ELECTRIC POWER RESEARCH INSTITUTE

Heat Stress for Workers in the Electric Power Industry

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Heat Stress for Workers in the Electric Power Industry

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Abstract

Electric power workers can be exposed to the high temperatures and humidity of the coastal and Midwest regions of the United States during the summer or the hot, dry conditions typical for the Southwest of the United States. In addition, linesmen may be required to don personal protective equipment such as coveralls, a helmet, and rubber gloves as well as flame- and arc-resistant clothing that allow them to work electrical power transmission and distribution lines without service interruption. Personnel working indoors may be required to don respirators and chemical or specialized protective garments to create a barrier between their respiratory system and skin surface and the potential hazards of their work environment. The resultant rise in body temperature, or heat strain, could place these workers at increased risk of heat injury.

Currently, the severity of the exposure to heat stress and the resultant heat strain experienced by electric power workers is not known. Information about the rates of heat production required to conduct daily operational work tasks and rates of fluid loss together with the thermal burden associated with wearing specific protective clothing ensembles is critical to help prevent heat injuries. Knowledge of those factors that place workers at greatest risk of becoming a heat casualty will provide opportunities for implementing intervention strategies to manage these risks. As a result, time lost due to workplace injury or poor health could be reduced and productivity may be increased.

This report summarizes the factors that determine body heat storage and subsequent heat tolerance. In addition, the report discusses options that have been used successfully in other occupational settings to help slow the rate of increase in body temperature and/or increase the worker's ability to safely store heat, while identifying areas in which additional research would be of direct benefit to workers in the electric power industry.

Keywords

Body heat storage
Body temperature regulation
Heat tolerance
Protective clothing
Thermal strain

List of Abbreviations

ACGIH	American Congress of Government Industrial Hygienists
ARC	arc resistant clothing
ATP	adenosine triphosphate
C	convective heat transfer
CON	control
C_{resp}	respiratory convective heat transfer
dht_c	dry heat transfer coefficient
E	evaporative heat loss
E_{resp}	respiratory evaporative heat loss
E_{sk}	skin evaporative heat loss
eht_c	evaporative heat transfer coefficient
EPRI	Electric Power Research Institute
H_b	body heat content
hc_b	heat capacity of the body
K	conductive heat transfer
kg	kilogram
kJ	kilojoule
M	metabolic rate of heat production
m^2	surface area
NFPA	National Fire Prevention Association
OHSD	Occupational Health and Safety Database
P_{amb}	ambient vapor pressure
P_{sk}	skin vapor pressure
R	radiative heat transfer
S	heat storage
T_{amb}	ambient temperature
T_b	body temperature
$T_{b,\ Final}$	final body temperature
$T_{b,\ Initial}$	initial body temperature
T_{sk}	skin temperature

TT	tolerance time
T2D	Type II Diabetes
W	watts
W_{ex}	external work
°C	degrees Celsius
λ	proportion of skin wettedness

Glossary of Terms

arteriovenous anastomoses	a network of blood vessels located near the skin surface in the palms of the hands and the finger tips and soles of the feet and toes that promote an effective transfer of warm arterial blood to the skin surface
body mass index	a ratio between height and mass often used to establish norms for individuals of different body dimensions
body water	the total amount of fluid contained with the body, which can vary between 50-70% of body mass
cardiovascular strain	the increase in heart rate
compensable heat stress	environmental conditions (temperature and relative humidity) that promote sufficient evaporative and/or dry heat loss to match the rate of heat production and maintain heat balance
conductive heat transfer	the rate of heat transfer in a solid material down a thermal gradient
convective heat transfer	the rate of heat transfer in a moving gas or fluid down a thermal gradient
core temperature threshold	body temperature associated with an increase in the effector response for processes governing sweat production or vasodilation of skin blood flow
dehydration	a dynamic process that occurs when the avenues of body fluid loss exceed those of fluid replacement

dry heat transfer	the transfer of heat through the combined processes of convection, conduction and radiation
dry heat transfer coefficient	the ratio of heat transfer through the combined processes of convection conduction and radiation to the temperature difference between the skin surface and the environment
extracellular fluid volume	the volume of fluid located outside of the cells in the body
euhydration	a normal state of body water content
evaporative (wet) heat loss	heat loss through the evaporation of water from the skin surface and the respiratory tract
evaporative heat transfer coefficient	the ratio of heat transfer through evaporation to the vapor pressure difference between the skin and the environment
heat acclimation	the adaptive changes that occur within the body, in response to repeated exposure to hot ambient environments, that result in a reduction in heat strain and improved heat tolerance
heat balance	the condition where heat gain in the body equals heat loss to the environment
heat casualty	an individual being unable to physically and/or mentally function due to heat strain
heat content	the amount of heat in the body determined as the product of its mass, mean body temperature and specific heat
heat injury	a condition associated with a continuum of clinical conditions, such as headache, nausea, general fatigue, exhaustion and confusion
heat sink	the transfer of heat from the body to a bolus of ingested cold water

heat storage	the rate of increase in the heat content of the body caused by the imbalance between heat production and heat loss
heat strain	the increase in body temperature
heat tolerance	the ability to tolerate high ambient temperatures and large increases in heat strain
heat transfer	the process, or rate, where heat energy is transferred
hypohydration	a lower than normal body water content
intracellular fluid volume	the volume of fluid within the cells of the body
metabolic heat production	the transformation of chemical energy into heat
metabolic rate	the rate of heat production
microclimate cooling	various systems that incorporate air, liquid or phase change materials to provide direct cooling to the body when it is worn
microenvironment	the temperature and humidity within the clothing layers that surround the skin surface
orthostatic intolerance	an inability to maintain an upright posture
plama volume	the volume of fluid contained within the blood vessels of the body
protective clothing	the clothing ensemble required by workers to protect them from the hazards of their work environment
radiative heat transfer	the rate of heat transfer through radiation between two objects down a thermal gradient
radiopill	a pill that is swallowed and as it transverses through the intestinal tract a radio signal is transmitted that is proportional to the internal body temperature
skin wettedness	the proportion of the skin surface covered by sweat

specific heat	the amount of heat required to raise the temperature of an object's unit mass one degree Celsius
surface area to mass ratio	the ratio governing heat exchange to the environment
thermal burden	the associated thermal and cardiovascular strain to the body
thermal equilibrium	synonym to heat balance
thermal properties of clothing	both the thermal resistance, or insulation, and evaporative resistance, or water vapor permeability, of the clothing ensemble
thermal strain	synonym to heat strain
uncompensable heat stress	environmental conditions together with rates of heat production that lead to continued increases in heat storage and body temperature
urine specific gravity	a value measured in the urine that indicates the body's state of hydration
vapor pressure	the pressure exerted by water vapor determined by the temperature and relative humidity

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Section 1: Introduction

Humans are homeotherms and under most conditions regulate their body temperature (T_b) within a narrow range between 35°C and 39°C regardless of the external environment[1]. When heat production is increased during periods of work or exercise, humans are generally successful in maintaining a thermal steady-state by activating heat loss mechanisms to dissipate the excess body heat. However, under certain conditions where environmental temperature and humidity are very high or the necessity to wear protective clothing restricts the body's ability to dissipate internal heat, T_b can continue to increase to dangerously high levels (for review see[2]). Indeed, electrical power workers can be exposed to the high temperatures and humidity of the coastal and Midwest regions of the United States during the summer months or the hot, dry conditions typical for the Southwest of the United States. In addition, linesmen may be required to don personal protective equipment such as coveralls, a helmet and rubber gloves and flame and arc resistant clothing that allow them to work electrical power transmission and distribution lines without service interruption. Other personnel working indoors may also be required to don respirators and chemical or specialized protective garments to create a barrier between their respiratory system and skin surface and the potential hazards of their work environment.

The resultant rise in T_b, or heat strain, could place these workers at increased risk of heat injury; a condition associated with a continuum of clinical symptoms, such as headache, nausea, general fatigue, exhaustion and confusion, which lead to reduced productivity[3] and time away from work[4]. In addition, the acute increase in heat strain affects cerebral metabolism[5-8] and psychomotor function[9-12] creating an increased likelihood of workplace accident or injury due to reduced vigilance and poor decision-making[13, 14]. The Electric Power Research Institute provides an annual report of injury rates for a number of utility companies in the U.S.[15] Overall, injury rates averaged close to 3.5 per 100 employee-years in 2009 with sprains and strains representing the most common type of injury with the highest associated medical costs[15]. In addition, injury rates were highest among linesmen and meter readers working outdoors. While the Occupational Health and Safety Database (OHSD) is a valuable initiative, it is of interest to note that neither the environmental conditions nor the time of day are considered as independent factors to characterize these injury rates. Clearly environmental heat stress and the resultant body heat strain is expected to be higher during the summer months and fatigue and T_b will likely be greater in the afternoon or during the latter portions of the work day[16] and this in turn may increase the likelihood of accidents[14, 17].

Currently the severity of the exposure to heat stress and the resultant heat strain experienced by electric power worker is not known. Information about the rates of heat production required to conduct daily operational work tasks and rates of fluid loss together with the thermal burden associated with wearing specific protective clothing ensembles is critical to help prevent heat injuries. Knowledge of those factors that place workers at greatest risk of becoming a heat casualty will provide opportunities for implementing intervention strategies to manage these risks. As a result, time lost due to workplace injury or poor health could be reduced and productivity may be increased.

The following review summarizes those factors that determine body heat storage and subsequent heat tolerance. In addition, the review discusses options that have been used successfully in other occupational settings to help slow the rate of increase in body temperature and/or increase the worker's ability to safely store heat, while identifying areas where additional research would be of direct benefit to workers in the electrical power industry.

Section 2: Principles of Temperature Regulation

Heat Transfer

Mechanisms of heat transfer are grouped into two general categories consisting of dry (radiative (R), conductive (K), convective (C)) and wet (evaporative (E)) pathways. Dry heat exchange is dependent on the temperature gradients within the organism (e.g., core to periphery) and also between the organism and the environment. In addition, the rate of cutaneous blood flow to transport heat from the core to the periphery as well as the wind speed over the skin surface influence the degree of dry heat exchange[18]. Conductive heat transfer requires physical contact between two objects and would be most relevant in an occupational setting when workers are sitting in hot vehicles. For workers in an outdoor setting or moving freely indoors, the following equation can be used to determine dry heat transfer between the body and the environment[19];

$$[R+C] = (T_{sk} - T_{amb}) \cdot dht_c \qquad \textit{Equation 2-1}$$

where T_{sk} represents mean skin temperature, T_{amb} represents ambient dry-bulb temperature and dht_c represents the dry heat transfer coefficient. It is very important to recognize that dry heat transfer defines a source of ***body heat loss*** only if T_{sk} exceeds T_{amb}. Once T_{amb} exceeds about 37°C, dry heat transfer represents a source of ***body heat gain*** which will be magnified by higher wind speeds. Thus individuals working outdoors in hot windy conditions will gain additional heat from the environment while they perform various tasks.

Redistribution of regional blood flow to the skin[20] is the only controllable means by which heat can be transferred from within the body core to the skin surface when it can be exchanged with the environment. Therefore, vasodilation of the cutaneous vasculature, and the subsequent increase in skin blood flow, is an important process to help maintain heat balance during work in hot environments. Increases in skin blood flow during heat stress are primarily stimulated by increases in T_b [21], such that skin blood flow increases linearly with increases in T_b beyond a core threshold temperature[22]. The ultimate purpose of increasing skin blood flow is to induce changes in skin temperature which affect the rate of dry heat exchange with the environment (see Equation 2-1). When T_{amb} exceeds T_{sk}, increasing skin blood flow will serve to raise T_{sk}, which decreases the temperature gradient between the skin and ambient air, consequently reducing the rate of dry heat gain from the environment. In contrast, when T_{sk} exceeds T_{amb}, increasing T_{sk} via increased skin blood flow will create a greater skin to air temperature gradient, favoring a greater rate of dry heat loss to the environment.

Wet heat loss arises from the evaporation of water, typically secreted by the sweat glands within the skin. The potential for evaporative heat loss is determined primarily by the water vapor pressure gradient between the body surface and the environment, which in turn may be modified both by the environment, clothing and wind speed[23]. The following equation defines evaporative heat loss from the body[19];

$$E = \lambda \cdot (P_{sk} - P_{amb}) \cdot eht_c \qquad \textit{Equation 2-2}$$

where λ is the proportion of skin wettedness, P_{sk} represents the vapor pressure on the skin surface, P_{amb} is the ambient vapor pressure and eht_c represents the evaporative heat transfer coefficient, which increases with increasing wind speed over the skin surface. Vapor pressure is determined by temperature and relative humidity. Thus in very hot but dry environments despite the high T_{amb} the low humidity creates a vapor pressure gradient away from the skin surface, which maintains effective evaporative cooling as an avenue for heat loss from the body. Maximal P_{sk} would occur when T_{sk} approached 37^{o}C and the entire skin surface was wet ($\lambda = 1.0$). However, high levels of skin wettedness are not only very uncomfortable[24,25] but they slow the rate of sweat production to help conserve body fluid loss through excessive dripping of sweat from the skin surface[26].

Each gram of sweat evaporated at the skin surface releases 2.43 kJ of heat from the body[27]. Millions of sweat glands are distributed all over the body[28] and sweat is secreted above a threshold T_b with the sweat rate increasing in direct proportion to the rise in T_b [29,30]. As a result, a high sweat rate for normally inactive individuals unaccustomed to heat exposure would indicate a high T_b. However, as individuals improve their cardiovascular fitness through regular aerobic exercise, sweat rates will increase at any given T_b above the threshold temperature for the initiation of the sweating response[31]. In addition, repeated daily exposures to the heat that elevate T_b for several hours per day will decrease the threshold temperature that initiates the sweating response[31] and further increase the sweat rate at any given T_b. If this process of ***heat acclimation*** is performed in a humid environment sweat rates also will be less affected by increasing levels of skin wittedness[26]. Collectively, optimal sweat rates to promote evaporative cooling will be evident for those individuals who are regularly active and accustomed to work in hot environments. The adaptations that occur in the sweat rate response to a given T_b are shown in Figure 2-1 below.

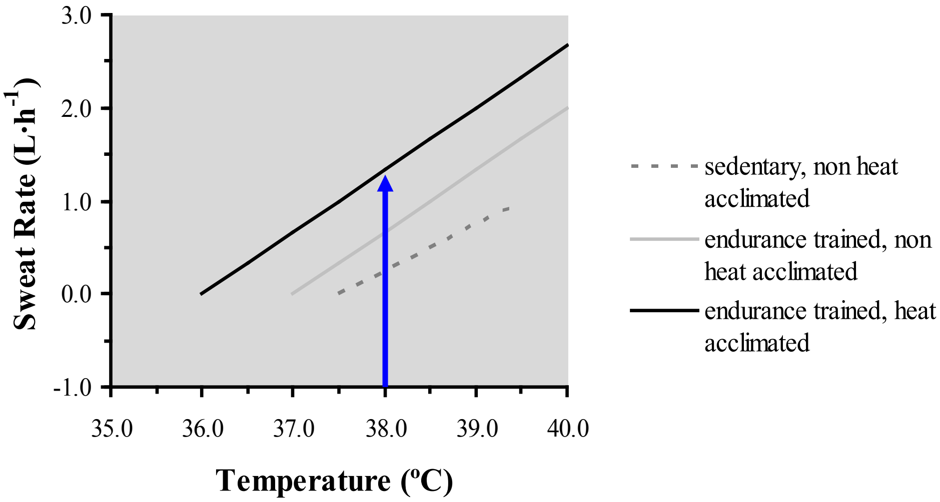

Figure 2-1
Sweat Rate Adaptation to Regular Aerobic Exercise and Heat Acclimation [Adapted from Nadel et al.[31]]

The blue vertical line indicates the increase in sweat rate that would occur at a T_b of 38.0ºC through the process of regular aerobic exercise together with daily exposure to a hot environment. The higher sweat rates would support greater rates of evaporative cooling and heat loss from the body, thereby enabling greater rates of heat production through work to be sustained during exposure to a hot environment (see below).

Influence of Clothing

When unclothed, the regulation of thermal energy exchanges between humans and the ambient environment can occur directly across the skin. When clothing is worn, however, an air layer is formed directly above the skin surface, and this microenvironment forms the initial environmental layer between the body and the environment. Multiple clothing layers form a successive series of microenvironments, each with its own thermal characteristics of temperature and humidity, through which metabolically generated heat must pass before being dissipated to the ambient environment[32]. Therefore, the thermal properties of clothing, such as its insulation, ventilation, and permeability to water vapor, have a significant influence on the rate of heat transfer between the skin and the ambient environment[33].

Maximal evaporative heat dissipation from the body occurs when secreted sweat is vaporized at the skin[29]. When wearing protective clothing, much of the sweat may become absorbed into the clothing and trapped. The wetting or saturation of clothing by sweat may affect both the thermal or protective characteristics of the clothing and also influence the rate of heat transfer[34]. In addition, the site of phase change may be raised above the skin due to the clothing microenvironment and a portion of the heat energy of vaporization may come from the environment rather than the body, thus further decreasing the efficiency of evaporative heat loss[35]. This process is shown below schematically in Figure 2-2.

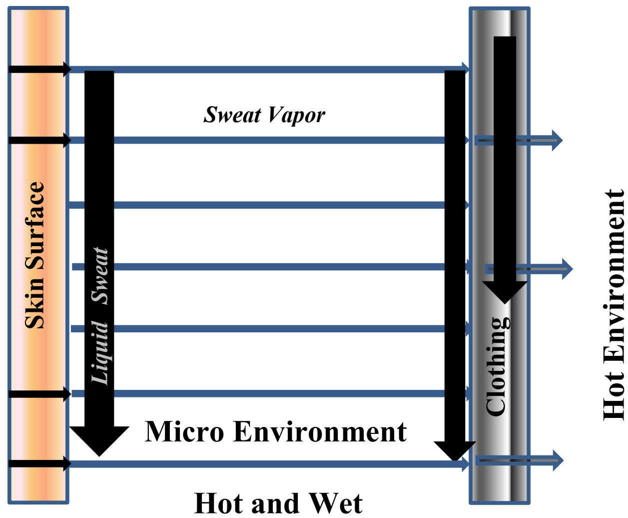

Figure 2-2
Sweat Production and its Vaporization through Clothing Together with Sweat Lost through Dripping off the Skin Surface and Condensation in the Clothing Layers.

The wearing of protective clothing is often required to shield the individual from environmental hazards or from injury. While protective clothing is being continually improved and lightened, the requirement for environmental protection is generally contradictory to the desire for adequate ventilation. Protective clothing is typically heavy, thick, multi-layered, and bulky. For electric power line workers protective clothing may include impermeable rubber gloves and aprons or flame and arc resistant suits depending on the method used to work on live power grids. Figure 2-3 below depicts some of the protective clothing that might be used. Also, note that there is no airflow within the bucket used to guide workers to work on overhead power lines, thereby further limiting any evaporative heat transfer.

Figure 2-3
Examples of Protective Clothing worn by Electrical Power Workers

Indeed, recent Occupational Safety and Health Administration guidelines require the use of the flame and arc resistant clothing that comply with the National Fire Protection Association's (NFPA) consensus standard for electrical safety in the workplace, commonly known as NFPA 70E. An example of this heavy shirt and its use are depicted below in Figure 2-4.

In addition, the thermal strain associated with the use of this arc resistant clothing was recently demonstrated in our human calorimeter. Participants exercised for 30 minutes at a moderate work rate of 600 W exposed to 35ºC and 20% relative humidity while wearing either a standard cotton shirt and pant or this arc resistant clothing. These preliminary findings are shown in Appendix A, where it can be seen that the change in body heat content (and therefore the level of thermal strain) during exercise was 58% greater with the arc resistant clothing (332 kJ) as compared with the standard cotton shirt and pant uniform (210 kJ). This was paralleled by an elevated level of cardiovascular strain (end-exercise heart rate of 160 and 144 beats·min^{-1} for the arc resistant clothing and standard cotton shirt and work pant clothing conditions, respectively).

Figure 2-4
A Flame and Arc Resistant Protective Shirt worn by Electrical Power Workers

Heat Production

A constant supply of energy is required for muscles to continue to contract and perform work. The oxidation of metabolic fuels such as carbohydrate and fatty acids in the mitochondria of the muscle fibers produces adenosine triphosphate (ATP). Through the hydrolysis of ATP, energy is released to support muscle contraction. However, the hydrolysis of ATP also releases heat. As the intensity and/or duration of work increases, greater amounts of oxygen must be consumed to support the continued demand for ATP production to support the muscle contraction. As a result, greater amounts of heat are produced, which must be released from the body to prevent excessive heat storage and rise in T_b.

The increased heat production by the active muscles at the onset of work is not immediately matched by an increased heat loss response. In fact, much of the heat produced in the early stages of work or exercise will be stored in the active muscles and muscle temperature will increase[36]. As muscle temperature increases, heat transfer within the body will occur through conductive heat exchange between the working muscle and the blood, and from the working muscle to the surrounding tissues and compartments[37]. As heat is stored, T_b will rise beyond the threshold values necessary to activate heat loss responses through cutaneous vasodilation and sweating[18].

Regardless if the work involves contraction of the arm or leg muscles, the amount of heat produced is a function of the amount of oxygen consumed[38]. However, a larger muscle mass would have a greater capacity to consume oxygen and would demonstrate less fatigue over time than a smaller muscle mass. Work tasks are generally classified as light, moderate or heavy based upon their rates of heat production. The demarcation between classification categories can vary somewhat but, as an example, the American Congress of Government Industrial Hygienists (ACGIH) uses 225 and 400 W to define the upper limits of work classified as light and moderate, respectively. Table 2-1 describes work tasks that could represent some of the duties of electric power workers. It should be noted that the rates of heat production associated with these tasks are estimates and, with the exception of the effort involved with digging to lay underground cable[39], have not been verified in the field with direct measurement; there is clearly a need to more accurately validate the rates of heat production that represent these work tasks.

Table 2-1
Description of a sample of typical work tasks for electric power workers categorized into light, moderate, or heavy rates of heat production.

Light (< 225)	Standing for extended periods of time while in hooks, ladders and buckets or on poles and towers performing repairs and servicing wires. Driving vehicles to and from work sites, patrol lines. Crouching or kneeling to perform repairs.
Moderate (> 225 and < 400)	Operating trucks and heavy equipment. Working in awkward positions on towers and poles including overhead and frontal reaching to perform repairs. Connecting secondary service wires. Walking on level ground to obtain meter readings. Connecting conduit. Forming the ends of a lead sleeve.
Heavy (> 400)	Climbing poles and towers. Walking for extended periods and distances while patrolling sites over rough, steep and uneven terrain. Lifting and carrying tools and equipment over extended distances. Loading equipment onto carts and pushing carts extended distances through utility plants. Pulling equipment and tools from the ground to the tower utilizing hoists and riggings. Driving ground rods and connecting ground wires. Storage and handling of prepackaged hand coils of wire. Loading/unloading cross arms onto trucks. Installing portable roadway systems and bridges. Digging pole holes and installing anchors on private property or digging to lay underground cable. Pulling cable through conduit in manholes or vaults. Dowelling concrete. Levelling padmount transformers. Excavating to expose underground utilities. Moving large breakers. Installing and removing temporary wire and cable.

Heat Storage

Heat storage (S in kJ) is the difference between all sources of heat gain and all avenues of heat loss by the body. Often S is expressed per unit of time indicating a rate of heat storage in watts (W or $J \cdot s^{-1}$). To account for differences in body size, surface area (m^2) or body mass (kg) may be included in the expression for the rate of heat storage. If at any given time, S is zero then the body is in thermal equilibrium and there will be no change in T_b. If the rate of S is zero, then T_b will be constant over time. Conversely, if S is positive then T_b will increase. The equation used to calculate the rate of S is shown below;

$$S\ (W) = M - W_{ex} \pm (C+R+K) - E_{sk} - E_{resp} \pm C_{resp} \qquad \textit{Equation 2-3}$$

where M is the rate of heat production, W_{ex} is external work, C,R and K are convective, radiative and conductive dry heat transfer, respectively, E_{sk} is skin evaporative heat loss, E_{resp} is evaporative heat loss through respiration and C_{resp} is convective heat transfer through respiration. Since C,R and K are a function of the temperature gradient between the skin surface and air layer above the skin (or between inspired and expired air temperature) these values can represent an avenue of heat loss (if skin temperature exceeds air temperature) or source of heat gain (if the reverse conditions exist).

In very cool environments, avenues of dry heat loss may be sufficient to match the sources of heat production such that little or no E_{sk} is required. However, as the thermal gradient between the skin and surrounding air layer decreases then a greater proportion of heat loss through E_{sk} is required to maintain a thermal equilibrium.

Environmental conditions (temperature and relative humidity) that promote sufficient evaporative and/or dry heat loss to match the rate of heat production and maintain a thermal equilibrium are defined as ***compensable heat stress.*** The state of thermal equilibrium, or zero rate of S, can be maintained for hours as long as fluid replacement matches the fluid lost through E_{sk} and E_{resp}.

In contrast, environmental conditions together with rates of heat production that lead to continued increases in rates of S and T_b are defined as ***uncompensable heat stress***. These conditions can be the result of wearing protective clothing and/or high environmental vapor pressures that restrict E_{sk} (see above). In addition, uncompensable heat stress can result because the rate of sweat production is insufficient to generate sufficient heat loss through E_{sk} (see Figure 2-1). As a result, the same environmental conditions and rates of heat production may define uncompensable heat stress for a sedentary individual, whereas for endurance trained and/or heat acclimated individuals these conditions may define compensable heat stress. Thus, even though workers may be performing the same tasks in the same environmental conditions, some of them may be at risk to heat injury whereas others can continue being productive with no associated health concerns.

Heat Tolerance

During laboratory studies, tolerance time (TT) during heat stress exposure is defined as the time where one of several end-point criteria could be reached. The exact end-point criteria are typically driven by ethical considerations or by experimental design, and may therefore vary at different laboratories or even within the same laboratory from one experiment to another. Typically, ethical constraints revolve around the allowable increase in T_b and heart rate; this increase in T_b, for example, can vary by at least 1°C with typical ceilings reported between 39.0°C and 40.0°C[40-43]. In addition, other factors such as nausea, ataxia, syncope, voluntary termination or a maximum length of exposure may define TT. In an occupational setting, TT would represent the time when a worker becomes a heat casualty and collapses or becomes nauseous and unable to work due to the increase in cardiovascular and/or thermal strain.

There is no consensus among thermal physiologists as to what limits tolerance in the heat. Some researchers relate heat tolerance to the highest core temperature that can be tolerated prior to exhaustion[40, 44], whereas others relate heat tolerance to an increase in S[45]. With the former definition, heat tolerance is affected only by those factors that alter the core temperature tolerated at exhaustion, while with the latter definition factors that influence both the initial and final core temperature, as well as the heat capacity of the body would affect heat tolerance.

Tolerance time during the heat stress exposure can be influenced by three factors; the initial T_b, final T_b, and the rate of increase in T_b from the beginning to end of the heat stress exposure, as shown in the following equation.

$$TT = (T_{b,\,Final} - T_{b,\,Initial}) \cdot hc_b \cdot \text{body mass} \cdot (S{\cdot}t^{-1} \cdot 60)^{-1} \qquad \textit{Equation 2-4}$$

where TT is expressed in minutes, hc_b is the heat capacity of the body in joules · $kg^{-1} \cdot {}^{o}C^{-1}$, and $S{\cdot}t^{-1}$ is in watts. Strategies to improve workers' tolerance to the heat can be directed towards any or all of these factors that influence TT as described in the sections that follow.

Section 3: Factors Affecting Heat Tolerance

Aerobic Fitness

During aerobic exercise T_b increases as a result of the increase in heat production. One of the many adaptations that occurs as the individual becomes accustomed to performing the aerobic activity several times a week is the ability to produce more sweat at any given T_b [31] (see Figure 2-1). If there is no encumbrance to the evaporation of this sweat and release of body heat at the skin surface, the aerobically fit individual will be able to work longer at a given rate of heat production with a lower T_b. As a result, they will be less likely to succumb to heat injury compared with their less fit sedentary counterpart. Indeed, individuals with a lower aerobic fitness and higher body fatness are 9 times more likely to become a heat casualty[46]. Given the current demographics of the workforce within the electric power industry[15] it is likely that employees, in general, are at an increased risk of succumbing to heat injury due to their age and weight distribution.

There are additional benefits for aerobic fitness, which become evident during more severe uncompensable heat stress conditions. It has been repeatedly demonstrated that individuals who are involved with regular aerobic exercise several times a week can tolerate higher T_b before experiencing exhaustion[41, 47, 48]. It is common for aerobically-fit individuals to reach ethical ceilings of 40.0°C during laboratory studies[41,43] or sustain even higher T_b during competitive events[49]. In contrast, less fit individuals may become exhausted and unable to continue to exercise or work as T_b approaches 38.5°C[41, 47]. Thus at similar rates of heat storage, which may occur when sweat evaporation is restricted with the use of protective clothing, an increase in aerobic fitness can increase total body heat storage by 50% assuming that resting T_b is close to 37.0°C. In addition, aerobic fitness reduces the inflammatory response at a given level of thermal strain, maintains gut barrier integrity to reduce endotoxin leakage and increases heat stress protein synthesis which helps sustain cell function at high T_b[42, 50]. Thus the aerobically-fit individual can work longer and can tolerate **safely** higher T_b. It is noteworthy that many of the injuries described for the electric power industry involve falls from the same or higher levels[15], indicating a loss of balance or impaired motor function. If some of these accidents, in otherwise sedentary and overweight employees, were occurring due to the increase in T_b, then an increase in aerobic fitness could reduce their incidence and associated medical costs for time lost away from work.

Hydration

Given that the body is approximately 60% water[51], maintaining a proper state of hydration is essential for sustaining effective intra- and extracellular fluid volumes. The loss of body water with sweating during work or exercise leads to dehydration if fluid replacement is insufficient to match rates of fluid loss. Initially, it is the extracellular fluid compartment that defends this fluid loss through sweating. However, if this fluid deficit is not replaced after the work period is finished then both the intra- and extracellular fluid compartments become hypohydrated. Consequently, the worker may begin the next work period in a state of hypohydration. Becoming dehydrated during work or beginning work in a hypohydrated state will suppress the sweating response and elevate T_b at any given rate of heat production[52, 53].

The general consensus is that both physical and cognitive performance will be affected once the amount of fluid loss exceeds 2% of body mass[54]. However, it is interesting that levels of dehydration as small as 1% of body mass have been reported to reduce tolerable limits of thermal strain and work productivity in fire fighters wearing standard issue fire fighter protective clothing[55]. Beginning work in a hypohydrated state will elevate resting T_b[47] and lower the T_b tolerated at exhaustion[47, 56], which together significantly reduce heat storage capacity (see Equation 2-4) and increase the individual's risk of succumbing to heat injury at a lower T_b.

An individual's current state of hydration can be monitored accurately and easily by measuring urine specific gravity with a value above 1.020 indicating a state of hypohydration[57]. Recommendations for fluid replacement could be made at the beginning and end of the work day based on these measurements. Indeed, such procedures have been successfully implemented in the mining industry in northern Australia to help lower the incidence of heat injury for their workers[58].

Heat Acclimation

Regular daily exposure to hot environments during work or exercise can induce a state of heat acclimation[59] where the number of exposures required to induce the acclimation is inversely related to aerobic fitness[60]. For more sedentary individuals, up to 2 weeks of daily exercise and heat stress exposure may be required for complete heat acclimation[60] but the rate of decay of the adaptations is slow, occurring over several weeks, and the reinduction of heat acclimation can be achieved rapidly[60]. Heat acclimation produces a series of adaptations in the sweating response that serve to increase the rate of sweat production. An increased sweating rate with heat acclimation is partly mediated at the central thermoregulatory integrators, with a reduction in the core temperature threshold for the initiation of the sweating response[31] (see

Figure 2-1) as well as both morphological and functional changes of the sweat gland leading to a more dilute sweat with a lower sodium content[61].

In a compensable heat stress environment the benefits of being heat acclimated for reducing cardiovascular and thermal strain through increased evaporative heat loss are quite substantial[59]. Indeed the classical work of Lind and Bass reveals a reduction in T_b and heart rate of almost 1°C and 40 $b \cdot min^{-1}$, respectively, and a 15% increase in sweat rate during 100 min of continuous exercise following 9 days of heat acclimation to a hot desert environment[62]. In addition, the incidence of exertional heat illness in U.S. Marine Corps recruits or the incidence of workplace accidents requiring hospitalization in Italy is highest during the beginning summer months when individuals are unacclimatized to the heat[17, 63].

However, as the ambient humidity levels increase or the requirement to wear protective clothing restricts evaporative heat loss, the benefits of the heat acclimation process become less pronounced[64]. Heat acclimation to a hot, humid environment will lower resting T_b[47, 65, 66] and increase heat storage capacity according to Equation 2-4 described above for TT. Yet despite the other benefits of being heat acclimated, such as an expanded blood volume[59] and less sweat suppression with increased skin wittedness[26], the T_b tolerated at exhaustion does not appear to be increased[47].

As with other occupational workgroups, electrical power workers would be at greatest risk for heat injury during the beginning summer months when they are unacclimatized to the heat. Regular supervised exposures to hot environments will greatly reduce their thermal and cardiovascular strain during their workday if conditions are favorable for evaporative heat loss. However, both employers and employees should not expect great improvements in heat tolerance through heat acclimation programs if their work environment involves very humid conditions or the requirement to wear protective clothing for prolonged periods.

Sex

In general, women have a greater surface area to mass ratio than men, which promotes more effective dry heat transfer to the environment as long as skin temperature exceeds ambient temperature[67]. Men rely on greater rates of evaporative heat loss and typically in very hot, dry environments where ambient temperature exceeds skin temperature they have a thermoregulatory advantage compared with women[67] as evidenced by their higher sweat rate at any given T_b[68]. However, men will require higher rates of fluid intake to match these increased rates of fluid loss. If men and women are matched for levels of aerobic fitness and body fatness there is little, if any, difference between them in their thermoregulatory response to work in hot environments[69, 70]. At similar rates of heat production women will have a greater increase in T_b due to their higher levels of body fatness[70, 71]. In addition, women, in general, are not able to tolerate the same increase in T_b at exhaustion when protective clothing is worn, which results in a reduced TT compared with men[70].

Current demographics for the electric power industry reveal that approximately 25% of the workforce is female[15]. It is of interest to note that women in non-office occupations such as meter readers, line workers, mechanics and electricians also have higher injury rates than their male counterparts[15]. These differences could reflect, in part, differences in aerobic fitness and body fatness between the sexes and the resultant differences in thermal strain while executing certain work tasks (see Table 2-1) that generate a given rate of heat production[70, 71].

Body Composition

The heat capacity of adipose tissue is approximately 50% of lean tissue such as muscle, blood, bone and water[72]. Thus at similar rates of heat storage, expressed per unit of mass, T_b will increase at a faster rate for an individual with greater adiposity[41, 70, 73, 74]. Younger sedentary individuals with lower levels of aerobic fitness and higher levels of adipose tissue and body mass index are at an 9-fold greater risk of succumbing to heat injury[46]. Given that two-thirds of the electric power workforce is over age 40[15] it is likely that a very significant proportion of personnel are at increased risk of succumbing to heat injury due to a sedentary lifestyle and increased body mass index.

Age

In general, if older and younger individuals are matched for aerobic fitness the thermoregulatory response to exercise and heat stress is very similar[75-78]. However, individuals become less active as they age. As a result, aerobic fitness decreases and body fatness increases, both of which make the individual more at risk for heat injury[46, 79]. In addition, a sedentary lifestyle and increasing obesity make older individuals a greater risk for the onset of Type II Diabetes (T2D), which is a condition associated with increased incidence of heat injury during heat stress exposure[80].

Given the current aging demographic profile of the electric power workforce[15] it is important to encourage work-site physical activity and health intervention programs that promote an active and healthy lifestyle for all employees[81]. As mentioned above, many of the injuries reported for the electric power industry involve falls with resulting sprains and fractures[15]. For the older employees in particular, an increase in aerobic fitness and decrease in body fatness could lower the incidence and severity of their injury, associated medical costs and lost productivity.

Circadian Effects

The normal circadian rhythm leads to oscillations in resting core temperature that can vary by 0.5°C from early morning to mid-afternoon[82]. If T_b tolerated at exhaustion does not similarly show a circadian effect, then the higher resting core temperatures in the afternoon should reduce TT during heat stress exposure as described in Equation 2-4 above. However, it has been reported that exercise and heat stress trials conducted in the early afternoon were associated with an increased T_b tolerated at exhaustion that offset the circadian influence on resting

T_b, and thus, maintained TT during uncompensable heat stress conditions similar to trials conducted in the morning[16]. Given that other effector responses, such as the temperature threshold for the onset of sweating and skin vasodilation, occur at higher temperatures in the afternoon compared with the morning[83], it is possible that the T_b tolerated at exhaustion is also regulated at a higher temperature in the afternoon. This interpretation implies that it is not an absolute T_b that the body can tolerate before exhaustion occurs, but rather a given increase in body heat content or delta core temperature[45].

Nevertheless, current guidelines for managing workplace exposure to heat stress have been established to limit the rise in T_b to some absolute level[84, 85]. At this time it is unclear whether these practices are valid for managing the risk of heat injury for workers performing their duties at various times of the day.

Section 4: Intervention Strategies

Fluid Replacement

Ensuring a proper state of hydration prior to beginning work in a hot environment and preventing levels of dehydration of greater than 2% of body mass during work are convenient strategies available to help optimize physical and cognitive performance[52, 86, 87]. Fluid replacement during exercise contributes to the maintenance of plasma volume during exercise, aiding thermal and cardiovascular homeostasis[88, 89]. Restricting fluid intake during prolonged work in the heat for initially euhydrated individuals can eventually cause greater thermal and cardiovascular strain compared with beginning in a hypohydrated state when fluid replacement is provided[88]. However, any fluid that is ingested must first be emptied from the stomach and absorbed in the intestine before it can enter the body and affect performance. Both dehydration and elevations in thermal strain slow the rate of gastric emptying[90, 91], which can be countered by higher rates of rehydration[92]. Often it is difficult for workers to consume sufficient fluid to match their rate of fluid loss either due to an increased discomfort associated with the sensation of gut fullness or very high sweat rates that exceed rates of gastric emptying[55, 90]. If fluid is provided *ad libitum* during the work shift, greater volumes will be consumed if carbohydrate and electrolyte beverages are offered rather than water alone[93]. Also, due to variations in sweat rates among individuals at the same level of thermal strain it is very difficult to advocate standard volumes of fluid replacement[94]. Thus it becomes more critical to educate workforce personnel about the importance and benefits of fluid replacement strategies during exposure to hot environments and to recognize those symptoms that indicate insufficient levels of fluid intake such as the thirst response[95] and orthostatic intolerance[55, 96].

Fluid replacement during rest periods or following a day of work in a hot environment is also important to ensure that the worker begins the next work period or work day in a euhydrated state. The ingested fluid should contain small amounts of sodium for complete restoration of fluid balance[97, 98]. The measurement of urine specific gravity prior to beginning the work day is one way to monitor workers' state of hydration[58]; this practice would help prevent the negative effects of hypohydration on heat tolerance[47] and optimize worker safety and productivity[55].

The ingestion of a bolus of cold water[99] or ice slurry[100, 101] prior to beginning work in a hot environment is also an effective way to enhance heat tolerance by lowering T_b and increasing heat storage capacity according to

Equation 2-4. The ingestion of the refrigerated (4°C) fluid acts as a heat sink where each liter of fluid would absorb almost 140 kJ of heat to be warmed to the T_b of 37.0°C. This amount of heat loss to the ingested fluid could effectively lower resting T_b 0.4°-0.5°C for an 80-90 kg individual and increase their heat storage capacity by 20-25% assuming a maximum T_b of 39.0°C can be tolerated.

Cooling

If natural avenues for heat loss are insufficient to prevent large increases in body heat storage, macro- or micro-climate cooling options can be considered. The former involves engineering control procedures such as the installation of air conditioning or large industrial fans and misters that enhance avenues for heat loss by controlling workplace temperature, humidity and wind speed. However, these procedures are costly and not an option if the work activity must be conducted outdoors. For these workers, the use of microclimate cooling may be an effective strategy.

Micro-climate cooling systems are typically worn by the individual prior to, during or following work in the heat to help regulate T_b [102, 103]. Often these systems involve wearing vests that incorporate air- or liquid-cooling or phase change materials such as ice[104-107]. In addition, options exist to use the arteriovenous anastomoses to promote heat loss through the palms and fingers or soles and toes with immersion in cool water[108-111]. An example of the effectiveness of this method of cooling is shown below in Figure 4-1 where firefighters immersed their hands and forearms in approximately 20°C water for 20 minutes during rest periods that were interspersed throughout 50-min work periods while wearing their protective clothing and exposed to a warm environment (35°C and 50% relative humidity)[112]. More effective control of T_b was evident compared with no cooling or the use of a fan and mister. The use of hand and forearm cooling increased TT by 65% compared with no cooling and when combined with effective fluid rehydration practices total TT increased 100% compared with the condition that involved fluid restriction and no cooling[55, 112]. These dramatic improvements were managed with reduced heat strain to ensure worker safety while at the same time optimizing worker productivity.

Ultimately the decision to provide micro-climate cooling for employees will need to be supported through evidence-based findings that demonstrate the effectiveness of the system together with consideration of the cost and logistics of using these various systems in both indoor and outdoor locations. Perhaps the final decision might also include more than one option that provides the employer some degree of flexibility for when different systems might be selected.

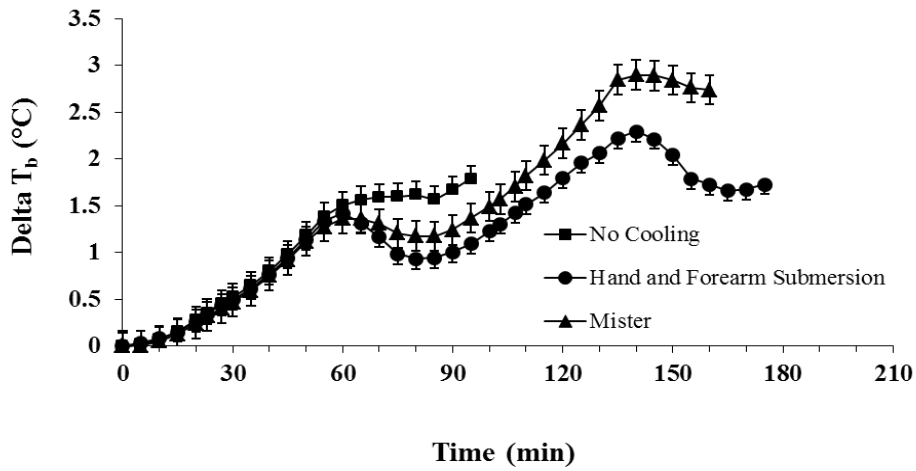

Figure 4-1
The change in body temperature with the use of no cooling, exposure to a fan and mister or the immersion of hands and forearms in 18°C water for firefighters working for 50-min and then resting for 20-min while exposed to 35°C and 50% relative humidity. [Adapted from Selkirk et al.[112]]

Work/Rest Schedules

The rationale for the use of work and rest schedules to manage thermal strain during the work day centers on the control of the rate of heat production (see Equation 2-3). Clearly heat storage will be reduced if the rate of heat production is lowered due to the interjection of intermittent rest periods. There is some debate, however, as to whether T_b would be identical if continuous and intermittent work and rest protocols were compared at identical average metabolic rates[113, 114]. Although self-pacing is sometimes an option to also reduce thermal strain during work or exercise[115], some work tasks demand a continuous effort and associated rate of heat production (see Table 2-1). Under these conditions, if T_b can be lowered during the rest periods then the worker will begin the next work period at a lower T_b than if the work were performed continuously, enabling a greater total work output to be achieved over the day with a reduced risk of succumbing to heat injury. If the worker can rest in shaded areas, remove protective clothing and also receive micro-climate cooling then thermal strain can be effectively managed[103, 112].

Guidelines currently exist to help manage thermal strain of industrial workers throughout the work day[84]. These guidelines consider the impact of the various components of the heat balance equation (see Figure 2-3) on T_b and recommend the implementation of periods of rest that increase in duration each hour if the environmental conditions become more severe and/or the rate of heat production increases[84]. Although these guidelines are quite helpful they were constructed and validated using data from young adult males. Given the influence of sex, body composition and age on the thermoregulatory response to heat stress the applicability of these guidelines to other workers, more representative of the electric power industry[15], is questionable. In addition these guidelines are not adjusted for work conducted at various times of the day.

Section 5: Relevance to the Electric Power Industry

Presently there is no evidence-base to substantiate whether electric power workers are experiencing increases in heat strain in the workplace that could lead to an increased risk of workplace injury, decreased work productivity or time lost due to sickness and the associated increased health care costs.

At the most fundamental level, information needs to be gathered that characterizes the electric power workers' environment, including measures of temperature and relative humidity since these establish the temperature and water vapor pressure gradients that govern heat transfer from the body. Additionally, it would be critical to assess the rate of heat production associated with the conduct of various representative tasks performed by electric power workers, since prolonged elevations in heat production throughout the work day may generate excessive increases in body heat storage and loss of body fluid through sweating. Finally, information is needed that characterizes the additional thermal strain associated with the use of essential protective clothing ensembles. As shown in Appendix A, our pilot work clearly revealed that the replacement of just the normal work shirt with the arc resistant shirt increased heat storage dramatically. Additional work is necessary to further define the limitations associated with wearing various protective garments at rates of heat production that represent the typical work tasks for electric power workers.

Once the heat stress of the work environment is characterized, workers need to be educated about those factors that may increase their risk of becoming a heat casualty. Although it is unlikely that employees will change their lifestyle and become more physically active to improve their aerobic fitness and lose body fatness, they should be aware of the critical importance of these issues in reducing one's risk to heat injury. Additionally, employees should be educated about proper workplace fluid replacement guidelines to help manage the risk of dehydration throughout the day.

Finally, there may be the specific need to be proactive and test the efficacy of specific intervention strategies that reduce thermal strain and increase worker productivity while, at the same time, reducing the worker's risk to heat injury. However, these intervention strategies, such as microclimate cooling techniques or specific hydration practices, need to be validated through controlled laboratory and field studies before they are implemented in the workplace.

Section 6: Recommendations for Future Research

The following topics represent areas of research that would help reduce the risk of heat injury and ensure the electric power worker's safety while at the same time optimizing their physical and cognitive performance and resultant work productivity.

1. **Measurement of metabolic rates that are representative work tasks for the electric power industry.**

As shown in Equation 2-3, the heat production is a major determinant of body heat storage. An accurate assessment of the rates of heat production associated with representative tasks performed by electric power workers (shown in Table 2- 1) is critical to enable valid recommendations regarding micro-climate cooling requirements, hydration practices and work and rest schedules.

Portable metabolic systems exist, which are fairly unobtrusive, and they could be used to collect information from the electric power workers while they perform some of these tasks. Indeed, one such portable system was used to document the advantage of an ergonomic intervention for lowering the energy cost of digging through wet, muddy soil[39], thereby demonstrating that the methodology can used in a field setting (see Figure 6-1 below). However, it would be immensely valuable to characterize the heat production associated with the conduct of the vast array of duties and tasks performed by electrical power workers and to construct a database that would assist occupational and exercise physiologists in their attempts to minimize the risk of heat injury to workers.

Figure 6-1
An example of the use of a portable metabolic system to measure energy expenditure in the field.

2. **Measurement of environmental conditions indoors at various companies and outdoors in regions of the country where high ambient temperatures and relative humidity exist.**

Together with knowledge concerning the rates of heat production it is essential that the typical temperature and humidity be characterized both for the indoor and outdoor work environments. Dry heat transfer (Equation 2-1) is dependent on the temperature gradient between the skin surface and the surrounding air layer, whereas wet heat transfer (Equation 2-2) is dependent on the vapor pressure gradient. Defining the micro- and macro-climatic conditions will help to define those workers who may be at greatest risk of heat injury.

3. **Measurement of T_b throughout the day in most at risk areas of the country and with most at risk workers.**

To confirm that some workers may be at risk to heat injury during their work day, the measurement of T_b should be performed with the use of a radiopill that tracts T_b as it passes through the intestine. This technology is also fairly unobtrusive and it provides an accurate and valid measure of T_b determined through more invasive sites of rectal or esophageal measurement[116, 117]. These measurements could be obtained at the same time as rates of heat production are being measured with a portable metabolic system.

4. **Determination of the impact of the use of protective clothing on T_b under controlled laboratory conditions that replicate those of the electric power industry.**

As described earlier in this document and as demonstrated by our pilot work presented in Appendix A, clothing further restricts heat exchange between the skin surface and the surrounding air layers. To accurately assess the impact of the protective clothing required for workers in the electric power industry, individuals should be monitored in a controlled laboratory environment while wearing these different clothing ensembles and performing work at various rates of heat production that represent the tasks performed in their work environment. Certainly the results of the pilot testing indicate that additional testing of the thermal burden associated with the use of the arc resistant clothing is critical.

5. **Measurement of urine specific gravity during the summer months to monitor before and after work hydration status of workers.**

This is a very simple and accurate way to assess whether some workers may not be properly hydrated prior to and during their work day. The findings from these assessments will help to determine whether defined hydration strategies need to be implemented for certain groups of workers.

6. **Demonstration of the effectiveness of various fluid replacement strategies to manage hydration throughout the day.**

Based on the outcomes from the findings above, the effectiveness of defined hydration strategies could be assessed for workers at greater risk for heat injury. These strategies might involve recommendations to ingest a bolus of fluid (e.g. 500 mL) at the beginning of the work day and *ad libitum* carbohydrate and electrolyte fluid ingestion throughout the work day. Urine specific gravity could be assessed at the beginning and end of the shift over several weeks to compare the benefits of current practice to a more defined hydration strategy.

7. **Implementation of workplace education program for issues pertaining to heat injury.**

A structured workplace education program could be developed and offered to the companies that represent the majority of the electric power workforce. The program should help to educate management and workers about the conditions that place workers at greater risk of heat injury, the signs and symptoms of heat illness, as well as the treatment and preventative strategies. The program could be available for learning on-line and through webinars as well as through face-to-face classroom instruction.

8. **Demonstration of cost effective cooling strategies to manage thermal strain and improve worker productivity.**

There are various micro-climate cooling strategies that could be tested for both indoor and outdoor workers at greatest risk of heat injury. The radiopill technology would be used to verify that thermal strain was being effectively managed compared with the use of no cooling. In addition, worker productivity could be assessed as the total time spent performing a defined task with T_b maintained below a certain threshold value (e.g. 38.0°C or 38.5°C).

9. **Recording environmental conditions and time of day associated with injuries.**

The environmental conditions and time of day should be included as part of the data recorded for the injuries reported in the OHSD maintained by EPRI. This information would help assess whether there are seasonal and time-of-day interactions that place electric power workers at greater risk of injury during heat stress.

Section 7: References

1. Bligh J. Regulation of body temperature in man and other mammals. In: Shitzer A and Eberhart RC. Heat transfer in medicine and biology. New York: Plenum Publishing; 1985:15-51.
2. Cheung SS, McLellan TM and Tengalia SA. The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. Sports Med. 2000;29:329-359.
3. Wyndham CH. The effects of heat stress upon human productivity. Arch Sci Physiol. 1973;27:A491-A497.
4. Prezant DJ, Freeman K, Kelly KJ, et al. Impact of a design modification in modern firefighting uniforms on burn prevention outcomes in new york city firefighters. J Occup Eniron Med. 2000;42:827-834.
5. Nunneley SA, Martin CC, Slauson JW, Hearon CM, Nickerson LD and Mason PA. Changes in regional cerebral metabolism during systemic hyperthermia in humans. J Appl Physiol. 2002;92:846-851.
6. Kiyatkin EA. Physiological and pathological brain hyperthermia. Progress Brain Res. 2007;162:219-243.
7. Nielsen B, Hyldig T, Bidstrup F, Gonzalez-Alonso J and Christoffersen GR. Brain activity and fatigue during prolonged exercise in the heat. Pflugers Arch. 2001;442:41-48.
8. Rasmussen P, Nybo L, Volianitis S, Moller K, Secher NH and Gjedde A. Cerebral oxygenation is reduced during hyperthermic exercise in humans. Acta Physiol 2010;199:63-70.
9. Hancock PA, Ross JM and Salzma JL. A meta-analysis of performance response under thermal stressors. Hum Factors. 2007;49:851-877.
10. Gaoua N, Grantham J, Massioui FE, Girard O and Racinais S. Cognitive decrements do not follow neuromuscular alterations during passive heat exposure. Int J Hypertherm. 2011;27:10-19.
11. Gaoua N, Racinais S, Grantham J and Massioui FE. Alterations in cognitive performance during passive hyperthermia are task dependent. Int J Hypertherm. 2011;27:1-9.
12. Hocking C, Silberstein RB, Lau WM, Stough C and Roberts W. Evaluation of cognitive performance in the heat by functional brain imaging and psychometric testing. Comp Biochem Physiol. 2001;128:719-734.

13. Hancock PA and Vasmatzidis I. Human occupational and performance limits under stress: The thermal environment as a prototypical example. Ergonomics. 1998;41:1169-1191.

14. Ramsey JD, Burford CL, Beshir MY and Jensen RC. Effects of workplace thermal conditions on safe work behavior. J Safety Res. 1983;14:105-114.

15. Occupational Health and Safety Annual Report 2010. EPRI, Palo Alto, CA: 2010. 1019906.

16. McLellan TM, Gannon GA, Zamecnik J, Gil V and Brown GM. Low doses of melatonin and diurnal effects on thermoregulation and tolerance to uncompensable heat stress. Journal of Applied Physiology. 1999;87:308-316.

17. Morabito M, Cecchi L, Crisci A, Modesti PA and Orlandini S. Relationship between work-related accidents and hot weather conditions in tuscany (central italy). Ind Health. 2006;44:458-464.

18. Sawka MN and Wenger CB. Thermoregulatory responses to acute exercise-heat stress. In: Sawka MN, Wenger CB and Pandolf KB. Human performance physiology and environmental medicine in terrestrial extremes Indianapolis: Benchmark Press; 1988:97-151.

19. Nishi Y. Meaurement of thermal balance of man. In: Cena K and Clark JA. New York: Elsevier Scientific Publishing Co.; 1981:29-39.

20. Rowell LB. Human cardiovascular adjustments to execise and thermal stress. Physiol Rev. 1974;54:75-159.

21. Wyss CR, Brengelmann GL, Johnson JM, Rowell LB and Niederberger M. Control of skin blood flow, sweating, and heart rate: Role of skin vs. Core temperature. J Appl Physiol. 1974;36:726-733.

22. Kenney WL and Johnson JM. Control of skin blood flow during exercise. Med Sci Sport Exerc. 1992;24:303-312.

23. Gonzalez RR, McLellan TM, Withey WR, Chang SK and Pandolf KB. Heat strain models applicable for protective clothing systems: Comparison of core temperature response. J Appl Physiol. 1997;83:1017-1032.

24. Gagge AP, Stolwijk JAJ and Hardy JD. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res. 1967;1:1-20.

25. Fukazawa T and Havenith G. Differences in comfort perception in relation to local and whole body skin wettedness. Eur J Appl Physiol. 2009;106:15-24.

26. Fox RH and Goldsmith R. Heat acclimatization by controlled hyperthermia in hot-dry and hot-wet climates. J Appl Physiol. 1967;22:39-46.

27. Wenger CB. Heat of evaporation of sweat: Thermodynamic considerations. J Appl Physiol. 1972;32:456-459.

28. Sato K. The physiology, pharmacology and biochemistry of the eccrine sweat gland. Rev Physiol Biochem Pharmacol. 1977;79:52-131.

29. Nadel ER. Control of sweating rate while exercising in the heat. Med Sci Sports Exerc. 1979;11:31-35.

30. Nielsen B and Nielsen M. On the regulation of sweat secretion in exercise. Acta Physiol Scand. 1965;64:314-322.

31. Nadel ER, Pandolf KB, Roberts MF and Stolwijk JAJ. Mechanisms of thermal acclimation to exercise and heat. J Appl Physiol. 1974;37:515-520.

32. Sullivan PJ and Mekjavic IB. Temperature and humidity within the clothing microenvironment. Aviat Space Environ Med. 1992;63:186-192.

33. Gonzalez RR. Biophysics of heat transfer and clothing considerations. In: Pandolf KB, Sawka MN and Gonzalez RR. Human performance physiology and environmental medicine in terrestrial extremes. Indianapolis: Benchmark Press; 1988:45-95.

34. Craig FN and Moffitt JT. Efficiency of evaporative cooling from wet clothing. J Appl Physiol. 1974;36:313-316.

35. McLellan TM, Pope JI, Cain JB and Cheung SS. Effects of metabolic rate and ambient vapour pressure on heat strain in protective clothing. Eur J Appl Physiol. 1996;74:518-527.

36. Gisolfi CV and Wenger CB. Temperature regulation during exercise: Old concepts, new ideas. . Exerc Sport Sci Rev. 1984;12:339-372.

37. Hardy JD. Physiology of temperature regulation. Physiol Rev. 1961;41:521-606.

38. Sawka MN, Gonzalez RR, Drolet LL and Pandolf KB. Heat exchange during upper- and lower-body exercise. J Appl Physiol. 1984;57:1050-1054.

39. *EPRI Ergonomics Handbook for the Electric Power Industry: Ergonomic Design for Substations and Ergonomic Interventions for Overhead, Underground, and Substation Applications*. EPRI, Palo Alto, CA: 2010. 1021128.

40. Latzka WA, Sawka MN, Montain SJ, et al. Hyperhydration: Tolerance and cardiovascular effects during uncompensable exercise-heat stress. J Appl Physiol. 1998;84:1858-1864.

41. Selkirk GA and McLellan TM. Influence of aerobic fitness and body fatness on tolerance to uncompensable heat stress. J Appl Physiol. 2001;91:2055-2063.

42. Selkirk GA, McLellan TM, Wright HE and Rhind SG. Mild endotoxemia, nf-kb translocation, and cytokine increase during exertional heat stress in trained and untrained individuals. Am J Physiol Regul Integr Comp Physiol. 2008;295:R611-R623.

43. Proulx CI, Ducharme MB and Kenny GP. Effect of water temperature on cooling efficiency during hyperthermia in humans. J Appl Physiol. 94:1317-1323.

44. Montain SJ, Sawka MN, Cadarette BS, Quigley MD and McKay JM. Physiological tolerance to uncompensable heat stress: Effect of exercise intensity, protective clothing, and climate. J Appl Physiol. 1994;77:216-222.

45. Webb P. The physiology of heat regulation. Am. J. Physiol. 1995;268:R838-R850.

46. Gardner JW, Kark JA, Karnei K, et al. Risk factors predicting exertional heat illness in male marine corps recruits. Med Sci Sports Exerc. 1996;28:939-944.

47. Cheung SS and McLellan TM. Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. J Appl Physiol. 1998;84:1731-1739.

48. Morrison SA, Sleivert GG and Cheung SS. Aerobic influence on neuromuscular function and tolerance during passive hyperthermia. Med Sci Sports Exerc. 2006;38:1754-1761.

49. Byrne C, Lee JKW, Chew SAN, Lim CL and Tan EYM. Continuous thermoregualtory responses to mass-participation distance running in heat. Med. Sci. Sports Exerc. 2006;38:803-810.

50. Selkirk GA, McLellan TM, Wright HE and Rhind SG. Expression of intracellular cytokines, hsp72, and apoptosis in monocyte subsets during exertional heat stress in trained and untrained individuals. Am J Physiol Regul Integr Comp Physiol. 2009;296:R575-R586.

51. Guyton AC. Textbook of medical physiology (8th edition). Philadelphia: W.B. Saunders; 1991:274.

52. Montain SJ and Coyle EF. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. J Appl Physiol. 1992;73:1340-1350.

53. Montain SJ, Latzka WA and Sawka MN. Control of thermoregulatory sweating is altered by hydration level and exercise intensity. J Appl Physiol. 1995;79:1434-1439.

54. Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ and Strachenfeld NS. American college of sports medicine position stand. Exercise and fluid replacement. Med Sci Sports Exerc. 2007;39:377-390.

55. Selkirk GA, McLellan TM and Wong J. The impact of various rehydration volumes for firefighters wearing protective clothing in warm environments. Ergonomics. 2006;in press.

56. Sawka MN, Young AJ, LAtzka WA, Neufer PD, Quigley MD and Pandolf KB. Human tolerance to heat strain during exercise: Influence of hydration. J Appl Physiol. 1992;73:368-375.

57. Armstrong LE, Pumerantz AC, Fiala KA, et al. Human hydration indicies: Acute and longitudinal reference values. Int J Sport Nutr Exerc Metab. 2010;20:145-153.

58. Brake DJ and Bates GP. Fluid losses and hydration status of industrial workers under thermal stress working extended shifts. Occup Environ Med. 2003;60:90-96.

59. Wenger CB. Human heat acclimatization. In: Pandolf KB, Sawka MN and Gonzalez RR. Human performance physiology and environmental medicine in terrestrial extremes. Indianapolis: Benchmark Press; 1988.

60. Pandolf KB, Burse RL and Goldman RF. Role of physical fitness in heat acclimatisation, decay and reinduction. Ergonomics. 1977;20:399-408.

61. Allan JR and Wilson CG. Influence of acclimatization on sweat sodium concentration. . J Appl Physiol. 1971;30:708-712.

62. Lind AR and Bass DE. Optimal exposure time for development of acclimatization to heat. Fed Proc. 1963;22:704-708.

63. Kark JA, Burr PQ, Wenger CB, Gastaldo E and Gardner JW. Exertional heat illness in marine corps recruit training. Aviat Space Environ Med. 1996;67:354-360.

64. McLellan TM and Aoyagi Y. Heat strain in protective clothing following hot-wet or hot-dry heat acclimation. Canadian Journal of Applied Physiology. 1996;21:90-108.

65. Buono M, Heaney J and Canine K. Acclimation to humid heat lowers resting core temperature. Am J Physiol. 1998;274:R1295-R1299.

66. Nielsen B. Heat acclimation—mechanisms of adaptation to exercise in the heat. International Journal of Sports Medicine. 1998;19 Suppl 2:S154-S156.

67. Shvartz E, Saar E and Benor D. Physique and heat tolerance in hot-dry and hot-humid environments. 1973;34:799-803.

68. Gagnon D and Kenny GP. Sex modulates whole-body sudomotor thermosensitivity during exercise. J Physiol. 2011;epub ahead of print.

69. Avellini BA, Kamon E and Krajewski JT. Physiological responses of physically fit men and women to acclimation to humid heat. J Appl Physiol. 1980;49:254-261.

70. McLellan TM. Sex-related differences in thermoregulatory responses while wearing protective clothing. 1998;78:28-37.

71. Gagnon D, Dorman LE, Jay O, Hardcastle S and Kenny GP. Core temperature differences between males and females during intermittent exercise: Physical considerations. Eur J Appl Physiol. 2009;105:453-461.

72. Buskirk ER, Bar-Or O and Kolloias J. Physiological effects of heat and cold. In: Wilson NL. Obesity. Philadelphia: Davis; 1969:119-139.

73. Havenith G and Middendorp H. The relative influence of physical fitness, acclimation state, anthropometric measures and gender on individual reactions to heat stress. . Eur J Appl Physiol. 1990;61:419-427.

74. Havenith G, Luttikholt VGM and Vrijkotte TGM. The relative influence of body characteristics on humid heat stress response. . Eur J Appl Physiol. 1995;70:270-279.

75. Pandolf KB, Cadarette BS, Sawka MN, Young AJ, Francesconi RP and Gonzalez RR. Thermoregulatory responses of middle-aged and young men during dry-heat acclimation. J Appl Physiol. 1988;65:65-71.

76. Pandolf KB. Aging and human heat tolerance. Exp Aging Res. 1995;23:69-105.

77. Kenney WL. Thermoregulation at rest and during exercise in healthy older adults. Exerc Sport Sci Rev. 1997;25:41-76.

78. Kenny GP, Gagnon D, Dorman LE, Hardcastle SG and Jay O. Heat balance and cumulative heat storage during exercise performed in the heat in physically active younger and middle-aged men. Eur J Appl Physiol. 2010;109:81-92.

79. Buskirk ER, Lundegren H and Magnusson L. Heat acclimatization patterns in obese and lean individuals. Ann N Y Acad Sci. 1965;131:637-653.

80. Semenza JC, McCullough JE, Flanders WD, McGeehin MA and Lumpkin JR. Excess hospital admissions during the july 1995 heat wave in chicago. Am J Prev Med. 1999;16:269-277.

81. Kenny GP, Yardley JE, Martineau L and Jay O. Physical work capacity in older adults: Implications for the aging worker. AM J Ind Med. 2008;51:610-625.

82. Kräuchi K and Wirz-Justice A. Circadian rhythm of heat production, heart rate, and skin and core temperature under unmasking conditions in men. Am J Physiol. 1994;267:R819-R829.

83. Stephenson LA, Wenger CB, O'Donovan BH and Nadel ER. Circadian rhythm in sweating and cutaneous blood flow. Am J Physiol. 1984;246:R321-R324.

84. ACGIH. Heat stress and strain: TLV physical agents documentation. In: American conference of governmental industrial hygienists (acgih). Cincinatti, OH: 2007:1-36.

85. McLellan TM and Selkirk GA. The management of heat stress for the firefighter: A review of work conducted on behalf of the toronto fire service. Ind Health. 2006;44:414-426.

86. Coyle EF. Fluid and fuel intake during exercise. J Sport Sci. 2004;22:39-55.

87. Sawka MN and Coyle EF. Influence of body water and blood volume on thermoregulation and exercise performance in the heat. Exerc Sport Sci Rev. 1999;27:167-218.

88. Candas V, Libert JP, Brandenberger G, Sagot JC and Kahn JM. Thermal and circulatory responses during prolonged exercise at different levels of hydration. J Physiol (Paris). 1988;83:11-18.

89. Candas V, Libert JP, Brandenberger G, Sagot JC, Amoros C and Kahn JM. Hydration during exercise. Effects on thermal and cardiovascular adjustments. Eur J Appl Physiol. 1986;55:113-122.

90. Neufer PD, Young AJ and Sawka MN. Gastric emptying during exercise: Effects of heat stress and hypohydration. Eur J Appl Physiol. 1989;58:433-439.

91. Rehrer NJ, Beckers EJ, Brouns F, Hoor Ft and Saris WH. Effects of dehydration on gastric emptying and gastrointestinal distress while running. Med Sci Sports Exerc. 1990;22:790-795.

92. Mitchell JW and Voss KW. The influence of volume on gastric emptying and fluid balance during prolonged exercise. Med Sci Sports Exerc. 1991;23:314-319.

93. Clapp AJ, Bishop PA, Smith JF and Mansfield ER. Effects of carbohydrate-electrolyte content of beverages on voluntary hydration in a simulated industrial environment. Aihaj. 2000;61:692-9.

94. Brown PI, McLellan TM, Linnane DM, et al. Influence of hydration volume and ambient temperature on physiological responses while wearing cbrn protective clothing. Ergonomics. 2010;53:1484-1499.

95. Adolph EF. Life in deserts. In: Physiology of man in deserts. New York: Interscience; 1947:329-341.

96. Carter 3rd R, Cheuvront SN, Vernieuw CR and Sawka MN. Hypohydration and prior heat stress exacerbates decreases in cerebral blood flow velocity during standing. J Appl Physiol. 2006;101:1744-1750.

97. Shirreffs SM, Taylor AJ, Leiper JB and Maughan RJ. Post-exercise rehydration in man: Effects of volume consumed and drink sodium content. Med Sci Sports Exerc. 1996;28:1260-1271.

98. Maughan RJ, Owen JH, Shirreffs SM and Leiper JB. Post-exercise rehydration in man: Effects of electrolyte addition to ingested fluids. Eur J Appl Physiol. 1994;69:209-215.

99. Lee JKW, Shirreffs SM and Maughan RJ. Cold drink ingestion improves exercise endurance capacity in the heat. Med Sci Sports Exerc. 2008;40:1637-1644.

100. Siegel R, Maté J, Brearley MB, Watson G, Nosaka K and Laursen PB. Ice slurry ingestion increases core temperature capacity and running time in the heat. Med Sci Sports Exerc. 2010;42:717-725.

101. Ross MLR, Garvican LA, Jeacocke NA, et al. Novel precooling strategy enhances time trial cycling in the heat. Med Sci Sports Exerc. 2011;43:123-133.

102. Bishop PA, Nunneley SA and Constable SH. Comparisons of air- and liquid personal cooling for heavy work in moderate temperatures. Am Indust Hygiene Assoc. 1991;70:802-111.

103. Bomalaski SH, Chen YT and Constable SH. Continuous and intermittent personal microclimate cooling strategies. Aviat Space Environ Med. 1995;66:745-750.

104. Pimenthal NA, Cosimini HM, Sawka MN and Wenger CB. Effectiveness of an air-cooled vest using selected air temperature and humidity combinations. Aviat Space Environ Med. 1987;58:119-124.

105. Cadarette BS, DeCristofano BS, Speckman KL and Sawka MN. Evaluation of three commercial microclimate cooling systems. Aviat Space Environ Med. 1990;61:71-80.

106. Shapiro Y, Pandolf KB, Sawka MN, Toner MM, Winsmann FR and Goldman RF. Auxiliary cooling: Comparison of air-cooled vs. Water-cooled vests in hot-dry and hot-wet environments. Aviat. Space Environ. Med. 1982;53:785-789.

107. McLellan TM and Frim J. Efficacy of air and liquid cooling during light and heavy exercise while wearing nbc clothing. Aviat Space Environ Med. 1999;70:802-11.

108. House JR. Extremity cooling as a method for reducing heat strain. J Def Sci. 1998;3:108-114.

109. 109. House JR, Holmes C and Allsopp AJ. Prevention of heat strain by immersing the hands and forearms in water. J R Nav Med Serv. 1997;83:26-30.

110. Livingstone SD, Nolan RW and Cattroll SW. Heat loss caused by immersing the hands in water. Aviat Space Environ Med. 1989;60:1166-71.

111. Livingstone SD, Nolan RW and Keefe AA. Heat loss caused by cooling the feet. Aviat Space Environ Med. 1995;66:232-237.

112. Selkirk GA, McLellan TM and Wong J. Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. J Occup Environ Hygiene. 2004;1:521-531.

113. Kraning KK and Gonzalez RR. Physiological consequences of intermittent exercise during compensable and uncompensable heat stress. J Appl Physiol. 1991;71:2138-2145.

114. Gagnon D and Kenny GP. Exercise-rest cycles do not alter local and whole body heat loss responses. Am J Physiol. 2011;300:R958-R968.

115. Tucker R, Rauch L, Harley YXR and Noakes TD. Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. Pflügers Arch - Eur J Physiol. 2004;448:422-430.

116. O'Brien C, Hoyt RW, Buller MJ, Castellani JW and Young AJ. Telemetry pill measurement of core temperature in humans during active heating and cooling. Med Sci Sport Exerc. 1998;30:468-472.

117. Wilkinson DM, Carter JM, Richmond VL, Blacker SD and Rayson MP. The effect of cool water ingestion on gastrointestinal pill temperature. Med. Sci. Sports Exerc. 2008;40:523-528.

118. Nishi Y. Measurement of thermal balance in man. New York: 1981.

Appendix A: Pilot Testing of Arc Resistant Protective Clothing Worn by Electrical Power Workers

Abstract

Within the Electric Power Industry, recent Occupational Safety and Health Administration guidelines require the use of the flame and arc resistant clothing that comply with the National Fire Protection Association's consensus standard for electrical safety in the workplace, commonly known as NFPA 70E. However, little is known about the effect of the safety clothing on whole-body heat exchange. Therefore, this pilot study evaluated the influence of arc resistant clothing on whole-body heat exchange and change in body heat content during work in the heat. Each participant performed 30-min of cycling at a constant rate of heat production of 600 W followed by 30-min of recovery in a whole-body calorimeter regulated at 35°C and 20% relative humidity donning one of the two clothing conditions: 1) wearing either standard cotton shirt and work pant (Control: **CON**) or, 2) arc resistant shirt and work pant (arc resistant clothing: **ARC**). For both conditions a hard-hat with ear-muffs, gloves and socks with closed-toed shoes were worn. We observed that the change in body heat content for ARC was greater compared to CON during exercise indicating that the rate of thermal strain was elevated to a higher degree for ARC (CON: 210 kJ; ARC: 332 kJ). During recovery, the negative change in body heat content was greater for CON (-154 kJ) as compared to ARC (-128 kJ). As a result, a 3.6-fold great residual heat storage was observed for ARC (204 kJ) as compared to CON (56 kJ). Heart rate was also significantly elevated for the ARC (160 beats/min) compared to CON (144 beats/min). These preliminary results suggest that arc resistant clothing can have a detrimental effect on whole-body heat loss during work in the heat.

Introduction

Performing work in a warm or hot environment is in general more thermally stressful than performing the same task in a neutral environment. Body heat storage of an individual is a consequence of an imbalance between the rates of heat production and total heat loss (dry and evaporative). As ambient temperature increases dry heat loss diminishes to point where the body absorbs heat from the environment. Under such circumstances, the only avenue of heat loss is via evaporation (primarily of sweat). While sweating rate and ambient humidity are of course the crucial parameters that determine the rate of evaporative heat loss for an individual, another primary influence is the insulative properties of the clothing ensemble worn.

Recent Occupational Safety and Health Administration guidelines require the use of the flame and arc resistant clothing that comply with the National Fire Protection Association's consensus standard for electrical safety in the workplace, commonly known as NFPA 70E. The wearing of protective clothing is required to shield the individual from environmental hazards or from injury. While protective clothing is being continually improved and lightened, the requirement for environmental protection is generally contradictory to the desire for adequate ventilation. Protective clothing is typically heavy, thick, multi-layered, and bulky. For electric power line workers protective clothing may include impermeable rubber gloves and aprons or flame and arc resistant suits depending on the method used to work on live power grids.

While thermal protection and comfort of the worker are of paramount concern to the electrical industry, little is known about the potential influence of the arc resistant clothing (**ARC**) on heat balance during work in the heat. Clothing acts as a resistance to heat and moisture transfer between the skin surface and the ambient environment. As such it can protect against extreme heat from external radiant sources but in parallel it also restricts the loss of excess heat produced by the body during work. The nature of this barrier for vapor transport from the body to the environment is determined by the physical properties of the materials that the clothing is composed of and the interaction of these clothing properties with the environmental parameters, such as changes in air temperature or wind speed; and the personal parameters, such as body movement and size. In order to ascertain the potential heat stress risk of an individual working in a hot environment an understanding of the complex dynamic behavior of the human-clothing system on whole-body heat balance is required.

It is generally accepted that the only way to accurately estimate the rates of whole-body evaporative and dry heat loss as well as the change in body heat content (and therefore the level of thermal strain) in humans is by performing simultaneous minute-by-minute measurements of the individual heat balance components by whole-body calorimetry. Therefore, we evaluated the influence of arc resistant clothing (**ARC**) on dynamic heat balance and body heat storage during and following exercise by directly measuring the individual components of heat production and heat loss using a whole-body calorimeter regulated to an ambient air temperature of 35°C.

Experimental Design

This protocol was performed using a standard experimental protocol approved by the University of Ottawa Health Sciences and Science Research Ethics Board. Subjects participated in 2 experimental testing sessions. During the two experimental sessions, the calorimetry experimental exercise protocol was performed. Testing days were separated by a minimum of 72 h. All calorimeter trials were performed at the same time of day. Participants were asked to arrive at the laboratory after eating a small breakfast (i.e. dry toast and juice), but consuming no tea or coffee that morning, and also avoiding any major thermal stimuli on their way to the laboratory. Participants were also asked to not drink alcohol or exercise for 24 h prior to experimentation. In order to promote euhydration, participants were asked to drink 250 ml of water the night before, as well as the morning of each experimental trial.

Following instrumentation of the participant with core and skin temperature sensors and a heart rate monitor, the participant entered the calorimeter regulated to an ambient air temperature of 35°C and 20% relative humidity. The participant, seated in the upright position, rested for a 30-min habituation period. Subsequently, the participant performed 30 minutes of upright seated cycling at a constant rate of metabolic heat production of ~600 W. Following cessation of exercise, participants remained seated resting for 60 minutes.

The two experimental trials were randomly assigned and differed in that the trials were performed while wearing either: 1) standard cotton shirt and work pant (Control: **CON**) or, 2) arc resistant shirt and work pant (arc resistant clothing: **ARC**) (Figure 2-1). The clothing ensembles also consisted of the standard accessories of protective equipment: hard-hat with ear-muffs, gloves.

Figure A-1
Subject sitting in calorimeter

Measurements

The individual components of the heat balance equation were measured by combined direct and indirect calorimetry (please see summary details of the calorimeter in Appendix B):

$$S = M - (\pm W) \pm (R + C + K) - E \quad \text{Watts} \qquad \textit{Equation A-1}$$

Where: S is the rate of body heat storage; M is the rate of metabolic energy expenditure; W is the rate of external work; R is the rate of radiant heat exchange; C is the rate of convective heat exchange; K is the rate of conductive heat exchange and; E is the rate of evaporative heat exchange.

The modified Snellen direct air calorimeter was employed for the purpose of measuring rate of evaporative (E) and dry ($R + C + K$) heat loss, yielding an accuracy of ± 2.3 W for the measurement of rate of total heat loss. The calorimeter incorporates a constant load eddy current cycle ergometer. The ergometer pedals are located inside the calorimeter and mechanically linked by chains to the resistance control unit, regulating rate of external work (*W*) at a pre-determined level, outside of the calorimeter so that any heat generated by the unit does not enter the calorimeter. The calorimeter is housed within a climatic chamber slightly pressurized (+8.25 mmHg) to nullify potential air leakage through the calorimeter walls. Differential air temperature and humidity are measured over the calorimeter by sampling the influent and effluent air. The water content is measured using precision dew point thermometry (RH Systems model 373H, Albuquerque, NM, USA), while the air temperature is measured using RTD high precision thermistors (± 0.002°C, Black Stack model 1560, Hart Electronics, UT, USA). Air mass flow through the calorimeter is estimated by differential thermometry over a known heat source (2 x 750 W heating elements) placed in the effluent air stream. Differential temperature over the heater is measured using a third aforementioned high precision thermistor placed down-stream from the heater. Air mass flow rate (kg air • min^{-1}) is continuously measured during each trial. Data from the calorimeter was collected continuously at 8 s intervals throughout the trials. The real time data was displayed and recorded on a personal computer with LabVIEW software (Version 7.0, National Instruments, TX, USA).

Rate of evaporative heat loss was calculated from the calorimetry data every minute using the following equation:

$$E = \frac{\left(Massflow \bullet \left(Humidity_{out} - Humidity_{in}\right) \bullet 2426\right)}{60} \quad \text{Watts} \qquad \textit{Equation A-2}$$

where mass flow is the rate of flow of air mass (kg air•s^{-1}); ($Humidity_{out}$ – $Humidity_{in}$) is the calorimeter inflow-outflow difference in absolute humidity (g water • kg air^{-1}); and 2426 is the latent heat of vaporization of sweat (J • g $sweat^{-1}$) at 30°C.

Rate of dry heat loss, from radiation, convection, and conduction was calculated from the calorimetry data every minute using the following equation:

$$R+C+K = \frac{\left(Massflow \bullet \left(Temperature_{out} - Temperature_{in}\right) \bullet 1005\right)}{60} \quad \text{Watts}$$

Equation A-3

where mass flow is the rate of flow of air mass (kg air • s^{-1}); ($Temperature_{out}$ – $Temperature_{in}$) is the calorimeter inflow-outflow difference in air temperature (°C), and 1005 is the specific heat of air (J• $(\text{kg air} \bullet °C)^{-1}$).

A 6 L fluted mixing box housed within the calorimeter was utilized for the concurrent measurement of metabolic energy expenditure. Expired gas was analyzed for O_2 (error of ± 0.01%) and CO_2 (error of ± 0.02%) concentrations using electrochemical gas analyzers (AMETEK model S-3A/1 and CD 3A, Applied Electrochemistry, Pittsburgh, PA, USA). Expired air was recycled back into the calorimeter chamber in order to account for respiratory dry and evaporative heat loss. Prior to each session gas mixtures of 4% CO_2, 17% O_2, balance nitrogen were used to calibrate the gas analyzers and a 3 L syringe was used to calibrate the turbine ventilometer (error ± 3%, typically <1%). Rate of metabolic energy expenditure was calculated from minute-average values of oxygen consumption and the respiratory exchange ratio[118].

The calorimeter data was then used to calculate change in body heat content (ΔH_b) using the following equation:

$$\Delta H_b \text{ @ time (t)} = \int_{t=0}^{t} (M - [E + R + C + K] - W)\, dt \quad \text{kilojoules} \qquad \textit{Equation A-4}$$

Heart rate was monitored using a Polar coded transmitter, recorded continuously and stored with a Polar Advantage interface and Polar Precision Performance software (Polar Electro Oy, Finland).

Thermal sensation was measured at the end of the exercise period using the ASHRAE 7-point scale ranging from 0-neutral to 7-very, very hot. The scale was affixed inside the calorimeter and during the last minute of exercise, the participants were asked to verbally provide their rating of thermal sensation.

All temperature data were collected using a HP Agilent data acquisition module (model 3497A) at a sampling rate of 15 s and simultaneously displayed and recorded in spreadsheet format on a personal computer with LabVIEW software.

Results

The simultaneous rates of metabolic heat production and whole-body heat exchange throughout the experimental protocol for each of the four clothing ensembles are given in Figure A-2. For the purpose of comparing whole-body heat loss responses during exercise between the two clothing ensembles, the rate of metabolic heat production during exercise was kept constant at 600 W.

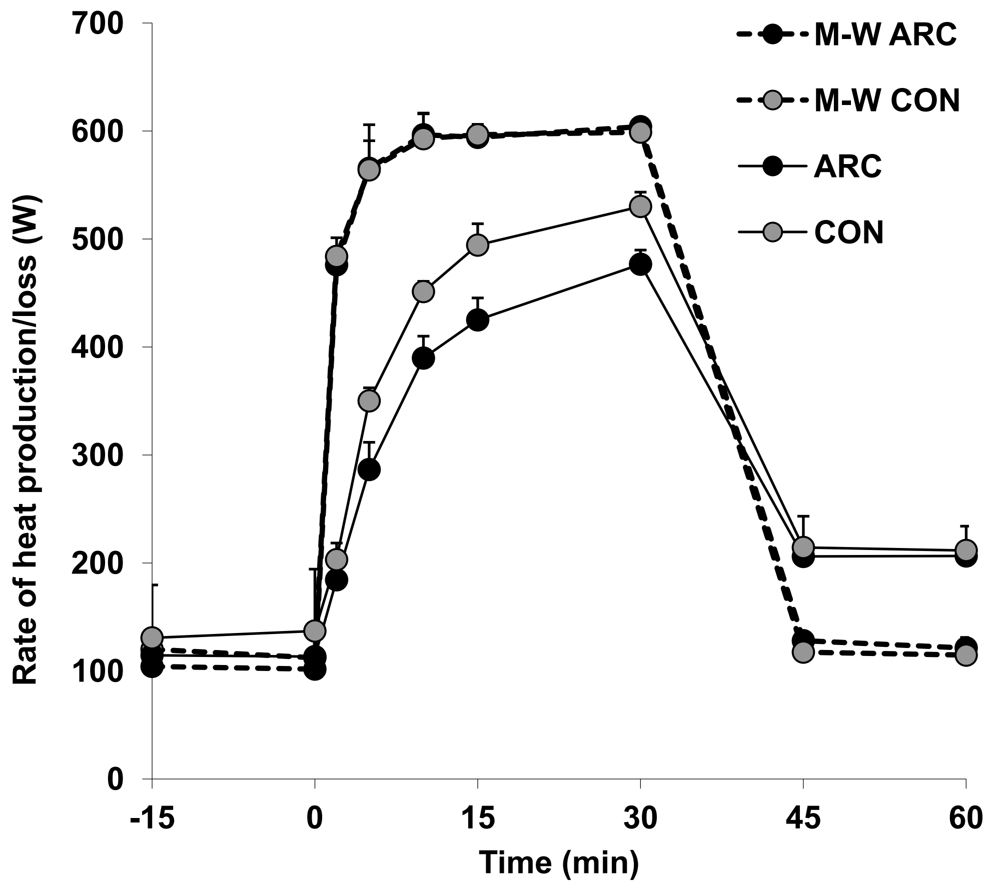

Figure A-2
Rate of whole-body heat loss for arc resistant clothing (ARC) and work pant or control (CON) cotton shirt and work pant during constant rate of heat production (M-W).

During exercise, a lower rate of heat loss was measured for the ARC compared to the CON condition. As a result, the change in body heat content was significantly different between conditions at the end of the 30-min exercise bout ($p<0.001$). The ARC clothing condition had a 58% greater change in body heat content compared to the CON (ARC: 332 kJ vs CON: 210 kJ) (Figure A-2).

During recovery, the change in body heat content was slightly greater in CON (-154 kJ) as compared to the ARC (-128 kJ) condition (Figure A-3). Ultimately, the residual body heat storage which represents the cumulative change in body heat content as measured following exercise and recovery was 3.6-fold greater for ARC (204 kJ) compared to CON (56 kJ).

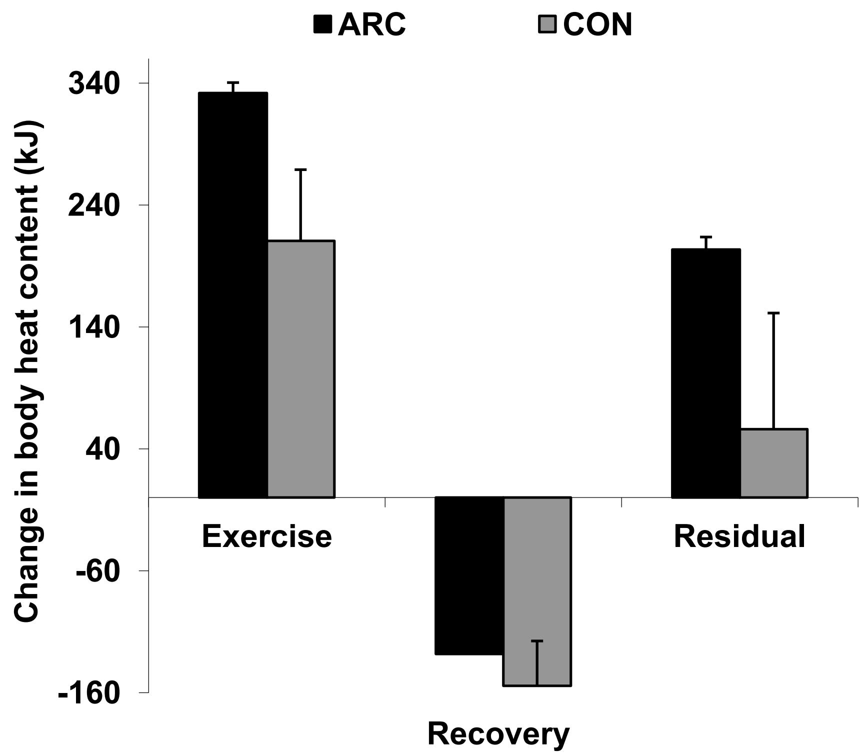

Figure A-3
Change in body heat content (ΔHb) during and following exercise for arc resistant clothing (ARC) or control (CON).

During exercise the heart rate for the ARC (160 beats/min) condition was higher than CON (144 beats/min) as measured at end-exercise (Figure A-4). During recovery, heart rate remained elevated for the ARC condition relative to CON.

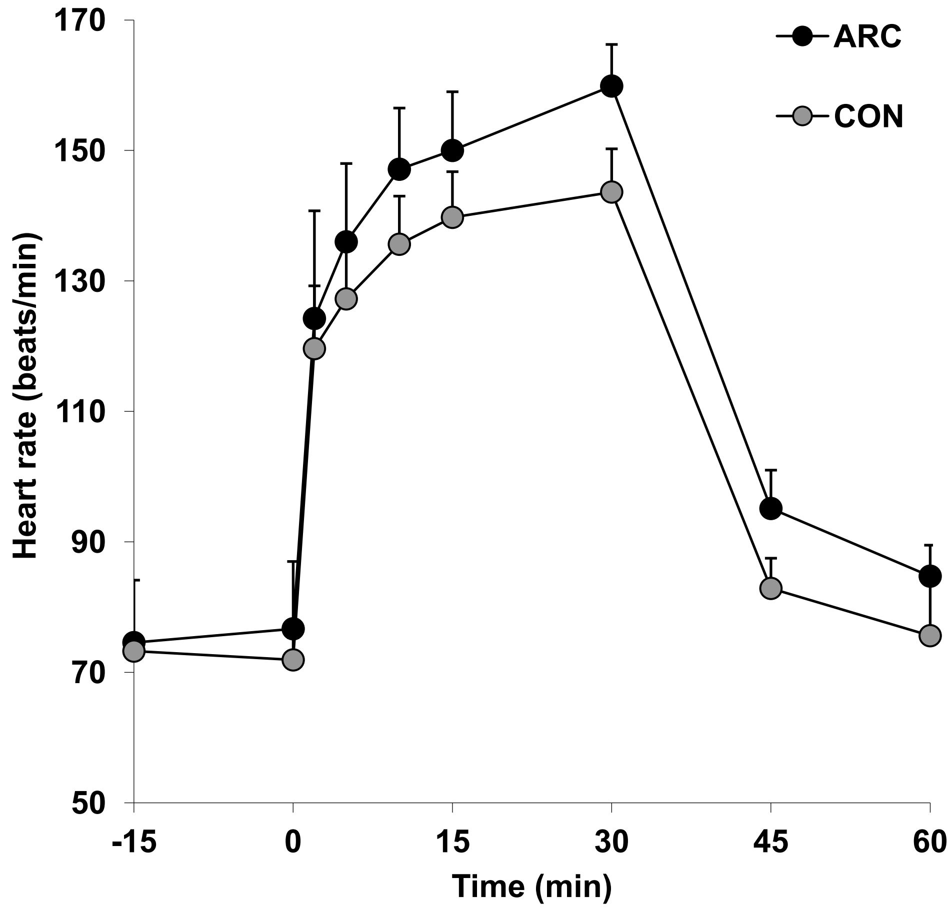

Figure A-4
Heart rate response during and following exercise for arc resistant clothing (ARC) or control (CON).

Thermal sensation for ARC condition was greater compared to the CON condition throughout baseline resting, exercise and recovery (Figure A-5).

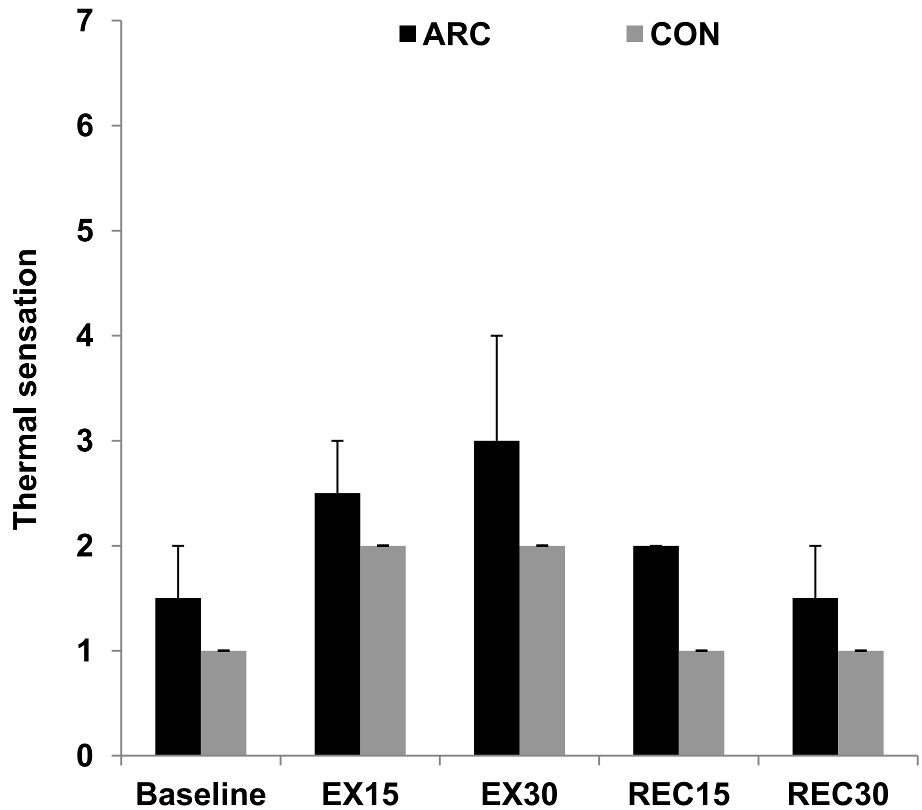

Figure A-5
Thermal sensation (note: EX15: at 15-min of exercise; EX30: at 30-min of exercise; REC15: at 15 min postexercise; REC30: at 30 min postexercise) for arc resistant clothing (ARC) or control (CON).

Conclusions

A key finding from this pilot study is that the arc resistant clothing consisting of the shirt only with commonly available work pants restricts whole-body heat loss during exercise heat. This resulted in a greater rate of heat storage and therefore level of thermal strain. This was paralleled by a concomitant increase in the level of cardiovascular strain as measured by a higher end-exercise heart rate. Further studies are required to evaluate the effects of the different clothing ensembles worn by electrical power workers on thermal strain and worker performance.

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Appendix B: Brief Overview of Calorimeter

The Snellen calorimeter provides the means of measuring evaporative and dry heat exchange of the human body with the environment. Calorimetry is the measure of heat energy and similarly, a direct calorimeter is a device for measuring heat emitted by a mass. As applied to whole organisms, direct calorimetry is a gold standard for measuring biologic heat release in humans subsequent to anaerobic and/or aerobic metabolism.

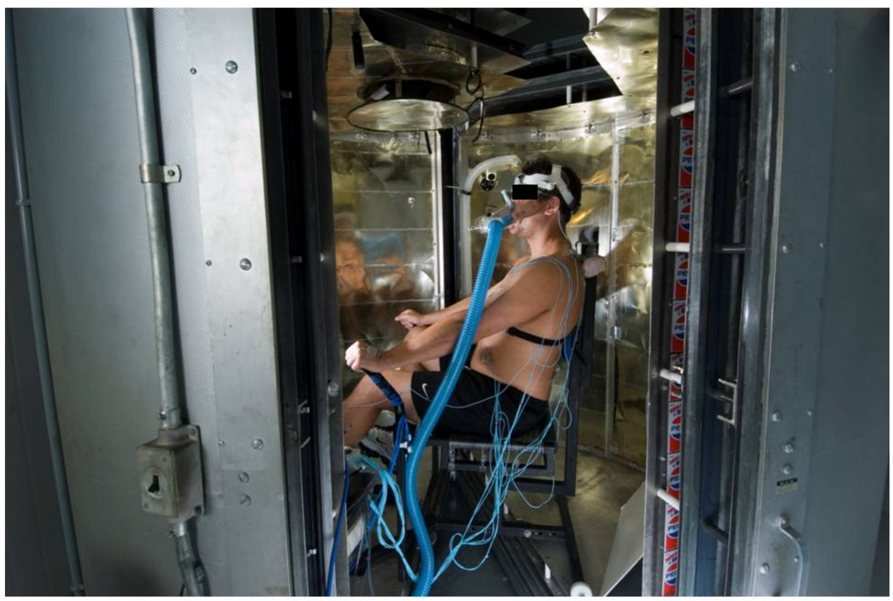

Figure B-1
The Snellen Calorimeter

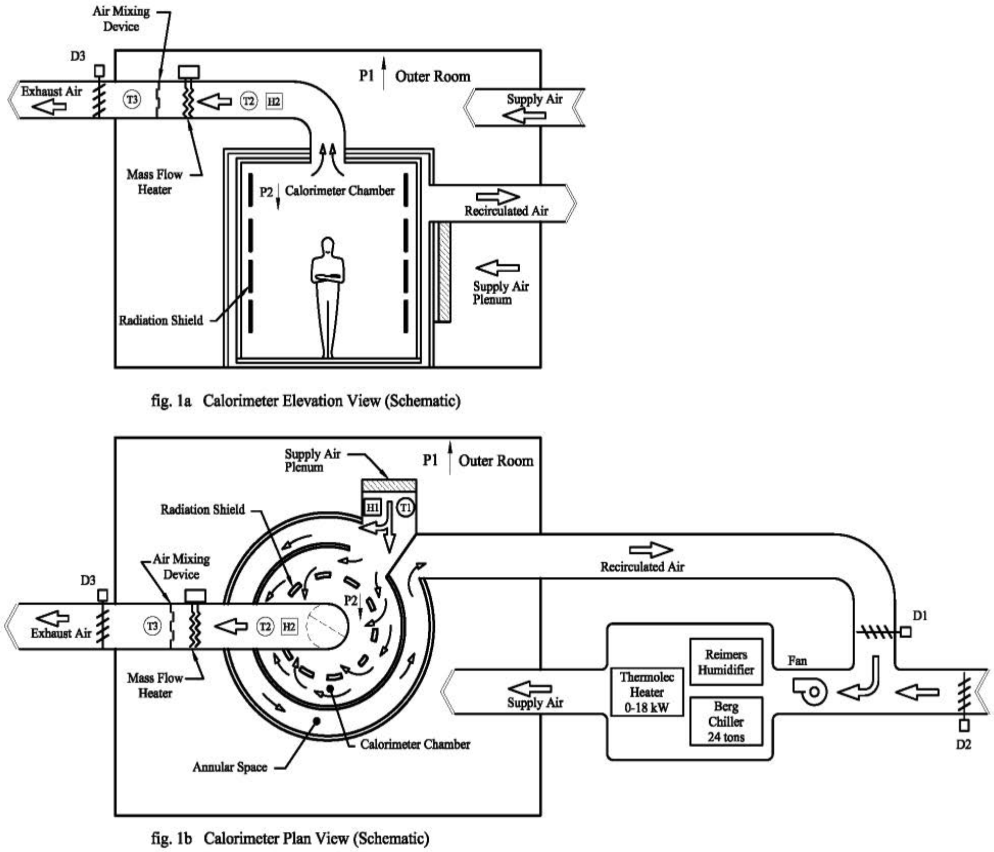

Figure B-2
A schematic diagram of the configuration of the modified Snellen calorimeter.

Panel a. The arrangement of the outer room, the calorimeter chamber and the air mass flow device. Air is supplied to the calorimeter under high pressure from the outer room through the input plenum. The air mass flow of the exhausted air through the calorimeter chamber is measured. ***Panel b***. The detail of the flow of the split air-stream through the calorimeter chamber and through the annular space around the calorimeter chamber (see Reardon et al. (2006) Med Bio Eng Comput, 44(8):721-728 for additional details).

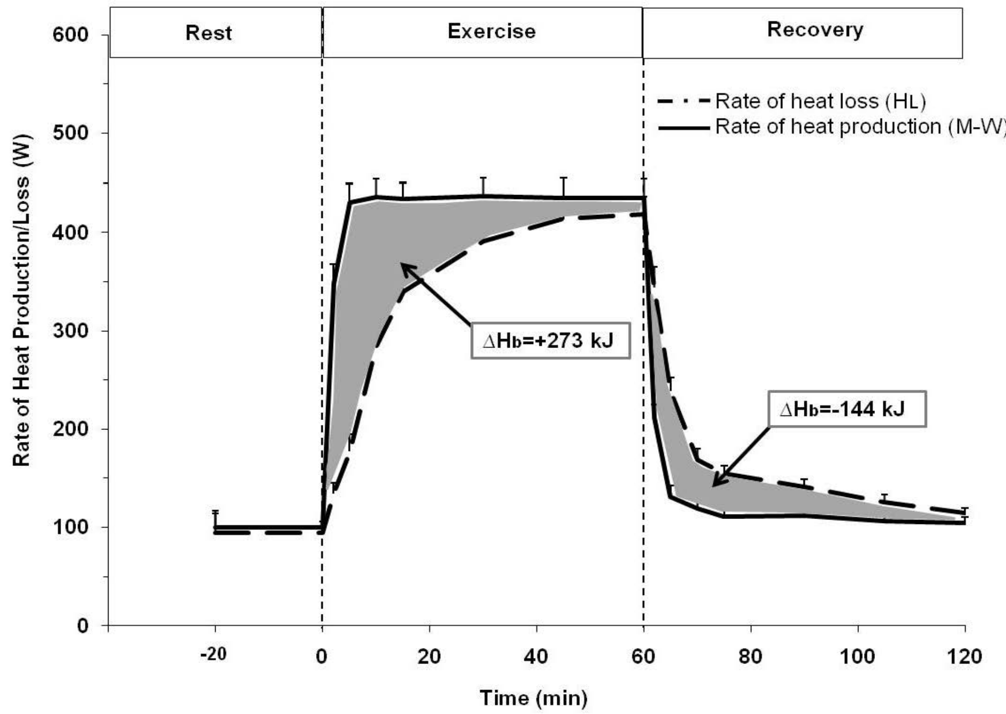

Figure B-3
Example of whole-body calorimetry data for rate of total heat production.

Example of whole-body calorimetry data for rate of total heat production (metabolic rate minus rate of external work) and rate of net heat loss after 60-min resting, followed by 60-min cycling at a constant rate of heat production of 450 W and 60-min of recovery. The change in body heat content (ΔH_b, grey shaded areas) during exercise and recovery is +273 kJ and -144 kJ respectively for a net residual storage of +129 kJ after a single exercise/recovery cycle (see Kenny et al. MSSE, 2009, 41(3):588-96).

Calculating change in body heat content (**ΔH_b**) - All of the heat dissipated by the subject in the chamber is reflected in the temperature difference (dry heat loss, H_D) and humidity difference (evaporative heat loss, H_L) recorded between the incoming and outgoing air. As such, the change in body heat content body (**ΔH_b**) can be calculated from the temporal summation (grey shaded area in Figure B-3) of metabolic heat production by simultaneous indirect calorimetry and the net dry and evaporative heat losses using the following equation:

$$\Delta H_b \text{ @ time (t)} = \int_{t=0}^{t} (M - [E + R + C + K] - W)\,dt \qquad \text{in kilojoules(kj)}$$

Where: *M* is the rate of metabolic energy expenditure; *W* is the rate of external work; *R* is the rate of radiant heat exchange; *C* is the rate of convective heat exchange; *K* is the rate of conductive heat exchange and; *E* is the rate of evaporative heat exchange.

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