Critical Heat Stress Evaluation of Two-Layer Clothing Ensembles and the Contribution of a Full-Face Negative Pressure Respirator

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Critical Heat Stress Evaluation of Two-Layer Clothing Ensembles and the Contribution of a Full-Face Negative Pressure Respirator

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Public Health
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Keywords: Heat strain, WBGT, evaporative resistance, clothing adjustment factor, physiological strain index

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# Table of Contents

List of Tables ii

List of Figures iii

Abstract iv

Chapter One: Introduction 1

Chapter Two: Literature Review 5
  Clothing Effects 5
    Effects of Evaporative Resistance 6
    Effects of Clothing Adjustment Factors (CAF) 7
    Effects of Air Permeability 9
    Effects of Metabolic Rate and Gender 9
  Respirator Effects 10
    Effects of Respirators on Thermoregulation and Core Body Temperature 11
    Effects of Respirators on Perceived Effort and Thermal Comfort 12
    Effects of Respirators on Cardiovascular Indices 13
    Effects of Respirators on the Respiratory System 14
  Objectives of the Study 14
  Hypotheses 15

Chapter Three: Methods 16
  Experimental Design 16
  Participants 16
  Clothing 18
  Equipment 18
  Protocols 20
    Acclimatization 20
    Experimental Trials 20
  Inflection Point and Determination of Critical WBGT 22
  Calculation of Clothing Parameters 23
  Data Analysis 24

Chapter 4: Results 26

Chapter 5: Discussion 30
  Limitations 33
  Conclusions 35

References 36
List of Tables

Table 1: ACGIH Screening Criteria for Heat Stress Exposure (WBGT values in °C) for 8 hour work day five days per week with conventional breaks 4
Table 2: Clothing Adjustment Factors for Some Clothing Ensembles 8
Table 3: Participant characteristics 17
Table 4: Metabolic rate and environmental conditions at critical condition by clothing ensemble 27
Table 5: Thermal characteristics of the clothing ensembles 28
Table 6: Physiological strain for each clothing ensemble at critical conditions 29
List of Figures

Figure 1: TLV® (solid line) and Action Limit (broken line) for heat stress 10
Figure 2: Work Clothes 19
Figure 3: TAP+CA (front and back) with respirator 19
Figure 4. TAP+CA+P (front and back) with respirator 19
Figure 5. VB+CA with respirator 19
Abstract

Protective clothing ensembles are worn by workers as a barrier to chemical and physical hazards, but can restrict heat loss and increase worker heat stress. The question of whether a respirator adds to heat stress or strain burden is a continuing concern among occupational health professionals. The purpose of this study was to determine if there are differences in heat stress or strain among the current Toxicological Agent Protective (TAP) ensemble and two ensemble variations used in demilitarization of chemical weapons. Four acclimatized adult males wore five ensembles in a balanced design while walking in a climatic chamber at a metabolic rate of about 170 W m\(^{-2}\). Heat stress (critical wet bulb globe temperature-WBGT\(_{\text{crit}}\), evaporative resistance-\(R_{e,T,a}\), Clothing Adjustment Factor [CAF]) and heat strain (physiological strain index [PSI]) were compared against work clothes (WC) without respirator (a baseline ensemble); the current TAP apron over cloth coveralls with respirator (TAP+CA); the current TAP apron over cloth coveralls with respirator plus Tychem F® chemical barrier pants (TAP+CA+P); and Tychem F® Coveralls over cloth coveralls with respirator (VB+CA). A no-respirator comparison with the Tychem F coveralls (VB+CA-noR) was added to evaluate the contribution of a full-face negative pressure air-purifying respirator to heat stress. A progressive heat stress protocol was used to determine WBGT\(_{\text{crit}}\), \(R_{e,T,a}\), CAF, and PSI. The results (WBGT\(_{\text{crit}}\) [°C-WBGT], \(R_{e,T,a}\) [kPa m\(^2\) W\(^{-1}\)], and PSI) were WC (35.5, 0.0112, 2.0), TAP (31.6, 0.0175, 1.8), TAP+P (27.7, 0.0240, 1.9), VB+CA (25.9, 0.0287, 1.8), and VB+CA-noR (26.2, 0.0293, 1.8). Mixed effects ANOVA was used to assess ensemble effects. Tukey’s test was used to determine where significant differences occurred. WBGT\(_{\text{crit}}\) was the WBGT at the upper limit of thermal balance. \(R_{e,T,a}\) increased while WBGT\(_{\text{crit}}\) progressively decreased going from WC to TAP+CA to TAP+CA+P to VB+CA. WBGT\(_{\text{crit}}\) was different between Work Clothes and TAP+CA and between WC and TAP+CA and the other ensembles. \(R_{e,T,a}\) was different among all ensembles, except no differences in WBGT\(_{\text{crit}}\) and \(R_{e,T,a}\) were observed between the presence and absence of a respirator with VB+CA. There were
no differences among all ensembles for rectal temperature, heart rate, and PSI. Based on both WBGT$_{crit}$ and R$_{e,T,a}$, there were significant increases in heat stress going from WC to TAP+CA to TAP+CA+P to VB+CA. No differences in WBGT$_{crit}$, R$_{e,T,a}$, and PSI were found for the presence or absence of a respirator, indicating no additional heat stress or strain burden. CAF is the WC WBGT$_{crit}$ minus the ensemble WBGT$_{crit}$. The recommended clothing adjustment factors (CAFs) are 0°C-WBGT for WC, 4°C-WBGT for TAP+CA, 8°C-WBGT for TAP+CA+P and 10°C-WBGT for VB+CA. As vapor-barrier ensembles are sensitive to humidity, adding 2°C-WBGT to VA+CA for a CAF of 12°C-WBGT is recommended. This implicates the type of protective clothing ensemble worn will play a much bigger role in workplace heat stress effects and risk than the wear of a respirator.
Chapter One:

Introduction

Heat-related illness (HRI) and mortality due to environmental and occupational heat exposures continue to be a significant health and safety concern despite readily available HRI prevention guidelines. Acute HRI occurs when heat exposure causes heat gain to exceed heat loss, increased sweating occurs and thermoregulation is lost; resulting in an array of medical disorders ranging from life-threatening heat stroke, to heat exhaustion, heat cramps and heat syncope. The Bureau of Labor Statistics Census of Fatal Occupational Injuries data estimates there were 230 heat-related deaths and 15,370 HRI that occurred from 2003 – 2009 [1]. The CDC noted 423 worker heat related deaths in agricultural and nonagricultural industries between 1992 to 2006 [2]. The U.S. Mining Industry reported 538 cases of heat illness from Jan 1, 1983 to Dec 31, 2001 [3]. There were 5246 hospitalizations and 37 deaths due to heat illness between 1980-2002 within the U.S. Army, with a trend towards declining hospitalizations but increasing heat stroke incidence noted [4].

Washington State found 446 state workers’ compensation claims for heat-related illness (HRI) between 1995-2004 at a $1,287 cost per heat-related illness claim.[5]. Thirty-three of these claims (7.4%) involved greater than 3 days of lost work and one fatality occurred. During the 1993 Midwest floods, the most frequently reported injury on medical claims filed by Illinois National Guard troops was HRI which accounted for 19.3 % of claims [6]. More recently, the NIOSH Report of Deepwater Horizon Response/Unified Area Command Illness and Injury Data (April 23 – July 27, 2010) noted 192 cases of heat illness [7]. Yet despite the continued HRI and heat related deaths, OSHA still has no specific heat stress standard.
Even without overt HRI, exposure to excessive heat results in increasing risk of heat related physiological and psychological effects. Symptoms often begin with fatigue, thirst, headache, increased heart rate, increased skin and core body temperature, increased respiratory rates, hypertension or hypotension, dehydration, dizziness, impaired performance, irritability, and abnormal spermatogenesis. Tachycardia and hypertension can increase the workload on the heart and myocardial oxygen consumption. Hypotension reduces coronary artery perfusion and ultimately cerebral perfusion. If heat exposure continues, symptoms can progress to mental status change, loss of consciousness, shock, coma and death. The effects on mental and cognitive performance can be subtle and often arise prior to the onset of acute HRI symptoms. Ramsey et al. found unsafe behaviors become more apparent when WBGT rose above 23 degrees Celsius [8]. A study in mine workers in Australia observed that heat stress degrades mental performance well in advance of any deterioration of physical performance [9]. This could in turn contribute to decreased productivity and increased accident frequency rate. These observations are supported by Misaqi et al. who identified dexterity and coordination, ability to remain alert during lengthy and monotonous tasks, and the ability to make quick decisions as attributes adversely affected by heat strain [10].

Maintenance of thermal balance is necessary to prevent both acute and chronic heat-related illness and heat strain effects. Loss of thermal balance occurs when heat gain exceeds heat loss, causing core temperature to continue to rise. The American Conference of Governmental Industrial Hygienists (ACGIH) defines heat stress as the net load to which a worker may be exposed from the combined contributions of metabolic heat, environmental factors (air temperature, humidity, air movement, and radiant heat) and clothing requirements. ACGIH defines heat strain as the overall physiological responses (dedicated to dissipating excess heat from the body) resulting from heat stress [11]. Risk factors for occupational susceptibility to heat stress and heat strain can be categorized as personal or workplace/occupational risk factors.
Personal risk factors include lack of acclimatization, dehydration, obesity, decreased fitness capacity, genetic predisposition to heat intolerance, history of heat illness, older age, use of medications that reduce sweating, cutaneous blood flow, act as diuretics or CNS depressants, new employee status or lack of worker experience and cardiac disease, including hypertension and diabetes mellitus. Even those without previous underlying heart disease are at increased risk of sudden cardiac events associated with HRI. Kark et al. looked at 269,124 recruits at Marine basic training in Paris, SC and the contribution of exertional HRI to sudden cardiac death and found that those with exertional heat illness were 3,400 times more likely to have a heart attack than those who did not have exertional heat illness [12]. Wild et al. assessed mortality rates in a cohort of French potash miners and found that among miners who left for medical reasons, ischemic heart disease mortality was five times greater in the heat-exposed group compared to non heat-exposed workers [13]. Gopinthan et al. found that impairment in mental performance was proportional to the degree of dehydration and is highly significant at 2% dehydration with a decrease in short-term memory, arithmetic efficiency, and visual motor tracking involving motor speed and attention [14]. At 4% dehydration, a 23% decrease in reaction time can be seen. Unacclimatized workers are less heat tolerant and will exhibit HRI signs and symptoms sooner when exposed to the same levels of heat as acclimatized workers.

Workplace or job risk factors are environmental heat, metabolic work demands and clothing requirements, including protective clothing ensembles. Environmental heat is most commonly assessed by measurement of the wet bulb globe temperature (WBGT). Although the heat strain protection goal is based on core body temperature, measuring this in workers on a regular basis is impractical. Therefore, wet bulb globe temperature (WBGT) is widely used to assess occupational heat stress limits. Heat stress can be thought of as a marker of heat exposure and evaluation requires knowledge of the effects of the job and workplace risk factors. Evaluation of heat stress is critical to recognizing and preventing exposure to conditions likely to lead to excessive core temperature increase and unacceptable physiological or psychological heat strain, resulting in HRI.
Current ACGIH guidelines for Heat Stress and Strain (2010) and National Institute for Occupational Safety and Health (NIOSH) exposure limits use WBGT as the primary factor to determine risk of heat stress. These exposure limits decrease with metabolic rate. ACGIH has developed the heat stress screening guidelines (see Table 1) to allow allocation of work and rest cycles. Use of these work/rest tables are preferred as self-monitoring for signs and symptoms of HRI are unreliable over longer periods of time.

Table 1. ACGIH Screening Criteria for Heat Stress Exposure (WBGT values in °C) for 8 hour work day five days per week with conventional breaks

<table>
<thead>
<tr>
<th>Allocation of Work in a Work/Rest Cycle</th>
<th>Acclimatized</th>
<th>Action Limit (Unacclimatized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Moderate</td>
<td>Heavy</td>
</tr>
<tr>
<td>75-100%</td>
<td>31.0</td>
<td>--</td>
</tr>
<tr>
<td>50-75%</td>
<td>31.0</td>
<td>27.5</td>
</tr>
<tr>
<td>25-50%</td>
<td>32.0</td>
<td>29.0</td>
</tr>
<tr>
<td>0-25%</td>
<td>32.5</td>
<td>30.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Very Heavy</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Very Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>75-100%</td>
<td>31.0</td>
<td>25.0</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>50-75%</td>
<td>28.5</td>
<td>26.0</td>
<td>24.0</td>
<td>--</td>
</tr>
<tr>
<td>25-50%</td>
<td>29.5</td>
<td>27.0</td>
<td>25.5</td>
<td>24.5</td>
</tr>
<tr>
<td>0-25%</td>
<td>30.0</td>
<td>29.0</td>
<td>28.0</td>
<td>27.0</td>
</tr>
</tbody>
</table>

Examples of work loads:

**Rest** - sitting (quietly or with moderate arm movements)

**Light work** - sitting or standing to control machines; performing light hand or arm work (e.g. using a table saw); occasional walking; driving

**Moderate work** - walking about with moderate lifting and pushing or pulling; walking at moderate pace; e.g. scrubbing in a standing position

**Heavy work** - pick and shovel work, digging, carrying, pushing/pulling heavy loads; walking at fast pace; e.g. carpenter sawing by hand

**Very Heavy** - very intense activity at fast to maximum pace; e.g. shovelling wet sand

Because of the physiological strain associated with Heavy and Very Heavy work among less fit workers regardless of WBGT, criteria values are not provided for continuous work and for up to 25% rest in an hour for very Heavy. The screening criteria are not recommended, and a detailed analysis and/or physiological monitoring should be used.

Adapted from: 2011 Threshold Limit Values for Chemical and Physiological Agents and Biological Exposure Indices. American Conference of Governmental Industrial Hygienists (ACGIH).
Chapter Two:

Literature Review

*Clothing Effects*

Protective clothing ensembles are worn to protect workers from chemical, biological and physical hazards. Clothing also functions as a barrier to heat and moisture transfer between the skin and environment and hampers the loss of superfluous heat during physical effort [15]. Therefore, when the question arises about changing protective clothing and equipment requirements, the related question of how will it affect heat stress exposure needs to be answered. Two approaches can be taken to assess the effects of clothing ensembles on heat stress. One approach is to create conditions of uncompensable heat stress by setting the environmental conditions to one or more typical environments under which protective clothing ensemble would be used with participants working at a fixed metabolic rate [16]. The maximal work time for the protective clothing ensemble in the typical environment of use is used to determine the average safe exposure time and represents the ensemble performance. An alternative approach is to follow a progressive exposure protocol during which environmental temperatures are increased until core body temperatures continue to increase and thermoregulation is lost. The environmental conditions and temperatures at which core body temperatures rise are used to determine the critical environment at the upper limit of compensable heat stress. Based on the critical environment, the total apparent evaporative resistance ($R_{e,T,a}$) and the critical WBGT ($WBGT_{crit}$) can be estimated [17-19]. By comparing the $WBGT_{crit}$ to that of work clothes, a Clothing Adjustment Factor (CAF) can be assigned to the ensemble of interest.
The two thermal characteristics and thermal balance of clothing are the resistance to evaporative cooling and total resultant insulation. Clothing insulation decreases heat flow by radiation, convection, and conduction. As conduction plays a minor role, the primary effect from insulation is a reduction in convection and radiation heat loss [15]. Evaporation of sweat reduces heat gain due to the loss of heat from the skin during the process of evaporation. $R_{e,T,a}$, WBGT$_{crit}$, and CAF are indices for the comparison of the evaporative cooling capacity of protective clothing ensembles.

Effects of Evaporative Resistance

One of the normal physiologic responses to increased core body temperature is an increase in sweat production in an effort to dissipate heat from the body. This evaporative loss of heat depends on rate of sweating, air movement, humidity and clothing effects. This ability to support evaporative cooling is limited by the clothing’s total evaporative resistance ($R_{e,T,a}$) and water vapor or air permeability. $R_{e,T,a}$ and water vapor or air permeability are in turn dependent on clothing fabric properties, garment style and fitting, and are affected by body posture, body motion and environmental conditions [20].

A previous study by Caravello et al. found an apparent total evaporative resistance for work clothes was 0.014 m$^2$ kPa W$^{-1}$, 0.013 m$^2$ kPa W$^{-1}$ for cotton coveralls, 0.015 m$^2$ kPa W$^{-1}$ for Tyvek 1424 (particle barrier coveralls), 0.018 m$^2$ kPa W$^{-1}$ for NexGen (water barrier coveralls), and 0.032 m$^2$ kPa W$^{-1}$ for Tychem QC (vapor barrier coveralls) [17]. Evaporative resistances were similar for work clothes, cotton coveralls, and Tyvek 1424, but were shown to increase with NexGen and Tychem QC. Apparent total evaporative resistance was shown to exhibit a linear relationship to CAF under conditions of 50 % relative humidity (RH), with increases in evaporative resistance resulting in increases in CAF [17]. Further studies by Bernard et al. demonstrated there were no interactions between three different RH (20%, 50%, and 70%) and resultant critical WBGT for work clothes, coveralls, Tyvek 1424, and NexGen clothing ensembles, meaning the WBGT$_{crit}$ was not different for work clothes, Tyvek 1424, and NexGen at all three different RH [18]. Only the Tychem QC or vapor barrier coveralls showed an effect from
different RH on the WBGT$_{crit}$. The difference of the Tychem QC WBGT$_{crit}$ from the work clothes WBGT$_{crit}$ ranged from 5.4 at 70% RH, 7.8 for 50% RH and 11.4 for 20% RH [18]. Protective conservative recommendations are to utilize the high end of the range and assign a CAF of 10.

**Effects of Clothing Adjustment Factors (CAF)**

In order to protect against heat strain in all individuals, the World Health Organization (WHO) has recommended that core body temperature not exceed 38°C (100.4° F) during sustained work periods. Although this heat strain protection goal is based on core body temperature, measuring this in every worker on a regular basis is often impractical. Therefore, wet bulb globe temperature (WBGT) is widely used to assess occupational heat stress limits as it requires only a few, easy measurements with simple instrumentation. WBGT for workplaces indoors or without direct exposure to sunlight is calculated as 0.7 $T_{nwb}$ + 0.3 $T_g$, while WBGT for areas with direct exposure to sunlight is calculated as 0.7 $T_{nwb}$ + 0.2 $T_g$ + 0.1 $T_{db}$. $T_{nwb}$ is the natural wet bulb temperature and is measured by placing a wetted wick over the temperature sensor and air is allowed to flow over the sensor naturally. $T_g$ is the globe temperature reflects radiant heat and is measured using a temperature sensor in a copper sphere painted matte black. $T_{db}$ is the dry bulb temperature and a direct measure of air temperature. Because WBGT is based on observed (empirical) relationships and not rational (biophysical) relationships, it is more difficult to account for clothing effects based on insulation and evaporative resistance [19].

For this reason, adjustments for clothing have been sought. Clothing adjustment factors (CAF) were first proposed by Ramsey and furthered by Bernard [18-19]. CAFs have now been adopted by the ACGIH (Table 2) as an empirical measure that accounts for clothing in WBGT-based heat stress exposure assessments [11]. The CAF is determined by the difference between the WBGT$_{crit}$ of the clothing ensemble in question and the WBGT$_{crit}$ of work clothes. Critical WBGT represents the upper limit of compensable heat stress, beyond which thermoregulation is lost. WBGT$_{crit}$ then provides another benchmark for the relative level of heat stress associated with the clothing ensemble [21, 22]. WBGT$_{crit}$ is calculated as 0.7 ($T_{pwb}$ + 1.0) + 0.3 $T_g$, where $T_{pwb}$ is the psychrometric wet bulb globe temperature measured similar to the $T_{nwb}$ except that air is
forced over the wetted wick at 3 m/sec. The higher the WBGT$_{crit}$ for an ensemble the more it can support evaporative cooling, which in turn decreases the risk of heat stress imposed by that clothing ensemble. The difference between the WBGT$_{crit}$s for work clothes and the ensemble of interest then represents the added burden of the ensemble on which occupational exposures are based. The measured environmental WBGT is increased by the resulting CAF, effectively increasing the environmental WBGT and decreasing allowable exposure time. Effective WBGT becomes measured WBGT plus the CAF.

<table>
<thead>
<tr>
<th>Clothing Type</th>
<th>Addition to WBGT [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work clothes (long sleeve shirt and pants)</td>
<td>0</td>
</tr>
<tr>
<td>Cloth (woven material) coveralls</td>
<td>0</td>
</tr>
<tr>
<td>Double layer woven clothing</td>
<td>3</td>
</tr>
<tr>
<td>SMS polypropylene coveralls</td>
<td>0.5</td>
</tr>
<tr>
<td>Polyolefin coveralls</td>
<td>1</td>
</tr>
<tr>
<td>Limited-use vapor-barrier coveralls</td>
<td>11</td>
</tr>
</tbody>
</table>

(Bounds cannot be added for multiple layers.)

Adapted from: 2011 Threshold Limit Values for Chemical and Physiological Agents and Biological Exposure Indices . American Conference of Governmental Industrial Hygienists (ACGIH).

Bernard et al. previously compared work clothes with cotton coveralls, particle barrier coveralls (Tyvek 1424, 1427), water barrier coveralls (NexGen) and vapor barrier coveralls (Tychem QC) and found resulting WBGT CAF (without hoods) 0 °C-WBGT °C-WBGT for cotton coveralls, 1.0 °C-WBGT for Tyvek 1424, 1427 coveralls, 2.5 °C-WBGT for NexGen coveralls, and 10 °C-WBGT for Tychem QC coveralls [18,19]. Although these CAFs are for clothing ensembles without hoods, Ashley et al. has examined the effects of hoods on WBGT CAF and found hoods lowered WBGT$_{crit}$ by an average of 1 °C and added 1 °C-WBGT to the WBGT CAF [23]. It is worth noting that previous studies examining the effects of clothing ensembles on WBGT$_{crit}$ and CAFs address work clothes, cloth coveralls and various particle, water and vapor barrier coveralls, but none address the WBGT$_{crit}$ and CAF associated with wear of chemical protective aprons or chemical protective aprons plus chemical protective pants. The current ACGIH CAF table also does not take into account effect of multiple layers of clothing, (i.e cotton coveralls under water barrier coveralls) on CAFs and states that CAF cannot be added for multiple layers.

Effects of Air Permeability
Air permeability can influence $R_{e,T,a}$ and CAF by affecting the amount of convective air movement through clothing material. Gonzales et al. demonstrated an increase in sustainable work in the same environment with an increase in fabric air permeability of single use coveralls [24]. Air permeability was a better predictor of fabric work limiting performance and work sustainability than moisture vapor transfer rate (MVTR) [24]. This work suggested that the ability to support convective transfer of water vapor is more important than diffusive transport. Therefore evaporative cooling can be increased and evaporative resistance reduced by boosting air movement or convection under and through clothing ensembles [21, 22, 24].

*Effects of Metabolic Rate and Gender*

Metabolic rate does affect the allowable WBGT exposure with higher metabolic rate demands decreasing the WBGT TLV (Figure 1). Ashley et al. compared effects of low metabolic rate (110 W/m²), moderate metabolic rate (160 W/m²), and high metabolic rate (250 W/m²) to gender while wearing five different clothing ensembles (work clothes, cotton coveralls, Tyvek 1424 or 1427 coveralls, NexGen coveralls, and Tychem QC coveralls) and found that as metabolic rate increased there was a concomitant decrease in $WBGT_{crit}$ and increase in heart rate (HR), rectal temperature ($T_{re}$), and physiological strain index (PSI) [25]. Women did demonstrate higher levels of heat strain compared to men as measured by increased HR, $T_{re}$, and PSI at the same $WBGT_{crit}$, but no gender effect was seen for actual $WBGT_{crit}$. Women exhibited similar heat stress effects with no gender differences in critical conditions or $WBGT_{crit}$ among all the ensembles [25]. Bernard et al. investigated the effects of metabolic rate on resultant CAFs. He showed that when $WBGT_{crit}$ at three different metabolic rates of 115, 175, and 250 W/m² (to approximate light, moderate and heavy work respectively) and resultant CAFs for varying clothing ensembles (cotton coveralls, Tyvek 1427 coveralls, NexGen coveralls, and Tychem QC coveralls) were compared, overall CAFs did not change with metabolic rate [19]. The CAF for the clothing ensemble worn, which is added to the environmental WBGT, will be the same regardless of the worker’s metabolic rate and can be used over a wide range of metabolic rates.
FIGURE 1. TLV® (solid line) and Action Limit (broken line) for heat stress.

**WBGT<sub>eff</sub>** is the measured WBGT plus the Clothing-Adjustment Factor.

Adapted from: 2011 Threshold Limit Values for Chemical and Physiological Agents and Biological Exposure Indices. American Conference of Governmental Industrial Hygienists (ACGIH).

**Respirator Effects**

Respiratory protective devices or respirators are added to protective clothing ensembles when inhalational hazard exposures cannot be controlled with engineering or administrative controls. However, workers often avoid wearing respirators due to the discomfort, perceived heat strain and stress, or other psychological factors associated with respirator wear. Respirator discomfort can be associated with a higher subjective thermal sensation and a rise in respiratory air temperature and skin temperatures. Several studies have also addressed whether respirator discomfort is associated with an increase in physiological strain, as measured by increases in core body temperature, heart rate, blood
Heat strain can be assessed by monitoring for sustained heart rate in excess of 180 minus age in beats per minute (bpm) over several minutes, recovery heart rate over 120 bpm at one minute after a peak work effort, or core temperature greater than 38.5 C (101.3 F) in acclimatized and greater than 38 C (100.4 F) in unacclimatized workers [11]. Moran et al. developed a physiological strain index (PSI) to evaluate heat stress that integrates HR and Tre to reflect the combined strain of the thermoregulatory and cardiovascular systems on a scale of 0-10, with 0 being no strain and 10 being very high strain [26]. PSI is calculated using the following equation: $\text{PSI} = 5(\text{T}_{re} - \text{T}_{re0})/(39.5 - \text{T}_{re0}) + 5(\text{HR} - \text{HR}_0)/(180 - \text{HR}_0)$, where $\text{T}_{re}$ and $\text{HR}$ represent initial values or values taken at any time and $\text{T}_{re0}$ and $\text{HR}_0$ represent baseline values. This PSI has been validated at various ages for men and women [26].

Most studies have examined the respirator effects on cardiovascular indices, respiratory indices, or effects of skin temperature increase on perceived thermal stress and comfort. Although some have looked at the effects of reported heat stress, many of these use changes in environmental temperatures inside or outside the mask or changes in temperatures of inspired and expired air to assess heat stress. Many did not address or control for acclimatization or humidity. Only a few studied or compared metabolic rate on the thermal effects of a respirator. No studies have addressed whether addition of a respirator increases heat stress as determined by the critical WBGT.

Effects of Respirators on Thermoregulation and Core Body Temperature

Core body temperature is a well recognized marker of heat gain by the body and increases as thermoregulation is lost. Rectal temperature is ususally used as the standard core body temperature measurement due to its long history as the core temperature laboratory measurement [27]. However, as measuring rectal temperature is invasive and uncomfortable, some studies use oral temperature as a surrogate for core body temperature. Core
temperature is commonly considered to be 0.5 to 1.0 °C higher than the oral temperature. When rises in core body temperatures were compared between respirator and no respirator conditions, a few studies revealed a rise in core temperature or thermal load with respirator wear, but a majority show no difference. Caretti compared the effects of powered air purifying respirator (PAPR) and full-face, negative pressure air-purifying respirator (APR) and found no significant differences in skin and rectal temperatures, except for prolonged heat exposure time greater than 100 minutes [28, 29]. Scanlan looked at the effect of the S10 (a full face, NP-APR) in the MK IV chemical PPE overgarments at 60% RH compared to no respirator and found no increase in rectal temperatures with use of the respirator [30]. James et al. examined the effects of a half and full face APR during high and low work demands and high (43.3 °C) and low (25 °C) environmental conditions and found oral temperatures rose significantly with use of the full face APR under high work and high heat conditions [31]. This rise in oral temperature was felt to be more likely due to the work demands than to heat stress due to the respirator wear [31].

Effects of Respirators on Perceived Effort and Thermal Comfort

Many studies have demonstrated that wear of respirators is associated with a perceived increase in effort, regardless of change in core body temperatures. A higher subjective thermal sensation and thermal discomfort has been associated with respirator wear. This discomfort is often associated with increased skin temperatures and increased sweating. Scanlan et al. noted marginally higher relative perceived effort with wear of a full face negative pressure APR and found thermal discomfort was higher for respirator use after 30 minutes of exercise [30]. Dubois et al. found respirators were rated as comfortable when skin temperature was below 34.5 °C with 50% of subjects reporting discomfort associated with skin temperatures above 34.5 °C [32]. Thermal discomfort was also associated with moderate sweating, but was more closely associated with skin temperature. Gwosdow et al. observed that with half face respirators, respirator acceptability was dependent on thermal conditions
inside the respirator [33]. Respirators were rated as acceptable and comfortable when skin temperature was less than 34.5 °C and respirator dew point temperature was less than 25 °C. Respirator and whole body thermal comfort were 100 % acceptable and comfortable when temperatures inside respirator were less than 33 °C [33]. Fox et al. also found that the comfort zone with wear of respirators at rest begins at a skin temperature of 34.5 °C and below, and with exercise at 31 °C and below [34]. Evaporative cooling of the face mask effectively reduced skin temperature to a comfort threshold.

Effects of Respirators on Cardiovascular Indices

Heart rate (HR) increases and blood pressure changes are indicative of increasing cardiovascular strain secondary to heat exposures with heart rate increase indicative of an immediate cardiovascular response to heat conditions. Most studies show no significant cardiovascular effects of wearing an negative pressure air-purifying respirators [35]. While the self-contained breathing apparatus (SCBA) does increase HR and cardiac strain, the cardiovascular strain is primarily related to the weight (15.5 kg) of the SCBA [35],[36]. When examining the effects of the APR on heart rate, Scanlan et al. and Harber et al. demonstrated no significant differences in heart rate with use of air-purifying respirators [30], [37]. Jones and Laird et al. demonstrated dose-related increases in heart rate with heavy work demands and use of a half-face APR respirator respectively [38, 39]. Increases in HR due to the respirator were small when compared with overall effects of activity with significant HR differences seen during heavy work. James et al. also showed an increase in heart rate under high work demands with wear of half and full face APRs and under low work demands with wear of the full face APR [31].

The effects of blood pressure can vary with an initial increase in blood pressure seen due to an increase in heart rate, followed by a drop in blood pressure as vasodilation increases and blood volume drops due to loss of fluids through sweat. As a result, blood pressure is not routinely used as a measure of the immediate physiological strain associated with heat strain.
A few studies have evaluated blood pressure responses associated with wear of respirators and heat exposures. Jones demonstrated increases in systolic blood pressure associated with wear of a disposable respirator, PAPR, full-face and half-face APRs with increases noted at rest and at high levels of work [38]. Bardsley et al. showed no effect on HR or blood pressure due to half-face and full-face APR as well as PAPR wear during moderate exercise [40].

Effects of Respirators on the Respiratory System

Increased respiratory effort can increase physiological strain. APRs, air-line supplied respirators, and SCBA have been shown to cause hypoventilation and an increase in the work of breathing [36]. APR substantially increase inspiratory resistance and the work of breathing by increasing the resistance to both inspiratory and expiratory airflow and increasing dead space ventilation with maximal tolerable workloads decreasing in a linear fashion with increasing inspiratory resistance [35]. Johnson et al. also showed performance times, time to volitional fatigue, and respirator discomfort were linearly decreased with increasing dead space ventilation volumes. For each 350 ml increase in external dead volume, a 19% decrease in performance time and 18% decrease in respirator comfort can be expected [41].

Objectives of the Study

The current protective configuration for demilitarization of chemical weapons is a TAP (Toxicological Agent Protection) apron and full-face negative pressure air purifying respirator (FF-NP-APR). The two alternatives to be tested are the TAP apron with chemical barrier trousers and FF-NP-APR, and chemical barrier coveralls with FF-NP-APR. The TAP apron is made from Tychem® F, a vapor-barrier fabric. The addition of chemical barrier trousers to the TAP apron over cloth coveralls configuration or use of a chemical barrier coverall ensemble instead of the apron would convey additional protection, but at the expense of potential additional heat stress.
The purpose of this study was to determine if there are differences in heat stress (critical wet bulb globe temperature-WBGT\textsubscript{crit}, evaporative resistance-R_{e,T,a}, Clothing Adjustment Factor [CAF]) or heat strain (physiological strain index [PSI]) among the Toxicological Agent Protective (TAP) ensemble and two ensemble variations used in demilitarization of chemical weapons. Of major interest were (1) the current TAP ensemble including respirator (TAP+CA); (2) the current TAP ensemble with respirator and Tychem F® pants (TAP+CA +P); and (3) Tychem F® Coveralls over cloth coveralls with respirator (VB+CA). All options included a base layer of clothing that was cotton coveralls and FF-NP-APR. Work clothes consisting of a long sleeve cotton shirt and pants was the baseline ensemble and used as a standard for comparison. A no-respirator comparison with the Tychem F coveralls (VB+CA-noR) was added to determine if the addition of a FF-NP-APR adds additional heat stress.

**Hypotheses**

The null hypotheses are:

1. There are no differences in heat stress or strain among (1) standard cotton work clothes, (2) TAP Apron with respirator, (3) TAP Apron with respirator plus pants, (4) Vapor-barrier coveralls with respirator, and (5) Vapor-barrier coveralls without respirator.

2. There are no differences in heat stress or strain between the presence or absence of a FF-NP-APR.
Chapter Three:

Methods

Experimental Design

The study was a randomized cross over clinical trial. Each participant completed a trial with each ensemble. The order of ensembles was randomized in a partially balanced cross over design. Each participant served as their own control by completing trials in work clothes compared to the other TAP ensemble variations and received each of the five treatments (ensembles). Since metabolic rate for all ensembles can effect resultant $\text{WBGT}_{\text{crit}}$ HR, Tre, and PSI levels and RH for the vapor barrier coverall ensemble can effect resultant $\text{WBGT}_{\text{crit}}$, they were treated as confounders. These confounders were controlled for in the experimental design by maintaining a fixed metabolic rate and RH. In addition, metabolic rate was controlled for in the data analysis.

Participants

Four acclimatized males participated in the experimental trials. The original plan was to use five participants in a complete factorial design, but after the first four participants were recruited, a decision was made to ask two participants to repeat the trials for a total of six sets of data. Participants were recruited from the University of South Florida Tampa Bay area by word of mouth and fliers posted in areas frequented by the target population, such as the student union, fitness center, COEd and COPH (Appendix A). Each participant wore all five ensembles in a balanced order, and two participants (participants S2 and S3) completed two sets of trials.
Table 3 summarizes the participant’s physical characteristics.

Table 3. Participant characteristics

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age [yr]</th>
<th>Height [m]</th>
<th>Weight [kg]</th>
<th>Body Surface Area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>21</td>
<td>1.78</td>
<td>72</td>
<td>1.89</td>
</tr>
<tr>
<td>S2 (x2)</td>
<td>21</td>
<td>1.93</td>
<td>78</td>
<td>2.08</td>
</tr>
<tr>
<td>S3 (x2)</td>
<td>22</td>
<td>1.80</td>
<td>106</td>
<td>2.24</td>
</tr>
<tr>
<td>S4</td>
<td>22</td>
<td>1.83</td>
<td>97</td>
<td>2.19</td>
</tr>
</tbody>
</table>

The study protocol was approved by the University of South Florida Institutional Review Board. A written informed consent was obtained prior to enrollment in the study (Appendix B). Each participant was examined by a physician and approved for participation. A medical, family, social and work history was taken to assess current state of health and to determine that participants healthy with no chronic disease or medication use known to influence or adversely affect thermoregulatory or cardiovascular response to heat. A physical examination for evidence of disorders of the vestibular system, pulmonary system, cardiovascular system, gastrointestinal system, genitourinary system, musculoskeletal system, and neurological system was performed and each participant underwent a resting 12-lead electrocardiogram. Inclusion criteria were males between ages 18-40 who passed the physical exam and were medically approved to participate. Participants were excluded if there was evidence of drug or alcohol abuse or use of the following classes of medication: alpha and beta (sympathetic) blocking agents, anticholinergics, antidepressants, lithium, antihistamines, calcium channel blockers, cocaine, diuretics, dopaminergics, ethanol, neuroleptics, and sympathomimetics.
Subjects were also excluded if they had a history of hypertension, cardiovascular disease, heart or lung disease, renal pathology, diabetes, asthma, or previous incidence of heat injury.

Participants were reminded of the need to maintain good hydration. On the day of a trial, they were asked to refrain from drinking caffeinated beverages three hours before the trial and not to participate in any vigorous exercise prior to each trial.

**Clothing**

For this study, there were five ensembles tested. The chemical protective barrier was Tychem® F®, also a vapor-barrier fabric.

1. WC: Work Clothes (without respirator) (Figure 2)

2. TAP+CA: TAP apron (Tychem F) over cloth coveralls with FF-NP-APR (Figure 3)

3. TAP+CA+P: TAP apron and pants (Tychem F) over coveralls with FF-NP-APR (Figure 4)

4. VB+CA: Protective coveralls (Tychem F) over cloth coveralls with FF-NP-APR (Figure 5)

5. VB+CA-noR: Protective coveralls (Tychem F) over cloth coveralls without respirator

The TAP apron is a full-length garment with long sleeves with an opening in the back with three buckle closures (see Figure 3). A cloth cotton coverall was worn underneath all the ensembles except work clothes. The base ensemble worn under the test ensembles was cotton tee shirt, gym shorts, socks and athletic shoes. No gloves or hoods were worn.
The trials were conducted in a controlled climatic chamber. The internal dimensions of the chamber are 2.7-m wide, 3.0-m deep and 2.2 m high. The possible range of environments in the climatic chamber were between 10 to 90% humidity and 4 to 60°C. Humidity for the experimental trials was controlled at 50% RH and air speed at 0.5 m/sec. Temperature was controlled according to protocol. The ambient environmental conditions inside the chamber were monitored using a Quest temperature monitor with measurements of the dry bulb, natural wet bulb and globe temperatures.

A motorized treadmill was used to control the metabolic rate and work demand through
settings of speed and slope to elicit a target metabolic rate of 170 W m$^{-2}$ and approximate moderate work independent of aerobic capacity.

Heart rate (HR) was monitored using a sports-type heart rate monitor (Polar Electro Inc., Lake Success, N.Y.). Rectal temperature was measured using a flexible thermistor inserted 10-cm beyond the anal sphincter muscle. Each participant self-inserted the rectal thermistor to a point 10 cm beyond the anal sphincter and self removed the rectal thermistor at the conclusion of each trial. Each participant was issued a sterilized rectal thermistor and used the same rectal thermistor over the course of the trials. After completion of each trial, the participants wiped down the probe with alcohol wipes followed by betadine wipes and then alcohol. Prior to the next trial and before each trial, staff wiped down the probe with alcohol wipes and then calibrated the rectal thermistor in a hot water bath with chlorine bleach. All other equipment was calibrated following laboratory standard procedures or per manufacturer’s recommendations.

Skin temperatures ($T_{sk}$) were measured using surface thermistors taped to four sites (chest, upper arm, thigh, and calf), following the method of Ramanathan [42]. Average skin temperature was $T_{sk} = 0.3 \ T_{ch} + 0.3 \ T_{arm} + 0.2 \ T_{th} + 0.2 \ T_{calf}$. Pre-trial and post-trial weight while wearing cotton tee shirt, gym shorts, socks and athletic shoes were taken on a Mechanical Linear Beam Medical Weight Scale.

Metabolic rate was estimated from assessment of oxygen consumption (VO2) using a Douglas bag method. Expired air was collected and sampled by having participants breath through a two-way valve attached to flexible tubing that was connected to the Douglas bag. The volume of expired air was measured using a dry gas meter. A small sample was removed from the collection bag and drawn into an oxygen analyzer to determine oxygen content. Comparison was then be made between the composition of inspired and expired air, allowing VO2 to be determined.
Protocols

Acclimatization

Prior to beginning the experimental trials, participants underwent a 5-day acclimatization to dry heat during which each participant walked on a treadmill for two hours at a metabolic rate of approximately 170 W m\(^{-2}\) in a climatic chamber set at 50°C and 20% RH. Participants wore the work clothes base ensemble during acclimatization trials. The acclimatization process is designed to maximize the sweating response.

Of concern was the 1 to 4% of the population that does not tolerate heat stress well and are considered heat intolerant. Heat intolerance will manifest itself in two ways during the acclimatization stage. First, the participant will not show signs of acclimatization by reaching a core temperature limit of 39 °C or heart rate limit of greater than 90% of the age maximum predicted heart rate (MPHR=220-age) in less than 60 minutes during the first two days or less than 90 minutes on the third day. Second, the participant will report nausea and/or vomiting associated with the heat exposure. If either of these two manifestations of heat intolerance had occurred, the participant would have been dropped from the study. None of the participants exhibited heat intolerance.

Experimental Trials

A progressive heat exposure protocol was used during the experimental trials. Each participant walked on the treadmill at a moderate rate of work (170 W m\(^{-2}\)). Each ensemble was worn by each participant. The order of ensembles was randomized in a balanced design. Pre-trial weight was recorded before the start of each trial and post-trial weight recorded at the completion of each trial. The heart rate monitor was secured with a chest strap. The four skin surface thermistors were attached, and rectal thermistor (after insertion by each participant in a
separate private dressing room) was taped to the participant’s upper buttock to prevent thermistor from being pulled out during trials. During trials, participants were allowed to drink water or a commercial fluid replacement beverage (Gatorade®) at will with volume of fluid ingested recorded each hour and at the end of each trial. If the pre-trial and post-trial weights showed a net loss of 1.5% or more of body weight, participant was advised to continue aggressive fluid replacement for the remainder of the day.

Initial dry bulb temperature ($T_{db}$) was set according to ensemble at 35°C for work clothes, 28 °C for TAP+CA and 23 °C for TAP+CA+P, VB+CA and VB+CA-noR. Relative humidity was set at 50% for all ensembles. Once the participant reached thermal equilibrium (no change in $T_{re}$ and heart rate for at least 15 minutes.), $T_{db}$ was increased 1 °C every 5 minutes.

Core temperature, heart rate and ambient environmental conditions (dry bulb, psychrometric wet bulb and globe temperatures, $T_{db}$, $T_{pwb}$ and $T_{g}$, respectively) were recorded at the start of each trial, then monitored continuously and recorded every 5 minutes. The metabolic rate was recorded for each trial and was the average of three estimates of oxygen consumption taken at approximately 30, 60, and 90 min into a trial. Metabolic rate was normalized to body surface area. In addition, participants were asked every 5 minutes how they felt and if symptoms such as lightheadness, dizziness, nausea, or increasing fatigue or weakness were present.

Trials were scheduled to last 120 minutes unless one of the following criteria was met: (1) a clear rise in $T_{re}$ associated with a loss of thermal equilibrium manifested as a 0.1 °C increase in $T_{re}$ every 5 min for 15 min, (2) $T_{re}$ reached 39 °C, (3) a sustained heart rate greater than 90% of the age- maximum predicted heart rate (MPHR=220-age), or (4) participants experienced sustained fatigue or weakness, light-headedness, nausea, dizziness, faintness, muscle cramps, or pains in the joints or muscles, or wished to stop.
At the end of each trial, participants were brought out of the chamber and the trial clothing ensemble was doffed and sensors (except rectal temperature) were removed. Participants were given water or other fluid replacement drink and asked if they wished to sit down for a while. All investigators and staff personnel remained in the area until each participant left the building. If during the trial, the participant was taken to 39 °C, rectal temperature is noted 5 minutes later to confirm that it is not increasing and monitored until it drops to 39 °C. If and of the above symptoms (i.e. dizziness, nausea, muscle cramps) occurred and core temperature was above 38.5 °C, then the temperature was also monitored to be sure that it did not continue to rise. None of these scenarios occurred during the experimental trials.

**Inflection Point and Determination of Critical WBGT**

The inflection point or critical condition marks the transition from thermal balance to the loss of thermal balance, where core temperature continued to rise. The chamber conditions five minutes before the noted increase in core temperature was taken as the critical condition. One investigator noted the critical condition and the decisions were randomly reviewed by a second investigator. The $WBGT_{crit}$ in °C was computed as $0.7 (T_{pwb} + 1.0) + 0.3 T_q^{[43]}$.

**Calculation of Clothing Parameters**

Estimations of $R_{e,T,a}$ from the progressive heat stress protocol are calculated with identification of the critical conditions at which the heat loss due to evaporative cooling is balanced by the net heat gain due to internal sources ($H_{net}$) and dry heat exchange $[17, 44, 45]$.

Evaporative cooling is derived from the vapor pressure difference between the environment [$P_a$] and the skin [$P_{sk}$] divided by the $R_{e,T,a}$. $H_{net}$ is derived from metabolic rate (M) minus the external work ($W_{ext}$), storage rate (S) and respiratory exchange rates by convection($C_{res}$) and evaporation ($E_{res}$). The dry heat exchange (for non-radiant environments)
is approximated by the difference between air \((T_{db})\) and skin \((T_{sk})\) temperatures divided by the resultant total insulation \((I_{T,r})\).

These relationships are illustrated by Equations 1 and 2 with values computed from trial data [17].

\[
R_{e,T,a} = \frac{(P_{sk} - P_a)}{(H_{net} + (T_{db} - T_{sk}) / I_{T,r})} \tag{1}
\]

\[
H_{net} = M - W_{ext} - S + C_{res} - E_{res} \tag{2}
\]

\(P_{sk}\) was the saturation pressure of water vapor at \(T_{sk}\). The external work \((W_{ext})\) was calculated \((W \text{ m}^{-2})\) as \(W_{ext} = 0.163 m_b \cdot V_w f_g / A_D\), where \(V_w\) was walking velocity in m/min, \(f_g\) was the fractional grade of the treadmill, and \(A_D\) was 0.202 \(m_b^{0.425} \cdot H^{0.725}\), where \(m_b\) was the mass of the body (kg) and \(H\) was the height (m) [45]. Respiratory exchanges, latent respiration heat loss \((E_{res})\) and dry respiration heat loss \((C_{res})\), were calculated as \(C_{res} = 0.0012 M (T_{db} - 34)\) and \(E_{res} = 0.0173 M (5.62 - P_a)\). \(A_D\) was 0.202 \(m_b^{0.425} \cdot H^{0.725}\) [44]. The rate of change in heat storage can be estimated knowing the specific heat of the body \((0.97 \text{ W h °C}^{-1} \text{ kg}^{-1})\), body weight \((m_b)\), and the rate of change of body temperature \((\Delta T_{re} \Delta t^{-1})\) as an average over the 20 minutes preceding the inflection point. That is, \(S = 0.97 m_b \Delta T_{re} A_D^{-1} \Delta t^{-1}[17, 45]\).

Static clothing insulation \((I_{T,stat})\) values were estimated for each ensemble. The resultant clothing insulation \((I_{T,r})\) to account for walking speed of an individual trial and air motion was estimated according to ISO 9920 (2007) (Equation 32) or \(CFI = \exp[-0.281 (v - 0.15) + 0.044 (v - 0.15)^2 - 0.492 w + 0.176 w^2]\), where air speed \((v)\) was taken as 0.5 m s\(^{-1}\) and walking speed \((w)\) was the treadmill speed (m s\(^{-1}\)) for the specific trial. The value of resultant clothing insulation was further reduced by 10% (multiplied by 0.9) to account for the reduction in insulation due to wetting [46, 47]. The estimated \(I_{T,r}\) was used to estimate \(R_{e,T,a}\) as noted in Equation 1 above (18). The CAF was calculated as the difference of the WBGT\(_{crit}\) for work
clothes minus the WBGT$_{crit}$ for the ensemble of interest.

Data Analysis

The primary dependent variables were $R_{e,T,a}$, WBGT$_{crit}$, HR, $T_{re}$, and PSI. Data were analyzed using statistical analysis software (SAS). Significance was tested at the $a < 0.05$ level ($p < 0.05$). A mixed effects analysis of variance (ANOVA) was used to determine if differences existed between the dependent variables and if clothing ensemble had any significant effect. Participants were treated as a random effect (clothing x participant [random effect]). Tukey’s multiple comparison test was used to determine where the main differences occurred.
Chapter Four:

Results

Table 4 summarizes the metabolic rates and critical conditions of the environment by ensemble. For metabolic rate normalized to body surface area (M), there were no differences among ensembles. Therefore the metabolic rate would not affect the outcome for WBGT\textsubscript{crit} and the other environmental factors at the critical conditions. Both the ambient air temperature (T\textsubscript{db, crit}) and vapor pressure (P\textsubscript{a, crit}) at the critical conditions decreased with clothing ensembles with higher evaporative resistances and clothing insulation (Table 5).

Table 5 summarizes the clothing thermal characteristics. The I\textsubscript{T,stat} (m\textsuperscript{2} °C W\textsuperscript{-1}) values were estimated and were treated as fixed values for all ensembles. The I\textsubscript{T,r} values were estimated following the ISO 9920 procedure (47). The standard deviation of the resultant insulation was very small (< 0.001 m\textsuperscript{2} °C W\textsuperscript{-1}) and therefore not included in the table. There were significant differences among ensembles for WBGT\textsubscript{crit} and R\textsubscript{e,T,a}. R\textsubscript{e,T,a} increased and WBGT\textsubscript{crit} decreased going from WC to TAP+CA to TAP+CA+P to VB+CA. WBGT\textsubscript{crit} was different between Work Clothes and TAP+CA and between WC and TAP+CA and the other ensembles, but there was no difference between TAP+CA+P and VB+CA or VB+CA-noR. R\textsubscript{e,T,a} was different between all ensembles, except no differences in WBGT\textsubscript{crit} and R\textsubscript{e,T,a} were observed between the presence and absence of a respirator with VB+CA.

Table 6 summarizes the physiological heat strain for each ensemble. There were no differences among all ensembles, including for the presence versus absence of the respirator, for rectal temperature, heart rate, and PSI.
Table 4. Metabolic rate and environmental conditions at critical condition by clothing ensemble.

<table>
<thead>
<tr>
<th>Clothing Ensemble</th>
<th>M* [W m⁻²]</th>
<th>T(_{db}), crit [°C]</th>
<th>P(_a), crit [kPa]</th>
<th>WBGT(_{crit}) † [°C-WBGT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>167 ±14</td>
<td>42.4 ±1.7</td>
<td>3.69 ±0.62</td>
<td>±1.5</td>
</tr>
<tr>
<td>TAP+CA</td>
<td>169 ±21</td>
<td>37.6 ±1.5</td>
<td>3.13 ±0.14</td>
<td>±1.3</td>
</tr>
<tr>
<td>TAP+CA+P</td>
<td>178 ±22</td>
<td>33.3 ±1.7</td>
<td>2.43 ±0.17</td>
<td>27.7 (^a)</td>
</tr>
<tr>
<td>VB+CA</td>
<td>175 ±19</td>
<td>31.0 ±1.7</td>
<td>2.18 ±0.20</td>
<td>25.9 (^b)</td>
</tr>
<tr>
<td>VB+CA-noR</td>
<td>172 ±23</td>
<td>31.4 ±1.4</td>
<td>2.24 ±0.14</td>
<td>26.2 (^a,b)</td>
</tr>
</tbody>
</table>

\(^*\)No significant difference in metabolic rate.

\(^†\) Values of WBGT\(_{crit}\) with the same letter are not significantly different.
Table 5. Thermal characteristics of the clothing ensembles.

<table>
<thead>
<tr>
<th>Clothing Ensemble</th>
<th>$I_{T,stat}$</th>
<th>$I_{T,r}$</th>
<th>$R_{e,T,a}$†</th>
<th>WBGT$_{crit}$†</th>
<th>CAF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m² °C W⁻¹]</td>
<td>[m² °C W⁻¹]</td>
<td>[m² kPa W⁻¹]</td>
<td>[°C-WBGT]</td>
<td></td>
</tr>
<tr>
<td>WC</td>
<td>0.18</td>
<td>0.106</td>
<td>0.0112</td>
<td>35.5 ± 1.5</td>
<td>0</td>
</tr>
<tr>
<td>TAP+CA</td>
<td>0.25</td>
<td>0.147</td>
<td>0.0175</td>
<td>31.6 ± 1.3</td>
<td>4</td>
</tr>
<tr>
<td>TAP+CA+P</td>
<td>0.27</td>
<td>0.159</td>
<td>0.0240</td>
<td>27.7 a</td>
<td>8</td>
</tr>
<tr>
<td>VB+CA</td>
<td>0.30</td>
<td>0.177</td>
<td>0.0287 b</td>
<td>25.9 b</td>
<td>10 / 12*</td>
</tr>
<tr>
<td>VB+CA-noR</td>
<td>0.30</td>
<td>0.177</td>
<td>0.0293 b</td>
<td>26.2 a,b</td>
<td>10 / 12*</td>
</tr>
</tbody>
</table>

† Values of $R_{e,T,a}$ and WBGT$_{crit}$ with the same letter are not significantly different.

* Due to the sensitivity of vapor-barrier clothing to humidity level, 12 °C-WBGT is the recommended CAF for a heat stress management program.
Table 6. Physiological strain for each clothing ensemble at critical conditions.

<table>
<thead>
<tr>
<th>Clothing Ensemble</th>
<th>$T_{re}$ [°C]</th>
<th>HR [bpm]</th>
<th>PSI†</th>
<th>$T_{sk}$ [°C]</th>
<th>$P_{sk, crit}$ [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>37.6 ±0.3</td>
<td>103 ±13</td>
<td>2.0</td>
<td>36.3 ±0.6</td>
<td>6.03 ±0.19</td>
</tr>
<tr>
<td>TAP+CA</td>
<td>37.5 ±0.4</td>
<td>107 ±16</td>
<td>1.8</td>
<td>36.4 ±0.2</td>
<td>6.05 ±0.08</td>
</tr>
<tr>
<td>TAP+P+CA</td>
<td>37.6 ±0.1</td>
<td>108 ±13</td>
<td>1.9</td>
<td>36.2 ±0.3</td>
<td>5.99 ±0.11</td>
</tr>
<tr>
<td>VB+CA</td>
<td>37.5 ±0.4</td>
<td>107 ±12</td>
<td>1.8</td>
<td>36.2 ±0.4</td>
<td>6.02 ±0.22</td>
</tr>
<tr>
<td>VB+CA-noR</td>
<td>37.7 ±0.2</td>
<td>104 ±18</td>
<td>1.8</td>
<td>36.4 ±0.4</td>
<td>6.08 ±0.14</td>
</tr>
</tbody>
</table>

† PSI = $5(T_{re} - T_{re0})/(39.5 - T_{re0}) + 5(HR - HR_{0})/(180 - HR_{0})$

where initial values were taken at time zero of the trial (26).
Chapter Five:

Discussion

The determination of WBGT\textsubscript{crit} is influenced by the metabolic rate [19]. As metabolic rate increases, the WBGT\textsubscript{crit} decreases [25]. The results in Table 4 show there were no significant differences in the mean metabolic rates among the ensembles. The mean metabolic rates for all the ensembles show that for each participant worked at a moderate metabolic rate. This means that there were no systematic effects related to differences in metabolic rate that would compromise the findings for WBGT\textsubscript{crit} or the physiological data.

Resultant clothing insulation (I\textsubscript{T,r}) were estimated from the ISO 9920 (2007) method and were further reduced by 10% to account for the reduction in insulation due to wetting of the clothes (46). The values for I\textsubscript{T,r} and R\textsubscript{e,T,a} Table 5 support that as clothing insulation increases so does the R\textsubscript{e,T,a} increase, indicating a decrease in evaporative cooling capacity with increased in clothing insulation.

The WBGT\textsubscript{crit} and R\textsubscript{e,T,a} for work clothes were 35.5 °C-WBGT and 0.0112 kPa m\textsuperscript{2} W\textsuperscript{-1} respectively. These values were similar to those reported in previous studies from USF using the same moderate work rate and 50% relative humidity protocol [17-19]. Both cotton coveralls and vapor-barrier coveralls were studied previously with reported values for R\textsubscript{e,T,a} of 0.013 and 0.032 kPa m\textsuperscript{2} W\textsuperscript{-1}, respectively [17]. The cotton coveralls in the current study were of similar weight and construction. The difference in the vapor-barrier clothing between the current study and previous study by Caravello [17] was the use of Tychem QC versus Tychem F in the current study. Tychem F is stiffer than Tychem QC. The VB+CA (with or without respirator) over cotton coveralls combination in the current study had a R\textsubscript{e,T,a} of 0.029 kPa m\textsuperscript{2}.
with a standard deviation of 0.003 kPa m² W⁻¹. Based on this comparison between the vapor-barrier (VB) ensemble alone in the previous Caravello study and the VB ensemble over cloth coveralls, there was little difference in evaporative resistance between a VB ensemble alone or VB ensemble over cloth coveralls. This implies by first order approximation that the $R_{e,T,a}$ was driven by the vapor-barrier ensemble construction alone with no real contribution from the cloth coveralls. There did not appear to be much difference between the $R_{e,T,a}$ between the Tychem F and Tychem QC (0.029 + standard deviation of 0.003 and 0.032 kPa m² W⁻¹ respectively) despite the increased stiffness of the Tychem F. The TAP apron and TAP apron plus pants were not tested previously. Table 5 demonstrates there was a clear increase in evaporative resistance moving from the TAP apron to the TAP apron plus pants to the vapor-barrier coverall. It is more difficult to know if stiffness was a contributing factor for these differences, but the increases in $R_{e,T,a}$ were likely due to the progressive decrease in the degree of air motion under the top layer of clothing [21,22].

Table 5 also clearly shows there was a progressive drop in WBGT_{crit} and similar increase in $R_{e,T,a}$ going from TAP+CA to TAP+CA +P to VB+CA, all while wearing a respirator. This inverse relationship was observed previously [17]. The WBGT_{crit} was adversely affected by the clothing ensemble worn and progressively decreased moving from WC to TAP+CA to TAP+CA+P to VB+CA, all while wearing a respirator. WBGT_{crit} was not adversely affected or changed with the wear of the respirator. These WBGT_{crit} results indicate that the heat exposure times will progressively decrease moving from WC to TAP+CA to TAP plus pants to VB+CA.

No differences in WBGT_{crit} and $R_{e,T,a}$ were observed for the presence or absence of a respirator with VB+CA, indicating there was no added heat stress associated with wear of the respirator. Therefore, heat exposures times would not be decreased with wear of a respirator.

Table 5 reports the CAFs for each clothing ensemble. CAFs increased going from WC to TAP+CA to TAP+CA+P to VB+CA. For VB+CA, CAF was 10 °C-WBGT. When compared to the 8 °C-WBGT for the VB ensemble reported previously [18] using the 50% RH progressive
heat exposure protocol, there was an increase of about 2 °C-WBGT that could be assigned to the double layer (VB+CA over cloth overalls) over the single layer VB ensemble used in the current study. While the $R_{e,T,a}$s were the same, there was a difference in CAF. The standard error of estimate of approximately 1.6 °C-WBGT in the previous study may help explain and account for these differences and discrepancies [18]. The CAFs follow the $R_{e,T,a}$ in a linear fashion as found previously [17].

Work clothes are the standard of comparison for CAF and thus 0 by definition. The TAP+CA ensemble exhibits a significant increase in heat stress potential with a CAF of 4 °C-WBGT. The CAF of 8 °C-WBGT for the TAP+CA+P represents a further important increase of 4 °C-WBGT secondary to the addition of pants. But the TAP+CA+P is still better than moving to a VB+CA with a CAF of 10 °C-WBGT, which is a change of 6 °C-WBGT from the standard TAP (TAP+CA). Conversely, there is an advantage and decrease in heat stress to moving from VB+CA to TAP+CA+P. Because the vapor-barrier ensemble is particularly sensitive to humidity, adding a further 2 °C-WBGT to the observed CAF as noted previously by Bernard et al. for VB+CA in this study would be recommended [18]. Thus the recommended CAF for heat stress management purposes is 12 °C-WBGT.

For a typical summertime humidity ($P_v = 2.5$ kPa), there is about a 2:1 change in air temperature for a change in WBGT. For example, the 4 °C-WBGT change associated with going from TAP+CA to TAP+CA+P would add 8 °C to the air temperature; and the 6 °C-WBGT (or 8 °C-WBGT in high humidity environments) change moving to the protective coveralls (VB+CA) from TAP+CA would be equivalent to adding 12 to 16 °C.

These changes in clothing requirements are very substantial. In comparison, moving from VB+CA to TAP+CA+P would be equivalent to lowering the air temperature by 4 °C. As there were no differences in WBGT$_{crit}$ for the presence or absence of a respirator, CAF for the VB+CA and VB+CA-noR are the same.
Based on the $\text{WBGT}_{\text{crit}}$, $R_{e,T,a}$ and CAF, there were significant increases in heat stress going from WC to TAP+CA to TAP+CA+P to VB+CA. Heat stress was primarily affected by the clothing ensemble, not the respirator. This implies that the type of protective clothing ensemble worn will play a much bigger role in workplace heat stress risk than wearing a respirator. This is an important point when medically clearing a worker for respirator wear. Consideration of the type of clothing ensemble needed for protection from workplace hazards that will impose the least heat stress burden would be the priority in lowering heat stress risk. A worker could add a respirator if needed for inhalational hazard protection without significant concern for increased heat stress.

Still open is whether a respirator adds to the physiological burden. Looking to the physiological state and strain at the critical conditions reported in Table 6, no significant differences were found for rectal temperature, skin temperature, heart rate, and PSI among any of the clothing ensembles. This was also seen in a past study with a larger cohort [25]. There was no difference in physiological strain due to respirator in the trials that compared the presence and absence of a full-face negative pressure respirator. This was consistent with the findings of other studies using fixed environment protocols [28, 29, 31, 35, 37, 40].

Of note, the PSI showed evidence of low heat strain at $\text{WBGT}_{\text{crit}}$ supporting use of WBGT as a better protective measurement in preventing increased physiological strain from heat exposures which can lead to HRI.

Limitations

The effect of the respirator was examined under one clothing condition, the VB+CA, which was the one most restrictive of evaporative cooling. The effect of the respirator should have been greatest under this condition. Although the TAP+CA and TAP+CA+P were not compared to a no respirator combination, it is unlikely that the respirator would have a measureable effect in these less restrictive ensembles.
In addition, randomized clinical trials can often exhibit selection bias which limits their external validity. The participants were young, healthy male volunteers which could potentially introduce a healthy worker and volunteer biases. This would primarily the heat strain effects, but not likely the heat stress effects. Although our study tested the various clothing ensembles in males only, Ashley et al. showed that despite women exhibiting higher PSI, women did not show significant differences in $\text{WBGT}_{\text{crit}}$ or heat stress compared to men [25]. Therefore, one could predict similar results for heat stress, $\text{WBGT}_{\text{crit}}$ and CAF had women been included in the current study. The study participants were of the same race, caucasian males. There is no evidence that there are racial differences in physiological response to heat stress. [48]. The average age was 21.5 with a range of 21-22. Studies of heat related mortality show a larger effect in the elderly with the risk increasing above age 50 [49]. Saha et al. has shown that cardiac strain is increased in older workers (mean age 48.9 +/- 2.7 yr) [50].

However, other studies have shown that if effects of chronic debilitation disease in those 64 and older are minimized, heat tolerance and thermoregulatory responses are comparable to younger individuals. [51]. Cardiac disease and older age are personal risk factors for HRI. Previous studies have shown HRI is associated with increased cardiac events and ischemic heart disease and those with underlying ischemic heart disease exhibit higher heat related mortality [12,13],[52]. However, If studies with older workers or those with chronic disease serve as their own controls, are acclimatized so they exhibit a full sweating response, with metabolic rates normalized, the resultant heat stress (CAFs and $\text{WBGT}_{\text{crit}}$) could be predicted to be similar to the current study. What would be different, potentially, in these populations would be the physiological strain exhibited at the $\text{WBGT}_{\text{crit}}$. The workforce is aging with the potential for the presence of chronic disease increasing. Future research into comparison studies in older workers or those with chronic disease compared to younger, healthy workers can confirm whether older workers or those with chronic disease truly exhibit the same predicted critical $\text{WBGT}$ and heat stress, with increased predicted heat strain. Future studies can also compare the various clothing ensembles in older workers and those with
chronic disease to determine if they would exhibit similar physiological strain among ensembles as our study demonstrated.

Conclusions

In summary, it is clear from this study that changing the TAP ensemble to include Tychem F pants or moving to Tychem F coveralls will place a significant added heat stress burden on the wearer. However, the addition of a full-face negative pressure respirator does not impose an increase in either heat stress or heat strain. The type of protective clothing ensemble worn will play a much bigger role in workplace heat stress effects and risk than the wear of a respirator.
References


