HUMAN TRIALS TO EVALUATE THERMAL PERFORMANCE SPECIFICATIONS FOR PRIVATE BUSHFIRE SHELTERS. 

PART 2: THE IMPACT OF CHANGES IN AIR TEMPERATURE, WATER VAPOUR PRESSURE AND CARBON DIOXIDE CONCENTRATION WITHIN AN AIR-TIGHT SHELTER SIMULATOR.

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**Human trials to evaluate thermal performance specifications for private bushfire shelters. Part 2: The impact of changes in air temperature, water vapour pressure and carbon dioxide concentration within an air-tight shelter simulator.**

**EXECUTIVE SUMMARY**

**General background:**
This investigation is the second of a series of three projects in which human subjects were tested under the maximal tenable conditions specified by the Australian Building Codes Board (2010) for private bushfire shelters. The need for shelter standards was identified by the Victorian Bushfires Royal Commission (2009), setup in response to the severe Victorian bushfires of 2009. The Board was advised that shelters that could restrict thermal stress to a maximal mean Modified Discomfort Index (MDI) of 39º would restrain the rise in core temperature to <2ºC, and would therefore support life during the critical occupancy phase. However, this thermal performance standard was not empirically derived via controlled physiological testing. In the first report from this experimental series (Taylor et al., 2012), along with observations from the current experiment undertaken by the Centre for Human and Applied Physiology (University of Wollongong), the outcomes of human physiological trials designed to evaluate the efficacy of this thermal performance standard are reported. The overall aim of this research was to provide the necessary experimental evidence for the Australian Building Codes Board to make informed decisions concerning this standard.

The current research was aimed at answering 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?”

**Overview of the research methods:**
In this experiment, 16 heat exposures were performed within a bespoke 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 39º (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 (humidity) 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 38.0ºC) 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 within the air-tight simulator were monitored continuously.

**Primary observations:**
The temperature of the air within this simulator 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:

\[
\text{Oxygen concentration (\%)} \text{ at time } t \text{ (min)} = 20.47 - 0.06 \times t \quad [r^2 = 0.994]
\]
\[
\text{Carbon dioxide concentration (\%)} \text{ at time } t \text{ (min)} = 0.129 + 0.063 \times t \quad [r^2 = 0.997]
\]

In addition, the water vapour content of the air within the shelter simulator gradually rose, terminating with a relative humidity of approximately 90%. This 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:

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

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.

**Conclusions:**
From these experiments, one may conclude that an appropriately insulated shelter that is isolated from the surrounding conditions, and that retains its integrity during a bushfire, will not experience a dangerous elevation in air temperature. Furthermore, the changes in oxygen and carbon dioxide concentration that accompany such an enclosed occupancy will not attain levels associated with significant health risks.

However, the water vapour content of this air will gradually rise, suppressing the evaporative cooling of sweat, and producing in a linear elevation in core temperature beyond the first 10 min of exposure. Nevertheless, this rise would not appear to approach either a 2°C increase or a value of 42°C during a 60-min exposure.

To this point, it appears that the current specifications (Australian Building Codes Board, 2010) are conducive to human survival. What now remains is to test the effects of these changes in air temperature and relative humidity on dehydrated individuals, as per experiment one of this series (Taylor *et al.*, 2012). That is, now that the worst-case thermal characteristics of a shelter have 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.
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1. INTRODUCTION

1.1 General background

This investigation is the second of a series of three research projects in which human subjects were tested under the maximal tenable conditions specified by the Australian Building Codes Board (2010) for private bushfire shelters. The need for shelter standards was identified by the Victorian Bushfires Royal Commission (2009), setup in response to the severe Victorian bushfires of 2009 that took 173 lives and caused more than $4 billion worth of damage. The Board was advised that shelters that could restrict thermal stress\(^1\) to a maximal mean Modified Discomfort Index (MDI) of 39\(^o\) would restrain the rise in core temperature to <2\(^o\)C (Ludovici et al., 2010), and would therefore support life during the critical, 60-min occupancy phase. However, this thermal performance standard was not empirically derived via controlled physiological testing, but instead arose from recommendations to set this standard on the basis of a thermal sensation (effective) scale rather than on a rational or heat strain scale. Thus, the thermal strain\(^2\) that may be expected to accompany such exposures remained both difficult to predict and unknown. In the first report from this experimental series (Taylor et al., 2012), along with results contained within the current report and the report that follows, researchers describe the outcomes of human trials in which the efficacy of this thermal performance standard was investigated. The overall aim of this research was to provide the necessary experimental evidence for the Australian Building Codes Board to make informed decisions concerning this standard.

1.2 Research background

In experiment one (Taylor et al., 2012), researchers performed a preliminary evaluation of thermal strain and heat tolerance during the 60-min exposure of sixteen individuals to three different thermal states (shelter conditions), each of which satisfied the Modified Discomfort Index standard of 39\(^o\). These exposures were conducted within a thermally regulated climate chamber, and with air temperature and relative humidity remaining constant. These conditions covered a 10\(^o\)C range in air temperature (40-50\(^o\)C) and a 40% range in relative humidity (30-70%):\(^3\)

\[\text{Shelter condition one: Hot and humid: 40\(^o\)C, 70% relative humidity.}\]
\[\text{Shelter condition two: Hot and quite humid: 45\(^o\)C, 50% relative humidity.}\]
\[\text{Shelter condition three: Very hot and dry: 50\(^o\)C, 30% relative humidity.}\]

From a first-principles understanding, the researchers knew 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 (Taylor et al., 2008). Thus, changes in water vapour pressure\(^3\) (relative humidity) would interact with air temperature and, in so doing, modify thermal strain and heat tolerance.

\(^1\) Stress is defined as any physical phenomenon that can be imposed upon the body (e.g. air temperature, relative humidity, changes in the composition of the air), resulting in a disturbance of homeostasis.

\(^2\) Strain refers to the physiological consequences of a stress that has been applied to the body, and is a measure of the extent of the resulting homeostatic disturbance (e.g. increased heart rate or core temperature).

\(^3\) Thermal energy moves continually from warmer to cooler regions (i.e. down the thermal gradient). Similarly, water vapour moves down a vapour pressure gradient. Therefore, for the evaporation of sweat (evaporative heat loss), the water vapour pressure of the air must remain less than that of the skin. In these experiments, air temperature and water vapour pressure were changed in opposite directions.
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 $39^\circ$ without experiencing either a critical core temperature of $42^\circ$C or a $2^\circ$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 $37.5^\circ$C) and moderate hyperthermia (core temperature $38.5^\circ$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. Accordingly, it was recommended that the Australian Building Codes Board should consider a modification of clause 3.2.1 of the performance standard to identify an elevated risk for such individuals.

On average, and across all three shelter conditions, the Modified Discomfort Index of $39^\circ$ was tolerated without either a core temperature of $42^\circ$C being obtained, or a $2^\circ$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 $39^\circ$, excessive hyperthermia in resting, semi-clothed young adults would be unlikely to occur.

Thus, this first experiment provided preliminary support for the specification of bushfire shelters to keep the internal conditions to a maximal mean Modified Discomfort Index of $39^\circ$ 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 the physiological impact of these changes were emphasised during this, the second experiment from this series.

1.2.1 Physiological consequences of an air-tight enclosure
Out of necessity, bushfire shelters must be air-tight to prevent the penetration of toxic gases that accompany structural and bushfires. Thus, the specifications for these shelters were determined with a view to supporting both the thermal tolerance and the respiratory gas
exchange requirements of individuals seeking refuge from bushfires. In the latter instance, this meant that, over a 60-min enclosure, the fractional concentration of oxygen must not decrease, nor the carbon dioxide concentration increase to intolerable levels. The calculations to determine the necessary internal fresh-air volume for each person are relatively simple, and these are well supported by the scientific evidence. However, since shelters must be airtight, then the oxygen concentration will be progressively reduced (mild hypoxia) and the carbon dioxide concentration must gradually rise (mild hypercapnia), and these changes are known to affect both sweating (Stokes et al., 1948; Bullard, 1964; Wood, 1991) and temperature regulation (Wright and Boulant, 2007).

Before discussing the implications of these gas composition changes, there are some more basic factors to first consider, and these relate to the changes in air temperature and humidity (water vapour content) that always occur when living organisms are enclosed within an airtight and insulated space. Humans continually lose moisture through the skin (transepidermal water loss). This will occur at rates between 25-75 g.h⁻¹ (Galeotti and Macri, 1914; Ikeuchi and Kuno, 1927; Burch and Sodeman, 1943; Park and Tamura, 1992; Machado et al., 2010), assuming a 1.8 m² body surface area. About 30 g.h⁻¹ is simultaneously lost from the respiratory surfaces (Benedict and Benedict, 1927). Thus, even without sweating, the water vapour pressure of the surrounding air must increase. Moreover, since the person within this enclosed space will continue to produce heat (thermal energy: 1.5 W.kg⁻¹: Berlin et al., 1975), which, for a resting, 75-kg adult within a thermoneutral environment, is dissipated to the surrounding air at a rate of about 5.4 kJ.min⁻¹ (assuming 20% metabolic efficiency: Berlin et al., 1975). Therefore, one may also expect to observe a gradual elevation in the temperature of an airtight, thermoneutral space (24-26°C). These first principles are universally accepted, and frequently experienced.

However, within this space, there will also be a gradual rise in the fractional concentration of carbon dioxide, and hypercapnia has long been known to stimulate sweating (Stokes et al., 1948; Bullard, 1964; Wood, 1991). Thus, in thermal conditions most alike those of the current shelter conditions (38° and 49°C), Bullard (1964) demonstrated that the inhalation of 6% carbon dioxide would elicit a significant elevation in sweat secretion. Within the current context, there are two implications for such an increase. Firstly, the moisture content (water vapour pressure) of the air within a sealed space will gradually rise. This will elevate thermal strain by reducing evaporative cooling. Secondly, a higher sweat rate will result in the gradual dehydration of the enclosed individual, and this too will elevate thermal strain. Indeed, partial dehydration is associated with a faster rise in core temperature (Montain and Coyle, 1992). Therefore, via each of these two mechanisms, one would predict that thermal strain would be greater within an air-tight shelter than within a climate chamber regulated at a constant air temperature and relative humidity, even though both chambers were initially equilibrated to a

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4 The current authors undertook an in-house safety confirmation: If one allows for an exaggerated resting oxygen consumption of 1 L.min⁻¹ (i.e. about four times greater than normal), then within 60 min, a resting individual would consume 60 L of oxygen. Since room air is about 21% oxygen, then this amount represents <25% of the oxygen volume specified by the ABCB standard (2010: 1.2 m³), and the final oxygen content of the room should remain >15%. In addition, if one assumes a respiratory exchange ratio of 0.83 (valid for resting individuals), then 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%.
Modified Discomfort Index of 39°.

However, the concentration of carbon dioxide was predicted to remain less than 5%\(^5\). When Bullard (1964) exposed subjects to a carbon dioxide concentration of 2.5% and an air temperature of 49°C, sweating remained largely unaffected, relative to that observed during the same thermal exposure without the carbon dioxide challenge. This condition was expected to most closely resemble that which may obtain at the end of a 60-min exposure within a sealed shelter that had an initial Modified Discomfort Index of 39°. Nevertheless, this required empirical confirmation, as did the thermal consequence of these changes.

At the same time as this hypercapnic stimulus is increasing, there will be a progressive reduction in the oxygen content of the enclosed space. This will also be a relatively mild stimulus. However, Kacin et al. (2007) have shown that a normobaric, hypoxic stimulus (13.5% oxygen) during exercise will also elevate sweat secretion, although this change may not be seen during hypobaric hypoxia (Kolka et al., 1987), and it appears not to occur when sweating is pharmacologically stimulated (DiPasquale et al., 2002). In fact, Kolka et al. (1987) and DiPasquale et al. (2002) observed lower sweat secretion in their experiments. Notwithstanding these experimental variations, which can largely be ascribed to differences in experimental design and the manner in which the hypoxic stimulus was applied, there is also an effect of hypoxia upon sweating and temperature regulation (Wood, 1991). Therefore, it was prudent to also consider these interactions upon thermal tolerance within the current experimental series.

1.3 Research aims

Accordingly, for people enclosed within an air-tight and insulated shelter, there will be 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 [occupancy] thermoregulation?”

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°C and a relative humidity of 50% (Modified Discomfort Index

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\(^5\) The final carbon dioxide concentration was predicted to be 4.8%, but to provide a significant safety margin, this prediction assumed a resting metabolic rate four times greater than normal. If the metabolic rate is halved, then the final carbon dioxide concentration would be 2.4%.
standard of 39ºC). 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 38.0ºC), 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 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).

2. METHODS
2.1 Subjects
Participants were 16 healthy, young males (Table 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).

<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>
</tbody>
</table>

The body core is made up from the deep body tissues. These tissues are within organs essential to life, and so physiological regulatory systems exist to prevent large temperature variations in these tissues. Thus, significant body core temperature changes only occur when people are exposed to more stressful thermal states.
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 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 the first experiment (Taylor et al., 2012). 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 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 the first experiment (Taylor et al., 2012). 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.
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 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 experimenters 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.

2.2.1 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. Before leaving the laboratory, 
subjects were rehydrated, consuming an iso-osmotic drink equivalent to 150% of the heat-
induced body mass change.

2.3 Experimental measurements
Physiological, psychophysical and psychological measures included: body core temperature, 
skin temperature, heart rate, sweat rate, hydration status, psychophysical responses and 
changes in psychological status (these last data are not reported in this communication). In 
addition, air temperature, relative humidity and the fractional concentrations of carbon 
dioxide and oxygen within the air-tight simulator were monitored continuously.

2.3.1 Body tissue temperatures
2.3.1.1 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. 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).
Data were recorded throughout each trial at 15-s intervals using a portable data logger (Grant 
2.3.1.2 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.

2.3.1.3 Mean skin and mean body temperatures
Mean skin temperature was derived using a weighted summation of the four skin temperatures (after Ramanathan, 1964):
\[ T_{skin} = 0.3 (T_{chest} + T_{arm}) + 0.2 (T_{thigh} + T_{leg}) \]
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):
\[ T_{body} = (0.9 * T_{core}) + (0.1 * T_{skin}) \]

2.3.1.4 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).

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

2.3.3 Hydration state and whole-body sweat rate
2.3.3.1 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.

2.3.3.2 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.

2.3.4 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.

2.3.4.1 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

2.3.4.2 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

2.3.5 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.).

2.4 Design and analysis
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. RESULTS AND DISCUSSION
3.1 Pre-experimental physiological status
3.1.1 Thermoneutral physiological baselines
As with the first phase of this experimental series, it was essential to ensure that subjects presented for this trial 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\(^7\), healthy and well-rested individuals.

Table 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 ((^\circ)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>

3.1.2 Pre-exposure thermal status of subjects
For this experiment, only one level of pre-exposure (mild-moderate) hyperthermia was induced, with a target core temperature of 38.0\(^\circ\) being sought. Data collected immediately upon entering the simulator are contained within Table 3, from which it is evident that the desired thermal state was successfully achieved. It is also clear that this thermal state resulted in significant cardiovascular strain, as noted within experiment one of this series (Taylor et al., 2012). Indeed, such thermal loading induces an elevation in cutaneous (skin) blood flow which facilitates the transfer of heat from the deep-body tissues to the skin surface for dissipation (convective heat delivery: Rowell et al., 1970; Taylor et al., 2008). The corresponding rise in heart rate is necessary to regulate blood pressure, for if cutaneous vasodilatation is not accompanied by an increase in the volume of blood that the heart pumps (cardiac output), then blood pressure will start to fall (Rowell et al., 1970).

Table 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 ((^\circ)C)</th>
<th>Skin temperature ((^\circ)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>

3.2 Experimental outcomes: physical status of the shelter simulator
3.2.1 Pre-experimental status of the simulator
Before participants entered the simulator, it was equilibrated (>30 min) to the conditions within the regulated outer chamber. This status is shown in Table 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.

Table 4: Shelter simulator data collected 15 s after subjects had entered the

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\(^7\) Hydration classifications based upon urine specific gravity: (a) well hydrated: <1.013; (b) euhydrated: 1.013-1.029; and (c) hypohydrated: >1.029 (Armstrong et al., 1994).
simulator. Data are means with standard deviations in parenthesis ($N=16$).

<table>
<thead>
<tr>
<th>Air temperature ($^\circ$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>

### 3.2.2 Shelter air temperature

Time series data for the changes in the temperature of the air within the shelter simulator are illustrated in Figure 3. Readers must recall that, within this experiment, the temperature and relative humidity within the air-tight and thermally insulated shelter simulator were regulated only up to the point at which the experimental subject entered the simulator. Beyond this time, both the subject, who had been pre-heated to approximately 38$^\circ$C, and the surrounding air within the shelter (Table 4), were isolated and insulated from the outer chamber. In this state, the temperature and relative humidity of this trapped air volume were now free to vary according to the heat and water vapour exchanges that would naturally occur between the occupant and the simulator over the 60-min occupancy.

Across every trial, the air temperature within the simulator declined in a curvilinear manner, such that, at the end of 60 min, the air temperature averaged 40.5$^\circ$C (SD 0.5), revealing a 3.2$^\circ$C reduction. For this to occur, a net loss of thermal energy from this trapped air to the occupants, or to the simulator, must have occurred. Since the shelter had been heated for $>30$ min prior to each exposure, then the latter exchange should have been minimal, although this possibility cannot not be excluded. Thus, it was more likely that the experimental subjects gained this heat, since they entered the shelter with a mean body temperature some 5.8$^\circ$C cooler than the initial air temperature of the simulator (Table 3).
Figure 3: Air temperature 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).

The vertical lines on Figure 3 show 10-min temperature changes. These will be used in the final experiment of this series, 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.

3.2.3 Shelter humidity
The relative humidity of the air within the shelter simulator demonstrated an approximately exponential rise over these 60-min exposures (Figure 4), terminating at an average of 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$^8$ of air next to each participant was relatively still, being influenced only by the natural convective flow of air over the body surface. 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.

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$^8$ Under relatively still conditions, the air in close proximity to the skin becomes warm and moist due to the transfer of heat from the skin, and the inexorable diffusion of water molecules through the skin and into this air. This air is known as the boundary layer, for it more closely approximates the thermal characteristics of the body than it does the surrounding (ambient) air. The thickness of this layer, however, is an inverse function of air velocity (relative or absolute).
**Figure 4:** 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).

On entering the simulator, the mean air temperature was 43.7°C and the relative humidity was 42.3% (Table 4). This equates to an initial water vapour pressure of 3.78 kPa. However, whilst the final air temperature fell to 40.5°C, the relative humidity climbed to 90.1%, resulting in a terminal water vapour pressure of 6.82 kPa. This represented an 80.6% increase (or 3.05 kPa) that was principally dictated by changes in the relative humidity (113.3% increase), since the change in air temperature was minimal (7.3%) and in the opposite direction. These conditions represent almost saturated air and, as such, permit only minimal sweat evaporation.

The vertical lines on Figure 4 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%.

### 3.2.4 Shelter oxygen concentration

The fractional concentration of oxygen within the shelter air decreased linearly over time (Figure 5), and this relationship was very strong ($r^2 = 0.994$), with the terminal oxygen concentrations averaging 16.7% (SD 0.8). This was, however, an entirely predictable outcome, due to the constant removal of oxygen from this air-tight space by the occupants, to support their steady-state metabolic rate. The only uncertainty within this prediction was the resting metabolic rate of the occupants within the simulator, which was known to vary as a function of body mass (Kleiber, 1947) and the level of physical activity at the time of measurement. 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. On average, these resting, but hyperthermic and sweating subjects consumed oxygen at the rate of 0.67 L.min$^{-1}$ (SD 0.20). This value is somewhat high for resting individuals, but hyperthermia will increase resting metabolic rate (Consolazio et al., 1963; Consolazio, 1964),

---

9 Water vapour pressure (kPa) = $\text{Exp}^{(16.6536-4030.183(\text{temperature (oC)}+235))}$ * relative humidity (%) [Santee and Gonzalez, 1988].

10 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$^{-1}$).
due to not just to the direct thermal influence upon chemical reactions (Q10 effect), but also due to heightened physiological responses (e.g. heart rate and sweat production). Thus, this first-principles approximation is not too unrealistic.

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:

\[ \text{Oxygen concentration (\%) at time } t \text{ (min)} = 20.47 - 0.06 \times t \quad [r^2 = 0.994]^{11} \]

Table 5 contains prediction times to reach concentrations of 19.5%, 13% and 10%.

3.2.5 Shelter carbon dioxide concentration

As each exposure progressed, the fractional concentration of carbon dioxide increased linearly (Figure 6; \( r^2 = 0.997 \)), with the terminal concentration averaging 3.94% (SD 0.72). This too was expected, permitting a prediction of the carbon dioxide concentration changes within an air-tight shelter constructed to these specifications. Thus (Table 5):

\[ \text{Carbon dioxide concentration (\%) at time } t \text{ (min)} = 0.129 + 0.063 \times t \quad [r^2 = 0.997] \]

Table 5 contains prediction times to reach concentrations of 4%, 5% and 7%.

---

11 The regression analyses for changes in oxygen and carbon dioxide concentration were performed using mean data only. This simplification ignores both the within- and between-subject variability. However, for the purpose of this exercise, this lack of precision can be tolerated. Indeed, the relative homogeneity of the sample meant that these gas concentrations followed quite similar relationships over time. This method was also applied to the modelling of the heart rate responses.
Figure 5: 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 6: 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 5: Predictions of times to reach different oxygen and carbon dioxide concentrations within an occupied, single-person bushfire shelter (1.2 m³).
<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; (c) 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; (c) 4%: Concentration deemed to be “immediately dangerous to life or health” (National Institute for Occupational Safety and Health (U.S.A.)).

Whilst it is suspected that these changes in the concentration of carbon dioxide further stimulated sweating (Stokes et al., 1948; Bullard, 1964; Wood, 1991), the extent to which this mechanism could explain the current results is uncertain, since the influences of rising core and skin temperatures were simultaneously present. As this experiment was not designed to evaluate the independent influence of carbon dioxide, then this effect remains unknown within the current trials.

3.3 Experimental outcomes: physiological responses

3.3.1 Heart rate

The pre-exposure level of cardiovascular strain was carried into the shelter exposures (Figure 7A), as noted within experiment one (Taylor et al., 2012), but this quickly declined upon assuming a seated and resting posture, as is expected when one returns to a resting state following these hot-water immersion and exercise pre-treatments. However, within the first experiment of this series, this physiological response soon attained a new steady state, albeit elevated relative to the thermoneutral baseline. In these trials, the rapid heart rate fall, seen immediately upon entering the simulator, was now followed by a gradual heart rate elevation (Figure 7A). That is, physiological strain was progressively rising. Whilst in the first experiment, subjects were able to attain a cardiovascular steady state within the first 10 min of exposure due to the thermal status of the chamber being regulated, in the present experiment, the thermal and gas composition characteristics of the shelter simulator were free to change, due to the presence of a hot and sweating person within the simulator. Under this circumstance, cardiovascular strain was elevated beyond the tenth minute of exposure, with heart rate increasing linearly thereafter (Figure 7B). This relationship was also most powerful:

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

During heat exposure, fatigue most commonly presents in the form of inadequate blood pressure regulation (Goldman, 1994; Taylor et al., 2008; Caldwell et al., 2011). Thus, this strong linear relationship permitted extrapolation to the point at which blood pressure regulation may possibly have been compromised in these participants (e.g. resting heart rate...
of 180 beats.min\(^{-1}\)). This was predicted to occur following 116 min of heat exposure\(^{12}\).

### 3.3.2 Core temperature

Unlike the first experiment from this series (Taylor et al., 2012), in which core temperature invariably fell from its pre-heated level during each exposure, before then attaining a significantly lower steady state, the current results revealed a clear core temperature elevation beyond 10 min (Figure 8A). When averaged across subjects (Table 6), the core temperatures beyond 10 min increased at a rate of 0.03 °C.min\(^{-1}\). This rise occurred whilst the air temperature was falling (Figure 3) and, for the current trials, the terminal core temperature averaged 39.3° C (SD 0.2).

Since subjects commenced in a pre-heated state (38.1°C, SD 0.1), ethical requirements prevented either a 2°C core temperature elevation, or a core temperature of 42°C from being encountered. Nevertheless, the very strong relationship between core temperature and time (\(r^2 = 0.989\); Figure 8B) permitted both of these outcomes to be predicted with considerable precision. Accordingly, a 2°C core temperature elevation would occur within about 80 min whilst a core temperature of 42°C could be expected to have occurred after 145 min of exposure within these conditions.

\[
\text{Core temperature (°C) at time } t \text{ (min)} = 37.53 + 0.03 \times t \quad [r^2 = 0.989]^{13}
\]

As highlighted above\(^{11}\), predictions derived in this manner do not adequately reflect subject variability and, in so doing, may imply an inappropriately high level of precision. To address this possible limitation, the raw core temperature data from every subject were separately modelled beyond 10 min (linear regression analyses), with the resulting parameters presented in Table 6. These data were then averaged to derive a prediction equation that reflects both the within- and between-subject variability in these core temperature responses. Notwithstanding the above qualification, these two prediction equations were almost identical due to the uniformity of the individual responses.

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

The latter prediction yielded an estimated exposure time, under the current experimental conditions, of approximately 74 min before a 2°C elevation in core temperature might be expected. However, it is predicted that, to achieve a core temperature of 42°C, the exposure would need to last 132 min, more than twice the duration of occupancy specified within the standard (Australian Building Codes Board, 2010).

\(^{12}\) This prediction uses data from the tenth minute onwards, and not the entire trial, since the first 10 min of each exposure was associated with a heart rate reduction in almost every subject.

\(^{13}\) This prediction also uses data from the tenth minute onwards, and not the entire trial, since the first 10 min of each exposure was associated with a core temperature reduction in almost every subject.
Figure 7: 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 8: 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 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>
<th>Change (°C.min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.998</td>
<td>37.69</td>
<td>0.054</td>
<td>0.052</td>
</tr>
<tr>
<td>S2</td>
<td>0.997</td>
<td>37.56</td>
<td>0.034</td>
<td>0.032</td>
</tr>
<tr>
<td>S3</td>
<td>0.998</td>
<td>37.40</td>
<td>0.038</td>
<td>0.040</td>
</tr>
<tr>
<td>S4</td>
<td>0.984</td>
<td>37.48</td>
<td>0.031</td>
<td>0.034</td>
</tr>
<tr>
<td>S5</td>
<td>0.993</td>
<td>37.32</td>
<td>0.027</td>
<td>0.027</td>
</tr>
<tr>
<td>S6</td>
<td>0.997</td>
<td>37.43</td>
<td>0.028</td>
<td>0.027</td>
</tr>
<tr>
<td>S7</td>
<td>0.995</td>
<td>37.42</td>
<td>0.031</td>
<td>0.030</td>
</tr>
<tr>
<td>S8</td>
<td>0.999</td>
<td>37.61</td>
<td>0.035</td>
<td>0.034</td>
</tr>
<tr>
<td>S9</td>
<td>0.994</td>
<td>37.46</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td>S10</td>
<td>0.990</td>
<td>37.50</td>
<td>0.033</td>
<td>0.032</td>
</tr>
<tr>
<td>S11</td>
<td>0.999</td>
<td>37.32</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>S12</td>
<td>0.998</td>
<td>37.57</td>
<td>0.033</td>
<td>0.034</td>
</tr>
<tr>
<td>S13</td>
<td>0.999</td>
<td>37.52</td>
<td>0.037</td>
<td>0.038</td>
</tr>
<tr>
<td>S14</td>
<td>0.996</td>
<td>37.33</td>
<td>0.036</td>
<td>0.035</td>
</tr>
<tr>
<td>S15</td>
<td>0.996</td>
<td>37.21</td>
<td>0.039</td>
<td>0.038</td>
</tr>
<tr>
<td>S16</td>
<td>0.995</td>
<td>37.43</td>
<td>0.034</td>
<td>0.031</td>
</tr>
<tr>
<td>Mean</td>
<td>0.995</td>
<td>37.45</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td>SD</td>
<td>0.004</td>
<td>0.12</td>
<td>0.006</td>
<td>0.006</td>
</tr>
</tbody>
</table>

How is that such elevations can be achieved under conditions in which core temperature was previously shown to fall (shelter condition two: Taylor et al., 2012)? Furthermore, how did this occur when the temperature of the air within the simulator decreased by 3.2°C? Two mechanisms can account for these observations.

Firstly, some thermal energy from the sealed simulator must have been transferred to the occupants, presumably through dry heat exchange to the skin tissues, and then via an internal convective path (mass flow: blood flow) to the deeper tissues. The air-to-skin thermal gradient averaged 7.9°C (43.7-35.8°C) at the start of these exposures. Indeed, the average temperature of the core and skin tissues (mean body temperature) was 5.8°C cooler than that of the simulator air at this point. Collectively, these thermal gradients could account for this
heat exchange if evaporative cooling was suppressed. Secondly, and of greater significance, the air within the simulator experienced an approximately exponential increase in its water vapour pressure (Figure 9). From about the fifth minute, the water vapour pressure rose sharply, with the air gradually becoming more saturated. There can be no doubt that this impeded evaporative heat loss. Thus, as a consequence of the combined effects of the above gain in thermal energy and this impaired heat loss, there was no option but for the core temperature to rise.

Figure 9: 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).

3.3.3 Skin temperature
The low and constant metabolic rate of the skin tissues dictates that its thermal energy content is primarily governed by dry and evaporative heat exchanges. In the first report from this experimental series (Taylor et al., 2012), the power of evaporation was highlighted, with the hottest experimental condition (shelter condition three) permitting the greatest evaporation of sweat, and thereby facilitating heat loss to the surrounding air even when the thermal gradient (11.5°C) of that condition favoured a net heat gain. In the current experiment, a condition that was 5°C cooler (shelter condition two) was now associated with an elevation of both core and skin temperatures. Indeed, it was the rise in ambient water vapour pressure that created this state, and this can be very easily seen in Figure 10 and Table 7, with skin temperatures rising to track these changes as evaporative efficiency declined (r²=0.968). The consequence of this was that very high skin temperatures were recorded towards the end of these trials. However, whilst these temperatures were high, at no time did they exceed core temperature (Figure 11).
Figure 10: 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 7: Mean skin temperature, skin and air water vapour pressures, and the corresponding water vapour pressure gradients (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</td>
<td>6.261</td>
<td>5.676</td>
<td>0.841</td>
</tr>
<tr>
<td>25</td>
<td>38.1</td>
<td>6.663</td>
<td>6.213</td>
<td>0.450</td>
</tr>
<tr>
<td>35</td>
<td>38.4</td>
<td>6.760</td>
<td>6.376</td>
<td>0.383</td>
</tr>
<tr>
<td>45</td>
<td>38.6</td>
<td>6.859</td>
<td>6.547</td>
<td>0.312</td>
</tr>
<tr>
<td>55</td>
<td>38.8</td>
<td>6.904</td>
<td>6.725</td>
<td>0.179</td>
</tr>
</tbody>
</table>

3.2.4 Whole-body sweat rate
In each of these trials, air temperature always exceeded both the core and mean skin temperatures, even though it decreased throughout each trial. In this circumstance, the only avenue for heat loss was via the evaporation of sweat (Taylor et al., 2008). This is a very powerful form of cooling, as illustrated in the first report from this series (Taylor et al., 2012). However, it gradually became ineffective within the current trials, due to the continuous elevation in the humidity of the simulator (Figure 4), and the corresponding reduction in the water vapour pressure gradient (Table 7). Consequently, subjects were unable, via physiological mechanisms, to prevent elevations in both core and skin temperatures (Figure 11), with these changes providing powerful stimuli for the secretion of sweat.
**Figure 11:** 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).

In these trials, the sweat rate averaged 0.71 L.h⁻¹ (SD 0.29). This is a relatively high resting sweat rate, and it was sustained by the subjects drinking 180 mL of isotonic fluid at 10-min intervals. The aim of this fluid replacement regimen was to prevent progressive dehydration and so to keep the shelter occupants sweating, thereby providing a rigorous evaluation of the changes in the internal status of an occupied, 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.

### 3.2.5 Psychophysical indices

The psychophysical indices followed unremarkable, and predictable responses (Table 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 course of heat exposure, with thermal discomfort attaining maximal values in five of the 16 subjects at the last point of measurement. Under humid conditions, such as those encountered within the shelter simulator, this subjective rating is driven primarily by the accumulation of moisture on the skin surface (Boutcher *et al.*, 1995). Thus, one may expect to see very uncomfortable people leaving a bushfire shelter at the end of a 60-min occupancy.

**Table 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>

### 4. CONCLUSIONS

It is reasonable to assume that a well-ventilated shelter constructed to the current specifications (Australian Building Codes Board, 2010), prior to its occupancy, will approximate the thermal status of the immediate ambient conditions. Thus, an above-ground shelter will be hot (*e.g.* >40°C) and dry, whilst a shelter that has been constructed
underground will be much cooler \((e.g. <30^\circ C)\), but also quite dry. One may, on the basis of
the evidence presented above, expect the former shelter to gradually cool as thermal energy is
transferred to each occupant. In the latter form of shelter, however, one may expect the air
temperature to rise, since the occupants will possess more thermal energy. The rate and size
of these thermal exchanges is dictated by the difference between air temperature and the skin
temperature of the occupants. However, one may conclude that an appropriately insulated
shelter that is isolated from the surrounding conditions, and retains its integrity during a
bushfire, will not experience a dangerous elevation in air temperature.

Nevertheless, within such a shelter, both the fractional concentrations of oxygen and carbon
dioxide will change linearly over time, but neither concentration will reach a level associated
with a significant health risk during a 60-min occupancy. From this investigation, the
following prediction equations for these gas concentrations were derived:

\[
\begin{align*}
\text{Oxygen concentration}(\%) \text{ at time } t \text{ (min)} &= 20.47 - 0.06 \times t \quad [r^2 = 0.994] \\
\text{Carbon dioxide concentration}(\%) \text{ at time } t \text{ (min)} &= 0.129 + 0.063 \times t \quad [r^2 = 0.997]
\end{align*}
\]

In addition to these changes, the water vapour content of the air within an air-tight shelter will
gradually rise, and it will do so in an approximately exponential manner, such that a relative
humidity of approximately 90% could be anticipated at the end of a 60-min occupancy. This
will have two consequence. Firstly, it will progressively reduce evaporative heat loss, and
thereby result in an inexorable rise in core temperature \((0.03^\circ C \text{ min}^{-1})\). Secondly, and far less
problematic, although no less unpleasant, it will lead to the occupants becoming very
uncomfortable. Using data for every subject beyond the first 10 min of exposure, an equation
was derived for predicting these core temperature changes:

\[
\begin{align*}
\text{Core temperature}(^\circ C) \text{ at time } t \text{ (min)} &= 37.45 + 0.03 \times t \quad [r^2 = 0.990]
\end{align*}
\]

Nevertheless, assuming a core temperature of 38.0^\circ C when entering this shelter, a 2^\circ C core
temperature elevation would not be expected before 75 min of occupancy under the current
experimental conditions, whilst a core temperature of 42^\circ C would not be expected within
<130 min of exposure.

To this point, it appears that the current specifications (Australian Building Codes Board,
2010) are conducive to human survival. What now remains is to test the effects of these
changes in air temperature and relative humidity on dehydrated individuals, as per experiment
one of this series (Taylor \textit{et al}., 2012). That is, now that the worst-case thermal characteristics
of a shelter have 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. The experimental conditions for the last stage of this
research are summarised in Table 9.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Time} \quad \text{(min)} & \text{Shelter condition one} & & \text{Shelter condition two} \\
\hline
& \text{Air} & \text{Relative} & \text{Air} & \text{Relative} \\
& \text{temperature} & \text{humidity} & \text{temperature} & \text{humidity} \\
& (^\circ C) & (\%) \quad (^\circ C) & (\%) \quad (^\circ C) & (\%)
\hline
0 & 40.0 & 70.0 & 45.0 & 50.0 \\
\hline
\end{array}
\]

Table 9: Temperature and relative humidity profiles for experiment three.
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>39.0</td>
<td>70.0</td>
<td>44.0</td>
<td>60.0</td>
</tr>
<tr>
<td>20</td>
<td>38.4</td>
<td>70.0</td>
<td>43.4</td>
<td>70.0</td>
</tr>
<tr>
<td>30</td>
<td>38.1</td>
<td>80.0</td>
<td>43.1</td>
<td>80.0</td>
</tr>
<tr>
<td>40</td>
<td>37.9</td>
<td>84.0</td>
<td>42.9</td>
<td>84.0</td>
</tr>
<tr>
<td>50</td>
<td>37.6</td>
<td>86.0</td>
<td>42.6</td>
<td>86.0</td>
</tr>
</tbody>
</table>
5. REFERENCES AND RECOMMENDED READING


Berlin, H.M., Stroschein, L., and Goldman, R.F. (1975). *A computer program to predict energy cost, rectal temperature, and heart rate response to work, clothing, and environment*. Edgewood Arsenal Special Publication (ED-SP-75011), Maryland, USA.


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