

## **THE INFLUENCE OF DIFFERENT MINING CLOTHING ENSEMBLES ON BODY HEAT STORAGE AND CORE TEMPERATURE REGULATION DURING PHYSICAL WORK**

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### **ABSTRACT**

An assessment of the energy expenditure of various mining tasks in Canada's deep mechanized metal mines, and the current environmental conditions under which they are performed, indicates the significant potential of evaporative cooling (of sweat) to protect workers. However, this process is affected by the type of clothing, the extent of its coverage and the number of layers. In Canada, it is not uncommon for underground miners to wear multiple layers of clothing which when combined with personal protective equipment results in greater than 90% of the body being covered. This significantly limits evaporation from open areas and can retard cooling elsewhere from the skin's surface. Recently, there have been trends towards the use of "sports" undergarments with enhanced wicking properties and also away from coveralls without knowing the consequences to the worker. To date, whole-body heat loss and changes in body heat content have been used to evaluate three clothing configurations against a semi-nude control condition. The heat values, determined through simultaneous direct whole-body and indirect calorimetry, were independent of core/skin temperature monitoring. This paper only discusses some of the preliminary results as the work is still on-going. The results to-date indicate the detrimental effects of clothing with time during both exercise and recovery to total heat loss and that the "sports" undergarment had neither beneficial nor detrimental effects despite being designed to promote the wicking of sweat.

**KEYWORDS:** *Heat Stress, Clothing, Calorimetry, Heat Loss/Storage, Mining*

### **1. INTRODUCTION**

In Canada's mines, the potential for underground workers to experience heat stress or strain is increasing due to a variety of factors, including the following: 1) Base and precious metal mines are becoming deeper reaching 3 km and the resultant

autocompression of the air entering the mine significantly increases the air temperatures in the workplace. 2) The mines are mechanized and the engine sizes of their mobile diesel equipment are generally increasing, 260 kW loaders and 490 kW haulage trucks which are not uncommon can be significant heat sources. 3) The workforce is aging, possibly more sedentary and increasingly prone to medical conditions, all of which can affect how the human body manages heat. 4) The workers wear extensive personal protective equipment covering the majority of the body which can inhibit heat transfer. 5) Any changes in climate that increase summer surface air temperatures will be transferred through to the underground workplace. It was in recognition of the increased need to manage heat stress that the Deep Mining Research Consortium (DMRC) has funded a series of heat stress related research initiatives which includes this clothing assessment.

### **1.1. Thermoregulation, Work, Heat Storage, Heat Loss and Clothing**

Similar to any machine, the human body generates heat when performing work. This heat is either stored by the body or lost to the environment depending on their relative conditions. If excessive heat is stored in the body, heat strain and stress can result. Performing work in a warm or hot environment is, in general, more thermally stressful than conducting the same task in a thermoneutral environment. Body heat storage of an individual is a consequence of an imbalance between the rates of metabolic heat production (based on work intensity) and total heat loss (dry and evaporative). As ambient temperatures increase dry heat loss diminishes to a point where it reverses and the body can absorb heat from the environment. Under such circumstances, the only avenue of heat loss is via evaporation (primarily of sweat). Here, the sweat rate of an individual and the relative humidity of the environment are crucial parameters which determine the potential rate of evaporative heat loss. However, clothing and its insulative properties also have a primary influence on the actual rate of heat loss.

Clothing can inhibit 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 character of this barrier in regard to allowing vapour transport from the body to the environment is determined by the physical properties of the materials that the clothing is composed of and their interaction with a wide range of environmental and human parameters. For example, air temperature and wind speed are environmental parameters, and body movement and size are human parameters. To ascertain the potential heat stress risk of an individual working in a hot environment a greater understanding of the complex dynamic behaviour of the human-clothing system under simulated work conditions is required. Of specific interest is the behaviour of this system during both the

work and rest elements of the intermittent work pattern that is prevalent in mechanized mining operations.

### 1.2. Clothing Tests

This evaluation used the Snellen whole-body calorimeter, a unique gold standard facility, available at the University of Ottawa (Reardon *et al*, 2006) (Figure 1). The calorimeter is contained within an environmental walk-in chamber that allows each test to be performed under precisely controlled and monitored conditions. The temperature, moisture content and flow rate of the air entering and leaving the calorimeter were monitored continuously to determine the heat lost by the clothed test subjects. The work of the subjects wearing the clothing was determined from a continuously monitored cycle ergometer working against a load/resistance which was external to the chamber. This clothing assessment methodology, is different from that used by others, for example in the determination of Wet Bulb Globe Temperature (WBGT) clothing adjustment factors (O'Connor and Bernard, 1999) (Bernard *et al* (2005).

Three clothing ensemble conditions were evaluated in the calorimeter against a *Semi-nude Control* where the subjects were just wearing a pair of shorts. The ensembles were: 1) *Mine Gear only*, the standard mining coverall (65% polyester, 35% cotton) as worn by workers in the Sudbury area, worn over the same shorts as the semi-nude condition plus associated safety equipment; 2) *Undergarments only*, a "sports" type sweat wicking two-piece undergarment (93% polyester, 7% spandex); and, 3) *Mine Gear/Undergarment*, a combined condition of the standard coverall over the two-piece undergarment. In the latter two tests *Mine Gear* also consists of the miner's typical personal protective or other equipment including a hard-hat with ear-muffs, gloves and socks with close-toed shoes. It should be noted that the typical mine footwear of leather or rubber safety boots were replaced by more comfortable closed-toed shoes to facilitate the 60-minute cycling task.

### 1.3. Test Conditions

The test environment employed within the chamber was an ambient air temperature of 40°C and 15%RH (i.e. a psychrometric wet bulb of 20°C). This hot, dry condition was chosen to maximize the evaporative cooling potential between the subjects and the environment.

The air was introduced tangentially into the calorimeter, flowed around the subject and then exited through a central exhaust on top of the calorimeter. The velocity of the air circulating around the subjects was  $\approx 0.3$  m/s. This low velocity was required to avoid discomfort, caused by cooling, during the 60-minute recovery period.



**Figure 1:** Test subject wearing mine clothing in the Snellen whole-body calorimeter

The work rate employed in the tests was 400 W, which is considered the onset of a “heavy” work demand according to the ACGIH screening criterion (2001). This value was greater than that observed to be typical from an assessment of mining activities (Reardon 2007). However, it was chosen to generate a significant difference between the temperature of the subjects and the environment to better measure the differences in heat loss through the various clothing ensembles.

#### **1.4. Whole-body Calorimetry**

A benefit of the calorimeter approach is that it gives a more direct measurement of human heat loss and/or storage rather than relying on thermometric methods. Using whole-body calorimetry, Jay *et al* (2007) showed that a traditional two-compartment thermometry model of core and skin (Burton, 1935), underestimates changes in body heat

content during steady-state work over 90-minutes by between 15 and 35% and by even larger amounts for shorter work periods. A greater underestimation of body heat content was measured at higher ambient temperature conditions. The source of error using the two-compartment model of core and skin is the lack of an independent expression representing the heat stored in muscle tissue. The consequence of this underestimation of the heat stored in the body is an overestimation of the heat loss from the body that could be passing through a clothing system and hence its performance.

Another important consideration coming from the calorimeter based research, relevant to mining, relates to intermittent work practices. Kenny *et al* (2009) has shown that during intermittent work, after each successive work bout and rest period, there is a progressive increase in the amount of residual heat remaining in the body. A possible consequence of this is that it might limit the amount of additional work that could be done before reaching a core temperature limit. However, on the other hand the additional heat stored in the body may help to initiate the cooling response earlier upon the resumption of work.

## 2. METHODOLOGY

### 2.1. Subjects

The participants selected for the clothing evaluations were neither mine-based nor had any acclimation to working in hot environments. The mean characteristics of the ten healthy non-smoking males who volunteered for the study were: Age,  $20 \pm 3$  years; Height,  $1.76 \pm 0.06$  m; Weight,  $78.2 \pm 9.8$  kg; Body fat,  $15.7 \pm 8.8\%$ ; Body surface area,  $1.96 \pm 0.14$  m<sup>2</sup>; peak oxygen consumption (VO<sub>2</sub> max),  $56.0 \pm 7.7$  ml/kg/min.

### 2.2. Experimental design

The participants agreed to five separate test sessions: 1 screening and 4 experimental sessions. During the first screening session, body composition and maximum oxygen consumption were measured. The subjects were also familiarized with the calorimeter and test protocol. In the subsequent test sessions the participants wore one of the four clothing options. All experimental trials were performed in random order. Testing days were separated by a minimum of 72 hours. 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 significant thermal stimuli on their way to the laboratory. Participants were also asked not to drink alcohol or exercise for 24 hours prior to experimentation.

**2.2.1. Experimental Protocol:** Each testing session within the calorimeter was composed of three parts. Initially, each subject was exposed to an ambient temperature of 40°C,

with a 15% relative humidity environment for a period of 30 minutes (habituation period) to establish base line conditions. Subjects were then required to exercise for up to 60 minutes at a constant heat production of 400 W. During this period the heat losses were determined. This was then followed by 60 minutes of recovery to establish any residual heat storage.

### **2.3. Measurements**

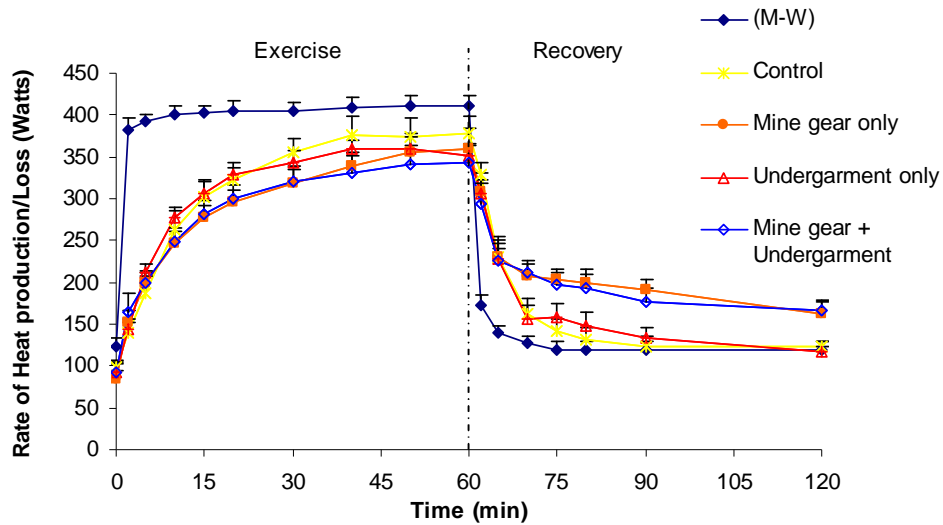
**2.3.1. Metabolic Heat Production:** The net rate of metabolic heat production was determined through indirect calorimetry from the difference of the subject's metabolic rate and their external work. The metabolic rate was determined using minute-average values of oxygen consumption and a respiratory exchange ratio. Inspired and expired air, oxygen and carbon dioxide concentration analysis, along with a ventilometer, provided the oxygen consumption rate.

A semi-recumbent constant load eddy current cycle ergometer was used to monitor and control the external work of the participants. To eliminate non-human heat sources, only the pedals of the cycle ergometer were within the calorimeter. The calorimeter was also designed to eliminate or minimize all other potential heat sources such as its lighting.

**2.3.2. Dry and Evaporative Heat Loss:** The heat loss of the subjects was determined through direct calorimetry every minute from the psychrometric conditions of the intake and exhaust air and the flow rate through the calorimeter. The air temperature and moisture content (humidity) were measured with precision RTD thermistors and dew-point analyzers. The mass flow rate through the calorimeter was determined through differential thermometry across a known heat source. The resulting accuracy of the Snellen whole-body calorimeter in a heat loss determination is  $\pm 2.3$  W.

**2.3.3. Temperatures:** Appropriate medical thermocouples were used to measure the changes in superficial and deep body temperatures. An esophageal temperature was obtained through a participant's nostril in the region of the left ventricle and aorta, corresponding to the level of the eighth and ninth thoracic vertebrae. The rectal temperature probe was inserted to a minimum of 12 cm past the sphincter. The tympanic probe was placed in the aural canal immediate prior to the tympanic membrane, held in position with cotton and isolated from the external environment with ear protectors.

The skin temperature, also measured with thermocouples, was determined at 12 points over the body surface representing the following regions: head, hand, upper back, chest, lower back, abdomen, bicep, forearm, quadriceps, hamstring, front calf, and back calf.



**Figure 2:** Mean rate of metabolic heat production and total heat loss during exercise and recovery

The mean skin temperature was derived from a weighted aggregate of these measurements.

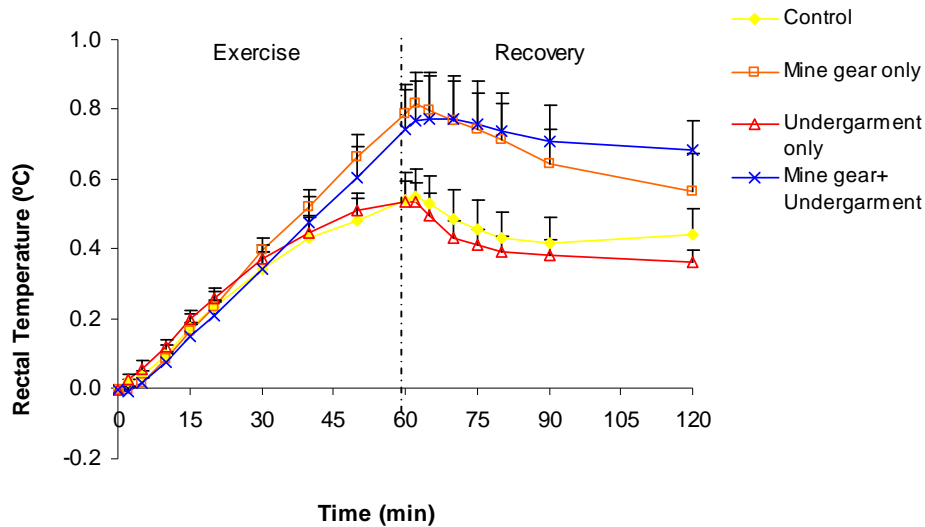
**2.3.4. Other Measurements:** Although not discussed in this paper, the testing methodology also included the measurements of: local sweat rate and forearm skin blood flow, skin temperature and heart rate.

### 3. RESULTS

The following results are from the analysis to date of ten subjects who completed all four clothing ensemble tests.

#### 3.1. Metabolic Heat Production and Total Heat Loss

Figure 2 shows the average metabolic heat production (M-W) determined indirectly from oxygen consumption and the total heat loss (dry and evaporative) for each clothing condition. This figure shows the immediate increase in heat production with the onset of exercise, its consistency during the activity and then decaying immediately upon the cessation of activity. The figure also shows the exponential type growth and decay, respectively, of total heat gain/loss with the onset and cessation of activity. The growth



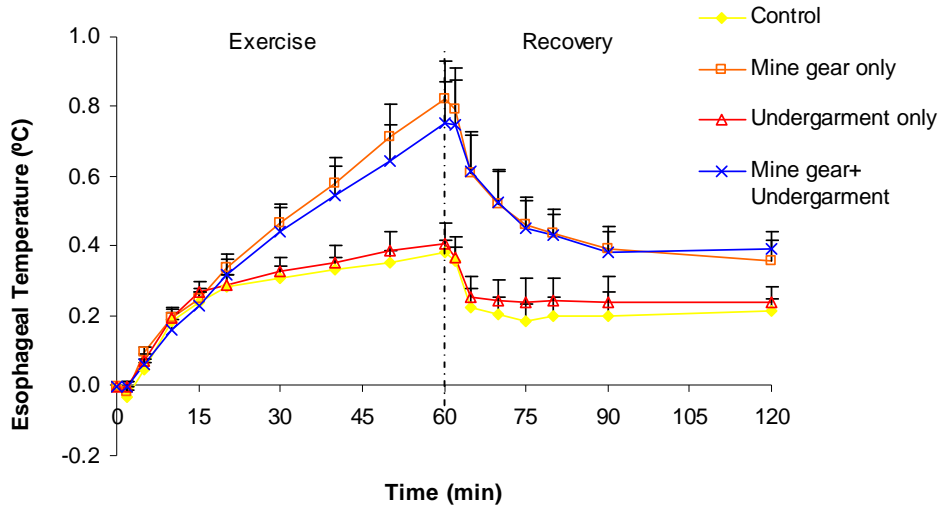
**Figure 3:** Mean relative change in rectal temperature during exercise and recovery

part of the curve generally shows that total heat loss is reaching a maximum value at 60 minutes and would not significantly increase with a longer duration exercise.

### 3.2. Temperature Changes

Figures 3 through 5 present the average changes in deep and superficial temperatures for the four clothing scenarios relative to a subject's initial baseline condition. Figure 3 shows the average rectal temperature change with time, after 60 minutes of exercise the maximum temperatures obtained were: Semi-nude Control 37.49°C, Undergarment only 37.45°C, Mine Gear only 37.68°C, and Mine Gear/Undergarment 37.71°C. This figure shows the increase in rectal temperature trending towards a stable condition for the Semi-nude and Underwear conditions as heat generation and loss balance each other out. However, for the two Mine Gear conditions, the rectal temperature consistently increased throughout the exercise period. This increase would probably have continued if the exercise lasted longer than 60 minutes because, as Figure 2 tends to show, heat loss has reached a maximum. This continued increase shows that both Mine Gear ensembles could cause core temperatures to exceed suggested limits, such as 38°C (ACGIH, 2001)

Figure 4 shows the average esophageal temperature change traces. After 60 minutes of exercise the maximum temperatures obtained were: Semi-nude Control 37.25°C, Undergarment only 37.29°C, Mine Gear only 37.66°C, and Mine Gear/Undergarment



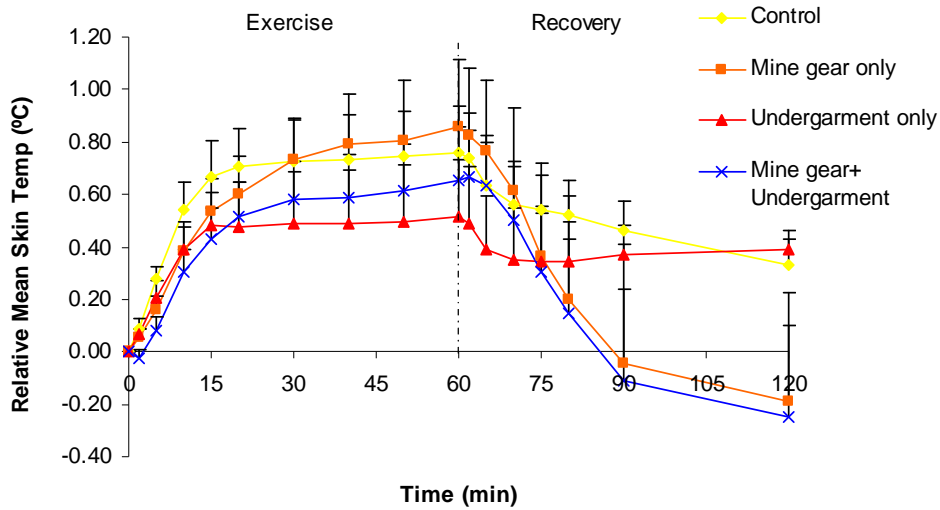
**Figure 4:** Mean relative change in esophageal temperature exercise and recovery

underwear 37.59°C. This figure similarly shows that the subject’s metabolic heat generation and loss had not reached equilibrium for either of the Mine Gear clothing/equipment ensembles.

Figure 5 shows the average mean skin temperature change with time. After 60 minutes of exercise the maximum temperatures obtained were: Semi-nude Control 35.67°C, Undergarment only 35.64°C, Mine Gear only 35.60°C, and Mine Gear/Undergarment 35.61°C. The mean skin temperature was the only measured parameter where there were notable differences due to wearing the “wicking” undergarment. Compared to the Semi-nude Control, the Undergarment only resulted in a lower mean skin temperature during exercise and for the majority of the recovery period. Similarly in the Mine Gear ensembles, the mean skin temperature was again lower during exercise when combined with the undergarments.

### 3.3. Changes in Body Heat Content

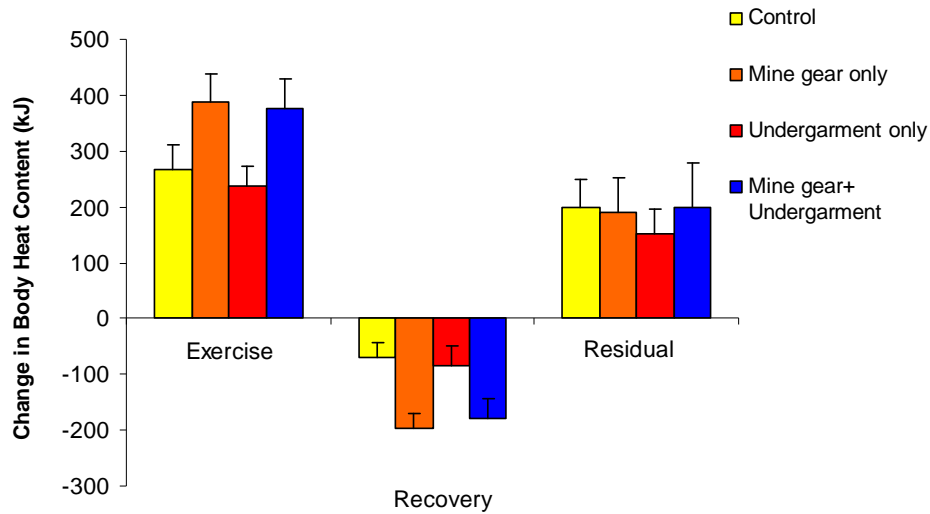
The actual changes in body heat content through the 60 minute exercise and 60 minute rest period were obtained from the difference of the metabolic heat production and total heat loss results presented in Figure 2 integrated over their respective time periods. The respective changes for each clothing condition during exercise and recovery, and then the residual heat stored by the body are shown in Figure 6. It indicates that there are no



**Figure 5:** Mean relative change in mean skin temperature during exercise and recovery significant differences in the change in body heat content during the 60 minute work period between the Undergarment only and Semi-nude Control condition. The residual heat storage after 60 minutes was also similar. However, there are notable differences between either the Semi-nude Control, or the Undergarment only condition, with both of the Mine Gear only and Mine Gear/Undergarment conditions. During exercise, the more significant increase in body heat content associated with both conditions using Mine Gear clothing ensembles is indicative of its insulative effect. During the recovery period, the loss of body heat with the Mine Gear only and Mine Gear/Undergarment conditions is also greater than for the Semi-nude Control or Undergarment only conditions; due to the higher body heat content prior to the start of the recovery period.

#### 4. DISCUSSION

These results show the benefits of using a calorimeter to evaluate clothing. Since, it can give a more direct measure of the dynamic performance of the clothing-human system plus the insulative properties of the clothing that limit heat loss during exercise and then promote heat storage during resting. Monitoring the intake and exhaust air temperatures and the air flow through the calorimeter chamber, along with the oxygen consumption and the external work of a test subject, provides all the data required for a heat balance analysis which is independent of deep body and superficial skin temperatures. However,



**Figure 6:** Mean and net changes in body heat content during exercise and recovery

these temperatures still remain important in the interpretation of the heat production, loss and storage data, for the development of work exposure limits to protect workers against heat strain.

The results show “wicking” type undergarments are neither beneficial nor detrimental compared to the Semi-nude Control condition of basic shorts. Furthermore, it is neither beneficial nor detrimental when worn under the Mine Gear ensemble. These results show that both Mine Gear ensembles (with or without undergarments) restrict whole-body heat loss to a similar degree. Hence, the Mine Gear is the main cause of the increased heat gain during work. Furthermore, both Mine Gear ensembles limit heat loss similarly during recovery. This again indicates that the Mine Gear itself is the primary cause; and could have detrimental effects during repeated work bouts performed in the heat. During exercise both Mine Gear ensembles prolong the continued increase in internal core temperatures. During rest, both Mine Gear configurations retard heat loss resulting in a higher level of hyperthermia as evidenced by the greater core temperatures relative to the Semi-nude Control and Underwear only conditions. The results show no significant difference between the overall performance of these one and two layer work clothing ensembles.

## 5. CONCLUSIONS

The testing reported here provides the baseline data needed to evaluate new clothing options available to the Canadian mining industry which may help mitigate the effects of working in heat. Further analysis is ongoing, including assessing other clothing ensembles such as light-weight coveralls and a workpant/wicking long-sleeved t-shirt combination, under three different environmental conditions and while performing intermittent work.

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