track oesophageal temperature under these conditions (Cotter et al., 1995). In a pilot trial, four core temperature indices (auditory canal, rectal, oesophageal and GI) were studied during cold water immersion, followed by 45°C cycle ergometry, the results are graphed in Figure 2.1 in Chapter Two, they display auditory canal temperature tracking oesophageal temperature throughout the trial.

4.2.4.1.2 Skin temperatures

Skin temperatures were measured from four sites (chest, arm, thigh, leg: Type EU, Yellow Springs Instruments Co. Ltd., Yellow Springs, OH, U.S.A.), with data recorded throughout each trial at 15-s intervals (Grant Instruments Ltd., 1206 Series Squirrel, U.K.). Thermistors
were attached to the skin with a single layer of waterproof tape.

4.2.4.1.3 Mean skin and mean body temperatures

Mean skin temperature was derived using a weighted summation of the four skin temperatures (after Ramanathan, 1964):

\[ T_{\text{skin}} = 0.3 \left( T_{\text{chest}} + T_{\text{arm}} \right) + 0.2 \left( T_{\text{thigh}} + T_{\text{leg}} \right) \]  

Equation 2

Mean body temperature was then obtained from the weighted sum of the auditory canal and mean skin temperatures (Sugenoya and Ogawa, 1985; Vallerand et al., 1992):

\[ T_{\text{body}} = (0.9 \times T_{\text{core}}) + (0.1 \times T_{\text{skin}}) \]  

Equation 3

4.2.4.1.4 Thermistor calibration

Thermistors were calibrated against a certified reference thermometer in a stirred water bath across a range of static and physiologically relevant temperatures (Dobros total immersion, Dobbie Instruments, Sydney, Australia).

4.2.4.2 Heart rate

Heart rate was monitored continuously (15-s intervals) from ventricular depolarisation (Vantage NV, Polar Electro Sport Tester, Kempele, Finland).

4.2.4.3 Hydration state and whole-body sweat rate

4.2.4.3.1 Hydration state

Prior to commencing each trial, urine specific gravity was measured for each subject (Clinical Refractometer, Model 140, Shibuya Optical, Tokyo, Japan). This was necessary since it was
important to start these trials with subjects in a normally hydrated state. Urine specific gravity was measured again at the conclusion of each heat exposure.

4.2.4.3.2 Sweat rate

Gross mass changes (before and after each trial: ±20 g) were used to determine changes in whole-body sweating (fw-150k, A&D scale, CA, U.S.A.) over the course of each trial. Data were collected prior to entering, and immediately after leaving the simulator.

4.2.4.4 Psychophysical measures

Subjective reports of thermal sensation and thermal discomfort were recorded during a resting thermoneutral (baseline) state, just prior to commencing each heat exposure, and at 15-min intervals throughout each heat exposure. Familiarisation with each of the rating scales preceded the first trial, with subjects receiving standardised written instructions, with responses being prompted using the same question for each index.

4.2.4.4.1 Thermal sensation

Thermal sensation was monitored using a modified version of the Gagge scale (Gagge et al., 1967), where the end points were extended to enable a better resolution of thermal sensation. Subjects were asked: “How does the temperature of your body feel?”:

13-point thermal sensation scale
1  Unbearably cold
2  Extremely cold
3  Very cold
4  Cold
5  Cool
6  Slightly cool
7  Neutral
4.2.4.4.2 Thermal discomfort

Thermal discomfort was evaluated using another scale (Gagge et al., 1967), and in response to the question: “How comfortable do you feel with the temperature of your body?”.

The 5-point thermal discomfort scale
1.0 Comfortable
1.5
2.0 Slightly uncomfortable
2.5
3.0 Uncomfortable
3.5
4.0 Very uncomfortable
4.5
5.0 Extremely uncomfortable

4.2.5 Design and analyses

This project was based upon a repeated-measures experimental design, with subjects acting as their own controls and participating in both trials. Data were first analysed to provide standard descriptive parameters (means, standard errors), with subsequent comparisons performed using paired t-tests. Alpha was set at the 0.05 level for all statistical comparisons. Data are reported as means with standard errors of the means unless stated otherwise.
4.3 RESULTS

4.3.1 Pre-experimental physiological status

4.3.1.1 Thermoneutral physiological baselines

As with each of the other two experimental Chapters, it was essential to ensure that subjects presented for these trials in a well-rested and adequately hydrated state. Table 4.3 contains the resting, thermoneutral baseline data, which verify that the standardisation procedures resulted in these trials being conducted on euhydrated (Armstrong et al., 1994) and well-rested individuals.

4.3.1.2 Pre-exposure thermal status of subjects

Mild hyperthermia was to be induced for this series of experiments (38.0°C). Data collected immediately upon entering the simulator are contained within Table 4.4, from which it is evident that the desired thermal state was again achieved. It is also clear that this thermal state resulted in significant cardiovascular strain, as noted within the first two Chapters.

4.3.2 Experimental outcomes: physiological responses

4.3.2.1 Heart rate

As with the previous Chapters, the pre-exposure cardiovascular strain was carried over into the simulator (Figure 4.2A). Upon adopting a rested, seated position these declined, following the hot-water immersion and exercise. During shelter condition one (air temperature 40°C, 70% relative humidity) heart rate reached a steady state past the tenth minute (Figure 4.2A), with an average heart rate of 106 beats.min⁻¹. As with Experiment One, heart rate spikes can be observed every 15 min, these coincide with subjects standing for body-mass measurements.
Table 4.3: Thermoneutral (baseline) data prior to commencing the pre-heating treatment. Data are means with standard deviations in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Shelter condition</th>
<th>USG</th>
<th>HR (beats.min⁻¹)</th>
<th>Core temperature (°C)</th>
<th>Thermal sensation (1-13)</th>
<th>Thermal discomfort (1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>1.012 (0.008)</td>
<td>78 (16)</td>
<td>36.6 (0.3)</td>
<td>7.0 (0.4)</td>
<td>1.0 (0.1)</td>
</tr>
<tr>
<td>Two</td>
<td>1.014 (0.006)</td>
<td>72 (15)</td>
<td>36.3 (0.3)</td>
<td>6.9 (0.4)</td>
<td>1.0 (0.0)</td>
</tr>
</tbody>
</table>

Notes: Shelter condition one: 40°C and 70% relative humidity; Shelter condition two: 45°C and 50% relative humidity; USG = urine specific gravity; HR = heart rate (beats.min⁻¹).

Table 4.4: Pre-heated physiological data collected 15 s after entering the simulator. Data are means with standard deviations in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Heart rate (beats.min⁻¹)</th>
<th>Core temperature (°C)</th>
<th>Skin temperature (°C)</th>
<th>Thermal sensation (1-13)</th>
<th>Thermal discomfort (1-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>131 (24)</td>
<td>38.0 (0.1)</td>
<td>34.0 (1.9)</td>
<td>9.6 (1.0)</td>
<td>2.2 (0.7)</td>
</tr>
<tr>
<td>129 (22)</td>
<td>38.1 (0.1)</td>
<td>36.5 (0.7)</td>
<td>9.7 (1.1)</td>
<td>2.5 (0.6)</td>
</tr>
</tbody>
</table>
In contrast, in shelter condition two, heart rate increased in a linear fashion from the 10th minute, although spikes during body-mass measurements is still evident (Figure 4.2B). Heart rate rose, on average 1.5 beats.min⁻¹, with an average of 138 beats.min⁻¹ for the entire exposure. Therefore, even though both trials began at a similar Modified Discomfort Index (38-39⁰), a greater cardiovascular strain occurred during shelter condition two. The failing air temperature and climbing relative humidity can explain this occurrence. At the termination of both trials the Modified Discomfort temperatures were 37-38⁰ (shelter condition one) and 43-44⁰ (shelter condition two). This difference of 6⁰ will explain the contrasting heart rate responses observed for each exposure. This ratifies how difficult it is to use a comfort index to control and equate physiological strain.

4.3.2.2 Core temperature

In contrast to Experiment One, where core temperature declined once a resting, seating position occurred, subjects had an obvious and pronounced elevation in core temperature (Figure 4.3). This trend is more consistent with the findings of Experiment Two. In shelter condition one (air temperature 40⁰C, 70% relative humidity), the rise in core temperature occurred after 30 min of exposure (Figure 4.3A). Whereas, in shelter condition two (air temperature 50⁰C, 50% relative humidity) this elevation began after 10 min of exposure (Figure 4.3B).

The consistency found between trials and genders is remarkable (Figures 4.3A and 4.3C). In respect to core temperature male and female subjects reacted identically, this is to be somewhat expected as women seem to be able to regulate temperature better at high humidities, so the gender gap would decrease (Shapiro et al., 1980). As such, subjects were treated as equal a
group henceforth, collective data are presented in Figures 4.2B and 4.2D.

Core temperature for every subject remained below 40°C in both shelter conditions, with only one subject (S13) having to terminate due to ethical termination requirements (39.5°C) during shelter condition two (air temperature 45°C, 50% relative humidity). This was not considered an issue as termination occurred at 57 min of a 60 min exposure, at that point in time the subject had only had an elevation in core temperature of 1.5°C having entered at chamber in a mildly hyperthermic state (38.0°C). Across all subjects the average change in core temperature for the exposure was only 1°C.

Following an initial decline, for both conditions, core temperature rose. For shelter condition one (air temperature 40°C, 70% relative humidity), core temperature rose to the shelter entry value (38.0°C) during the 60-min exposure (Figure 4.3B), with the highest terminating core temperature being 38.3°C (S13). Comparing core temperatures for the same shelter condition in Chapter two (Figure 4.3B), it can be noted firstly that the entry value is much higher for Chapter two (38.5°C). However, the second thing to note is that subjects cooled to a remarkably similar temperature. The step-wise increase in relative humidity (Table 4.2) occurring during this series of experiments reduced the evaporative heat loss of subjects by progressively saturating the surrounding air causing a failure to maintain core temperature at the steady state, which occurred during Experiment One.
Figure 4.1: Heart rate responses of pre-heated subjects (core temperature 38.0°C) during two seated, resting trials. Each trial commenced at a Modified Discomfort Index of 39°, with air temperature and humidity then modified at 10-min intervals to replicate changes observed within an air-tight shelter simulator (Chapter three). 1A (upper): Shelter condition one (air temperature 40°C, 70% relative humidity). 1B (lower): Shelter condition two (45°C, 50% relative humidity). Data are means with standard errors of the means at 2.5-min intervals (N = 16).
Shelter condition two, had the same humidity changes at 10 min intervals (Table 4.2), however, at the termination of trials a $6^\circ$ higher Modified Discomfort Index was present than in shelter condition one. This became pronounced when core temperature data were examined (Figure 4.3D). Beyond, the tenth min core temperature rose in a monotonic fashion (Table 4.5), with an average of $0.04^\circ \text{C.min}^{-1}$ across all subjects ($r^2 = 0.996$). Also displayed on Figure 4.3D are data from Experiments Two and Three for the same starting shelter, the only different being in pre-heating. During Experiment Two, subjects were able to cool to $< 37.6^\circ \text{C}$, but during this series of experiments and Experiment Three subjects showed no ability to regulate core temperature. The time series for this series of experiments ($0.04^\circ \text{C.min}^{-1}$) and Chapter three ($0.03^\circ \text{C.min}^{-1}$) run in parallel to one another. From these relationships, the following equations were derived to predict changes in core temperature:

**Chapter three:**

$$\text{Core temperature (}^\circ \text{C}) \text{ at time } t \text{ (min)} = 37.45 + 0.03 \times t \quad [r^2 = 0.990] \quad \text{Equation 8}$$

**Chapter four:**

$$\text{Core temperature (}^\circ \text{C}) \text{ at time } t \text{ (min)} = 37.03 + 0.04 \times t \quad [r^2 = 0.996] \quad \text{Equation 9}$$

Study of the second equation enables the prediction when a $2^\circ \text{C}$ core temperature elevation would occur after 68 min of the exposure, whilst a core temperature of $42^\circ \text{C}$ would be experienced after 125 min of exposure in these conditions. Both of these temperature points would occur beyond the required duration of occupancy (60 min) specified within the standard (Australian Building Codes Board, 2010), with the latter eventuating at over twice the required duration. However, the former, whilst still occurring outside the suggested period of occupancy is close to the limit of time. As such specific populations who have poor or compromised thermoregulatory systems, such as the elderly, young or infirm, may experience a $2^\circ \text{C}$ rise in core temperature before the 60 min period.
Figure 4.2: Body core temperatures of pre-heated subjects (core temperature 38.0°C) during two seated, resting trials. Each trial commenced at a Modified Discomfort Index of 39°, with air temperature and humidity then modified at 10-min intervals to replicate changes observed within an air-tight shelter simulator (Chapter three). 2A (upper left): Male and female subjects: shelter condition one (air temperature 40°C, 70% relative humidity). 2B (upper right): Comparison of data for shelter condition one from Chapter two and three (red curve). 2C (lower left): Male and female subjects: shelter condition two (air temperature 45°C, 50% relative humidity). 2D (upper right): Comparison of data for shelter condition two from Chapter two, three (red curve) and four (blue curve). Data are means with standard errors of the means at 2.5-min intervals (N=16).
Table 4.5: Linear regression parameters for changes in core temperature, with rates of core temperature change also presented.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Correlation coefficient</th>
<th>Intercept</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.995</td>
<td>36.84</td>
<td>0.033</td>
</tr>
<tr>
<td>S2</td>
<td>0.997</td>
<td>36.95</td>
<td>0.035</td>
</tr>
<tr>
<td>S3</td>
<td>0.983</td>
<td>37.06</td>
<td>0.037</td>
</tr>
<tr>
<td>S4</td>
<td>0.996</td>
<td>36.86</td>
<td>0.036</td>
</tr>
<tr>
<td>S5</td>
<td>0.993</td>
<td>36.64</td>
<td>0.036</td>
</tr>
<tr>
<td>S6</td>
<td>0.996</td>
<td>36.97</td>
<td>0.035</td>
</tr>
<tr>
<td>S7</td>
<td>0.999</td>
<td>37.17</td>
<td>0.035</td>
</tr>
<tr>
<td>S8</td>
<td>0.999</td>
<td>36.89</td>
<td>0.039</td>
</tr>
<tr>
<td>S9</td>
<td>0.996</td>
<td>37.1</td>
<td>0.034</td>
</tr>
<tr>
<td>S10</td>
<td>0.997</td>
<td>37.23</td>
<td>0.032</td>
</tr>
<tr>
<td>S11</td>
<td>0.999</td>
<td>37.01</td>
<td>0.037</td>
</tr>
<tr>
<td>S12</td>
<td>0.997</td>
<td>37.35</td>
<td>0.028</td>
</tr>
<tr>
<td>S13</td>
<td>0.997</td>
<td>37.12</td>
<td>0.041</td>
</tr>
<tr>
<td>S14</td>
<td>0.998</td>
<td>37.27</td>
<td>0.029</td>
</tr>
<tr>
<td>S15</td>
<td>0.999</td>
<td>37.2</td>
<td>0.035</td>
</tr>
<tr>
<td>S16</td>
<td>0.996</td>
<td>36.74</td>
<td>0.035</td>
</tr>
<tr>
<td>Mean</td>
<td>0.996</td>
<td>37.03</td>
<td>0.035</td>
</tr>
<tr>
<td>SD</td>
<td>0.004</td>
<td>0.2</td>
<td>0.003</td>
</tr>
</tbody>
</table>
4.3.2.3 Skin temperature

Resulting skin temperature responses from the two exposures are illustrated in Figure 4.4. A vertical displacement of \( \sim 0.5^\circ C \) between the two conditions that was consistent with the air temperature difference across these trials. In shelter condition one (air temperature 40\(^{\circ}\)C, 70\% relative humidity), skin temperature rose to until it matched the subsequent skin temperature at the same stage in shelter condition two (air temperature 45\(^{\circ}\)C, 50\% relative humidity); 36.7\(^{\circ}\)C (SD 1.0) versus 36.7\(^{\circ}\)C (SD 0.3). At no point during the trial did core temperature exceed that of skin, enabling conductive and convective (mass flow) delivery of thermal energy to the skin for is subsequent dissipation.

4.3.2.4 Whole-body sweat rate

As with the previous Chapters, air temperature always exceed that of core and skin temperatures. This means that the only avenue remaining for heat loss was through the evaporation of sweat. However, it gradually became ineffective during these trials, due to the incremental elevations in humidity and its associated reduction water vapour pressure gradient between the skin and air. As a result, subjects were unable to regulate core and skin temperatures, results in a powerful sweating response with mean sweat rates of 0.77L.hr\(^{-1}\) (shelter condition one) and 0.96L.hr\(^{-1}\) (shelter condition two). Urine specific gravity was significantly elevated at the conclusion of the trials: 0.022 and 0.027 (\(P<0.05\)).
Figure 4.3: Skin temperature changes in pre-heated subjects (core temperature 38.0°C) during two seated, resting trials. Each trial commenced at a Modified Discomfort Index of 39°, with air temperature and humidity then modified at 10-min intervals to replicate changes observed within an air-tight shelter simulator (Chapter three). 3A (upper): Shelter condition one (air temperature 40°C, 70% relative humidity). 3B (lower): Shelter condition two (45°C, 50% relative humidity). Data are means with standard errors of the means at 2.5-min intervals (N = 16).
Table 4.6: Thermal sensation (scale: 1-13) and discomfort votes (scale: 1-5). Data are means with standard errors of the means in parenthesis (N=16).

<table>
<thead>
<tr>
<th>Trial stage</th>
<th>Shelter condition one</th>
<th></th>
<th>Shelter condition two</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensation</td>
<td>Discomfort</td>
<td>Sensation</td>
<td>Discomfort</td>
</tr>
<tr>
<td>Baseline</td>
<td>7.0 (0.4)</td>
<td>1.0 (0.1)</td>
<td>6.9 (0.4)</td>
<td>1.0 (0.0)</td>
</tr>
<tr>
<td>0 min</td>
<td>9.6 (0.24)</td>
<td>2.8 (0.18)</td>
<td>9.7 (0.28)</td>
<td>2.5 (0.14)</td>
</tr>
<tr>
<td>15 min</td>
<td>8.3 (0.23)</td>
<td>2.3 (0.16)</td>
<td>10.3 (0.24)</td>
<td>2.9 (0.15)</td>
</tr>
<tr>
<td>30 min</td>
<td>7.9 (0.18)</td>
<td>1.8 (0.16)</td>
<td>10.9 (0.22)</td>
<td>3.3 (0.13)</td>
</tr>
<tr>
<td>45 min</td>
<td>8.8 (0.14)</td>
<td>2.4 (0.13)</td>
<td>11.6 (0.24)</td>
<td>3.7 (0.19)</td>
</tr>
<tr>
<td>60 min</td>
<td>9.5 (0.16)</td>
<td>2.8 (0.14)</td>
<td>12.0 (0.17)</td>
<td>4.1 (0.17)</td>
</tr>
</tbody>
</table>
4.3.2.5 Psychophysical indices

The psychophysical indices followed very predictable responses (Table 4.6). These subjective evaluations were elevated from the start of each exposure, due to pre-heating procedure. Both indices gradually increased during the course of the second trial (condition two). Under the more humid conditions experienced in that trial, this subjective rating of thermal sensation is driven primarily by the accumulation of moisture, through sweat on the skin surface (Boutcher et al., 1995).

4.4 DISCUSSION

This experiment aimed at evaluating the influence of progressively changing humidity and temperature conditions that would exist within an air-tight bushfire shelter. These changes were determined to represent the likely worst-case shelter conditions. The changing bushfire shelter profile was then evaluated using pre-heated and dehydrated individuals. This was critical, as core temperature has been found to rise at a faster rate in dehydrated individuals than it does in those who are adequately hydrated (Montain and Coyle, 1992), and so the core temperatures of these occupants was monitored, to determine if the likely worst-case bushfire shelter profile was tenable when dehydrated occupants were using seeking refuge in a bushfire shelter. No previous research had been conducted under conditions such as these, where humidity and temperature were progressively increasing. The results from these trials have revealed that mild dehydration does not cause core temperature to rise fast enough to pose a significant health risk to occupants of a bushfire shelter built according to the thermal and structural standards specified by the Australian Building Codes Board (2010).
4.4.1 Physiological responses

4.4.1.1 Cardiovascular responses

The heart rate responses in this experiment were elevated above resting heart rate, with 13 subjects recording peak heart rate values in excess of 140 beats.min\(^{-1}\). This value represents 70% of the group average theoretical maximum heart rate by the end of these exposures. This was again attributed to the influence of hyperthermia on skin blood flow (Fox et al., 1963; Rowell et al., 1970; Neilsen et al., 1993). Increasing skin blood flow will eventually cause a decline in central venous pressure which per the Frank-Starling Law means a decline in stroke volume, leading to an increased heart rate to maintain cardiac output.

However, dehydration in the heat has also been shown to significantly increase heart rate as well (Saltin, 1964; Montain and Coyle, 1992; Gonzalez-Alonso et al., 1997). A loss of fluid leads will lead to a decrease in blood volume (hypovolaemia). As hypovolaemia occurs central venous pressure decreases leading to vasoconstriction of the peripheral blood vessels, which opposes the vasodilation occurring during hyperthermia (Morimoto, 1990). If blood vessels remained rigid and cardiac output is not regulated during hypovolaemia, a lower blood volume will result in hypotension (low blood pressure). Blood pressure regulation takes precedence over temperature regulation, considering low pressures do not allow adequate tissue perfusion (Kenney et al., 2013), as this may result in cell damage. Therefore, an attempt to maintain blood pressure must occur. Hypovolaemia will induce a lower central venous pressure, thereby resulting in a smaller stroke volume (Frank-Starling Law). This will activate the baroreflex, which is a negative feedback loop. A negative feedback loop is a regulatory mechanism in which the stimulus causes a decrease in the output of a system in this case a decrease in the baroreflex response.
The response of the baroreflex is to maintain blood pressure. It responds in that if a lower blood pressure is detected, a nerve transmission is sent to the medulla to stimulate the sympathetic nervous system, resulting in an increased heart rate and cardiac output in order to maintain blood pressure (Sawka et al., 1985; Coyle and Gonzalez-Alonso, 1998).

4.4.1.2 Thermal responses

A net gain of thermal energy occurred in all individuals. This is a function of the progressively increasing humidity during the trials and air temperature exceeding that of body temperature. High humidity minimises the loss of heat via evaporation by saturating the air with water molecules, causing heat to be retained (Herrington et al., 1937; McArdle et al., 1947).

However, humidity is not the only factor playing a role in increasing the rate of the core temperature increase in this experiment. Previous authors have shown that a faster rise in core temperature occurs when individuals are dehydrated (Ekblom et al., 1970; Montain and Coyle, 1992). Dehydration of only 1\% has been shown to be associated with 0.3°C per minute faster rise in core temperature during desert walking (Adolf, 1947). It has been shown that the thermal strain associated with a heat exposure increases in proportion the severity of the dehydration, with a significant increase in thermal strain being found at 5\% dehydration (Sawka et al., 1985). These increases in thermal strain can be brought about from either a greater metabolic heat production or a slower heat dissipation. Considering dehydration does not influence the rate of aerobic or anaerobic metabolic heat production (Greenleaf and Castle, 1971; Sawka et al., 1983) it must be the decreased heat dissipation that is responsible.

Dehydration from excessive sweating causes both hypovolaemia (decreased blood volume) and
hyperosmolality (increased concentration of the electrolytes in the blood), both of which will influence the regulation of body temperature by suppressing evaporative cooling leading to a faster rise in core temperature (Senay, 1968; Nadel et al., 1980).

Hypovolaemia will cause a faster rise in core temperature by decreasing the rate of sweat production (Morimoto, 1990). A shift in blood to the periphery lowers central venous pressure creating a lower atrial filling pressure. Pressure in the atria is detected by baroreceptors, and in this instance a low pressure is detected and baroreceptor function decreases. Information is then assessed by the hypothalamus to provide an effector response, in this case that is a lower sweating to preserve hydration status and maintain blood pressure (Neilsen et al., 1971; Nadel et al., 1980, Sawka et al., 1985).

A strong correlation between hyperosmolality and a decreased sweat rate has been found (Senay, 1968). This noted decrease in sweat rate is caused by alterations in the neurons that control sweating in the hypothalamus (Armatruda and Welt, 1953; Myers and Veale, 1970). However, the exact mechanism through which this occurs is unknown. Many studies suggest that hydration status is monitored by osmoreceptors of the hypothalamus which detect changes in the osmolality of the blood (Nielsen, 1974; Thornton, 2010). Hyperosmolality is detected by the hypothalamus, and results in a decreased sweat rate to maintain hydration status and maintain the serum concentration.

However, the reason that these core temperature elevations occurred at a faster rate could also be partially explained by the test of thermodynamics on inanimate objects in Experiment One, since spheres which were cooler prior to experiencing an elevation in temperature rose at a
faster rate than those starting at a higher temperature. This is because Newton’s Law of Cooling states that the rate of change of the temperature of an object is proportional to the difference between the object’s surface temperature and the ambient temperature. Similarly during this experiment, occupants were found to cool to a greater degree before core temperature rose compared to the subjects in Experiment Two. This increased the gradient between the subject’s skin temperature and the ambient temperature, and this could explain why core temperature rose at a faster rate during Experiment Three compared to Experiment Two.

4.5. CONCLUSION

Experiment Two enabled an identification of a worst-case thermal profile for a bushfire shelter. However, is was unclear as to how this profile would influence a pre-heated (38.0°C) and mildly dehydrated individual. Considering dehydration is associated with a faster rise in core temperature it was necessary to conduct experiments to determine how it would impact upon occupants of a bushfire shelter (Ekblom et al., 1969; Montain and Coyle, 1992).

To determine the influence of dehydration, in Experiment Three male and female subjects of varying body sizes were pre-heated (38.0°C) and mildly dehydrated (2%) and then exposed to the worst-case thermal profile for 60 min. The results reveal that an elevation of 2°C in core temperature will not occur until the 68 min of exposure, and a core temperature of 42°C will not be achieved until 125 min (equation 9). Both of these fall outside the expected 60-min exposure outlined by the Australian Building Codes Board (2010).

However it should be noted that due to restrictions in the thermally regulated climate chamber,
we were unable to test shelter condition three (50°C, 30% relative humidity). This is because
the chamber is unable to maintain such a high temperature with the high humidity that was
required during this study. Based upon the results of Experiment One it can be speculated that
shelter condition three would provide a greater physiological strain than the other two
conditions. Speculation beyond this is tenuous at best without further data.

Therefore, it can be concluded that from this experiment, a bushfire shelter adhering to the
standards of the Australian Building Codes Board (2010) would support human survival during
a 60-min exposure for two out three of the shelter conditions that occur within the thermal
standard of 39° Modified Discomfort Index.
4.6. REFERENCES


5.1 CONCLUSIONS

Australia is prone to severe bushfires which pose a threat to the populace, and in fact during the 2009 Victorian bushfires 173 lives were lost. This prompted the initiative to develop a standard for bushfire shelters, which did not exist anywhere else in the world thus had to be developed on first terms basis. As such this study was conducted.

The principal aim of this series of experiments was to determine the efficacy of the thermal standard for bushfire shelters, with success being determined by the maintenance of core temperature below 42°C or preventing a rise of 2°C in one hour (Australian Building Codes Board, 2010). In this regard, a three-phased research project was conducted.

The first experiment had subjects exposed to the thermal standard of 39° Modified Discomfort Index for 60-min across its entire range, considering it can be achieved from a wide combination of air temperature and water vapour pressures this was deemed necessary to determine if the thermal standard would support adequate core temperature maintenance (Chapter Two). However, the presence of an occupant in a bushfire shelter would alter the internal environment of a shelter through respiration and thermoregulatory responses such as sweating. Therefore, in Experiment Two, occupants were exposed to conditions equalling a Modified Discomfort Index of 39° in an air-tight simulator (1.2m³: 2010) for 60 min (Chapter Three). Not only was the physiological strain of occupants monitored throughout this exposure but so to was the thermal conditions of the simulator. In the final experiment, the average change in air temperature and humidity which was found in Experiment Two was applied to
mildly dehydrated individuals in 10 min increments for 60 min (Chapter Four), this is necessary as dehydration is associated with a faster rise in core temperature (Montain and Coyle, 1992).

In a series of six experiments performed in Experiment One of this investigation, we tested the hypothesis that a Modified Discomfort Index of 39°C would not elicit a rise of core temperature to 39.5°C. The results revealed that pre-heated (38.5°C), mildly dehydrated subjects are able to tolerate the thermal standard of 39°C Modified Discomfort Index, for 60 min without a rise in core temperature. In fact, a decrease in core temperature occurred, and this decrease was apparent regardless of the combinations of air temperature and humidity used to determine the Modified Discomfort Index of 39°C.

Accordingly, subsequent experiments were conducted to determine the characteristics of an air-tight bushfire shelter in response to occupancy by a pre-heated (38.0°C), euhydrated individual, and the impact of these changes on physiological function (Chapter Three). Of particular interest were the concentrations of oxygen and carbon dioxide changes throughout the exposure. However, these concentrations were found not to alter to a level which would cause a significant health risk during a 60 min occupancy. The presence of a sweating individual in a hot environment will increase the water vapour pressure of the air, and in an air-tight simulator, water vapour pressure climbed exponentially throughout the exposure terminating at ~90%. This high water vapour pressure impaired the loss of heat via evaporation, and caused a 0.03°C.min⁻¹ rise in core temperature. However, these elevations on average, did not cause core temperature to exceed 39.5°C and therefore will not pose a health risk in a healthy individual, at least within the confines of the current experimental specifications.
Chapter Three enabled an identification of a likely worst-case thermal profile for a bushfire shelter. However, as the hydration state was to be maintained throughout this exposure it is was unclear as to how this profile would influence a pre-heated (38.0°C) and mildly dehydrated individual, as dehydration is associated with a faster rise in core temperature it was necessary to conduct experiments to determine how mild dehydration would impact occupants of a bushfire shelter (Ekblom et al., 1969; Montain and Coyle, 1992). This occurred in the final experiment of this study.

Finally, in Chapter Four male and female subjects of varying body sizes were pre-heated (38.0°C) and mildly dehydrated (2%) and then exposed to the likely worst-case thermal profile derived in Chapter Three for 60 min. It was hypothesised that core temperature would rise throughout the exposures. However, prediction equations would show that this rise would not cause core temperature to exceed 42°C. As would be expected from the results of previous studies, core temperature rose at a slightly faster rate when mild dehydration is induced prior to the exposure (Ekblom et al., 1969; Montain and Coyle, 1992). The core temperature of the subjects on average rose at a rate of 0.04°C.min⁻¹. However, these elevations caused core temperature to reach 39.5°C in only one subject. Moreover, it was derived from prediction equation 9 that a core temperature of 42°C would not occur until 125 min of exposure, which falls well outside the expected 60 min exposure outlined by the Australian Building Codes Board (2010).

It should be noted that we could not test shelter condition three (50°C, 30% relative humidity) due to an inability to sustain such a high temperature with a high humidity inside the thermally regulated climate chamber. Therefore it could not be predicted what would occur in conditions
such as these, however based on the results found in Chapter Two, this condition provided the most physiological strain and as such it would be expected that this trend would continue in conditions where humidity and temperature were changing. However, from this series of experiments, it can be concluded that a bushfire shelter adhering to the standards of the Australian Building Codes Board (2010), would facilitate life for a 60 min exposure in two out of three shelter conditions that satisfy the thermal standard of 39° Modified Discomfort Index.

It should be noted that the conclusions derived from this study were from a specific set of thermal conditions. Alterations from the air temperature and relative humidity values used in this study would yield a different result.

5.2 RECOMMENDATIONS

Whilst a tenable environment has been shown to be maintained, when dehydrated individuals are exposed to a likely worst-case bushfire shelter scenario, one could assume no further research needed to occur in the matter. However, it could be argued for a need to further investigate the influence of the high level of anxiety, which was observed in shelter occupants (Experiment Two). A high level of anxiety in a tightly enclosed space like a bushfire shelter would be of particular concern if a community or family shelter were to be considered, where multiple occupants would be present in a confined and stressful environment.

Therefore, a logical first study following the present investigation is to further examine the psychological impact of being exposed to the conditions found in a bushfire shelter and the social implications of these, particularly if family or community shelters were to be considered. Previous studies into bomb shelters have delved somewhat into family shelters (Murray, 1960;
Thor and Crawford, 1964). Findings showed that prolonged exposure to a crowded bomb shelter can cause a decrease in concentration, increased irritability and depression in male occupants during hot environments (Murray, 1960). However in such scenarios an attempt to maintain environmental conditions at a comfortable level occurred. This would be not be the case for a community bushfire shelter where conditions would be hot and humid inside the shelter, and would most likely become progressively less comfortable as the exposure continued (Experiment Two). The results of this study have shown these conditions would place physiological strain on the occupants, a key factor found with increasing physiological stress is increasing frustration, which is often expressed in the form of aggression (Dollard et al., 1939). Individual expressions of frustration can be many and varied, for example depression, aggression, regression and withdrawal may be some manifestations of frustration. The manifestation of frustration in a confined space would almost certainly cause destruction of the interpersonal relationships of the occupants. Thus, there is a need to determine if the stress associated with the occupancy of a bushfire shelter would cause these psychological alterations to occur within the short occupancy period (60-min).

It has been shown that emotional stressors, such as the occupancy of a bushfire shelter, would induce hyperventilation (Suess et al., 1980). Indeed there have been strong links with hyperventilation and panic attacks, thus if hyperventilation was to occur a panic attack may follow in some populations (Gorman et al., 1986; Rainey et al., 2010). The basic theory with hyperventilation is that anyone who hyperventilates is likely to becomes anxious, and that a greater inclination to anxiety is an inclination to hyperventilation (Roth et al., 2000). Therefore, placing an individual in an environment such as a bushfire shelter which has the potential to cause anxiety also has the propensity to cause hyperventilation. This become even more important when considering a bushfire shelter is by necessity air-tight, therefore it has a
limited volume of air. This becomes of importance because hyperventilation through emotional stressors would alter the gas concentrations at a faster rate.

A rising carbon dioxide concentration and falling oxygen concentration also have a role in exasperating anxiety. Studies have shown that both hypercapnia and hypoxia can increase anxiety (Papp and Gorman, 1995; Beck et al., 1999). During experiences of hypercapnia a propensity to hyperventilate occurs in order to lower carbon dioxide levels (Roth et al., 2000), however in an environment such as a bushfire shelter where it is air-tight this will not work as it only adds to the carbon dioxide in the environment and increases the re-breathed concentration of carbon dioxide.

Another type of stress which could be a factor for psychological stress in a community bushfire shelter would be noise. Noise can impair concentration, produce irritability, fatigue and aggression (Broadbent, 1958). Not only will noise influence emotions but it will also place strain on an already stressed cardiovascular system. The World Health Organisation (1999) has shown a correlation between noise and hypertension. This is primarily due to the release of stress hormones, via the activation of the pituitary-adrenal-cortical axis (Babisch, 2003).
5.3 REFERENCES


