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Prediction of human core temperature rise and moisture loss in refuge alternatives for underground coal mines

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Abstract

Research by the U.S. National Institute for Occupational Safety and Health (NIOSH) has shown that heat/humidity buildup is a major concern within coal mine refuge alternatives. High temperature and humidity levels inside a refuge alternative may expose occupants to heat stress. Due to the safety risks associated with testing using human subjects, NIOSH partnered with ThermoAnalytics Inc. to create detailed thermal simulation models of refuge alternatives with human occupants. The objective of this effort was to predict a miner's core temperature response and moisture loss in environments that may be encountered in a coal mine refuge alternative. These parameters were studied across a range of temperatures and relative humidity values to determine if the current 35 °C (95 °F) apparent temperature limit for refuge alternatives is reasonable. The results indicate that the apparent temperature limit is protective, provided that miners are supplied with sufficient water. The results also indicate that the body core temperature does not reach dangerous levels even at an apparent temperature of 54 °C (130 °F). However, the results show that moisture loss increases with apparent temperature. Therefore, if the apparent temperature limit were raised, the water provided in a refuge alternative would have to be increased to offset moisture loss.

Keywords

Coal mine; Refuge alternatives; Heat stress

Introduction

The purpose of this effort was to predict a miner's core temperature and moisture loss — from sweating and respiration — in environments that are likely to be encountered in a coal mine refuge alternative. A range of combinations of temperature and relative humidity were studied to determine whether the current 35 °C (95 °F) Steadman apparent temperature limit and 2.13 L/d (2.25 qt/day) water requirements for refuge alternative mandated by the U.S. Mine Safety and Health Administration (MSHA, 2016a, 2016b: 30 CFR 7.504 and 30 CFR 75.1507) are reasonable. The effects of metabolic heat rate (activity level), miner size (height and weight), and pose (sitting or lying) on core temperature and moisture loss were also studied.

Model description

TAITherm thermal modeling software (ThermoAnalytics Inc., Calumet, MI) was used to simulate humans in refuge-alternative-like environments in a range of temperature and relative humidity combinations. The TAITherm Human Thermal Model (HTM) predicts the dynamic thermal response of the simulated miners while accounting for clothing, human tissue thermal properties and active thermoregulation.

Human thermal model overview

The TAITherm HTM was used to simulate the heat generated by the shelter occupants, and to predict the miners’ skin and core temperatures along with their sweat evaporation rates. The thermoregulation model simulates the process by which the body attempts to maintain a constant core temperature by considering the effects of shivering, sweating and changes in skin blood flow. This model calculates surface and deep tissue temperatures within the human body as described by a surface mesh.

The model is based on a complex physiological model in which the body is divided into 20 segments, including face, head, neck, chest, and right and left shoulders (Curran et al., 2006; Fiala, Lomas and Stohrer, 1999, 2001). Segmented thermoregulation models are the most accurate way to predict the core temperature of a human body when subjected to transient, asymmetric environments. Tissue thickness and thermal properties are assigned to each of the 20 segments, including skin, fat, muscle, bone, lungs and brain. The model characterizes the transport of heat and moisture through tissue and clothing layers. Clothing is defined by its thermal resistance, evaporative resistance, and clothing area augmentation factor. The model predicts skin and underlying tissue temperatures as well as blood and body core temperatures based on environmental conditions, clothing and activity level.

An important determinant in the amount of heat generated by humans is their activity level. In a refuge chamber, the occupants will spend most of their time sitting, but there will be periods of activity, such as when maintaining the carbon dioxide (CO_2) scrubbers or eating. Activity level is commonly specified in terms of heat rate per body surface area with metabolic equivalent of task, or met, where 1 met is equivalent to 58.1 W/m^2 and corresponds to the activity of a human sitting quietly. The TAITherm HTM takes activity level as an input, but the actual metabolic heat rate produced in a human can increase if the human’s core temperature rises above the set point of 37 °C (98.6 °F).

The TAITherm HTM has been validated against test data collected from human subjects. Comparisons of body core temperatures, mean skin temperatures, and evaporative heat losses between the HTM and real human subjects have been previously shown for a sedentary activity in a hot environment (Klein and Hepokoski, 2016).

Miner thermal model description

The geometry of the human is described by a shell-element mesh, which the model uses to compute temperatures at each quadrilateral or triangular element from the surface of the clothing to the core of the body segment. Low-resolution surface meshes, with 180 surface elements, were used to minimize solution run-time. However, a high-resolution mesh, with 7,900 surface elements, was also tested to gauge the sensitivity to mesh density on model predictions. Figure 1 shows the mesh definitions of the human model with two different resolutions. A low-resolution mesh representing a human in a supine position is presented alongside a high-resolution human.

TAITherm models were set up to simulate miners in three different poses, as shown in Fig. 2. The conduction between the humans and the floor was approximated using a contact resistance of 0.01 m^2-K/W, and the contact area varied between the three poses. The air temperature, floor temperature and surrounding wall temperatures were set to be equal to one another and treated as constant, or steady. Radiation to the mine walls and roof were accounted for by using a constant temperature bounding box. To determine whether heat transferred to the floor through conduction affected body temperature, models were also run with calculated floor temperatures, assuming 1.8 m (6 ft) of siltstone under the person and an initial homogeneous rock temperature equal to the air temperature. For each pose, the temperatures were varied between 27 and 33 °C (between 81 and 91 °F) in 1 °F increments, and the relative humidity was held constant at 95 percent for a total of 11 temperature/humidity combinations, which yielded Steadman apparent temperatures between 31.4 °C (88.5 °F) and 55.4 °C (131.7 °F). The apparent temperature was calculated using the equation derived from the Steadman apparent temperature table (Rothfusz, 1990). The simulations were run for 24 hours at each unique temperature/humidity combination. A subset of the models were also run for 96 hours with steady temperature and relative humidity to determine if the core temperature would continue to increase beyond 24 hours. However, the human core temperature and sweating response were shown to become steady after a few hours when constant environmental conditions were specified within the simulation. Therefore, most models were run for 24 hours to reduce the total computation time.

In addition to temperature, humidity and pose variations, the human size and activity level, or metabolic rate, were also varied. Activity level was varied between 0.9 and 1.2 met, or between 102 and 140 W for a 1.75 m (5 ft 9 in.), 78.5 kg (173 lb) male. Table 1 shows how typical activities relate to activity level (Bernard, 2016). The regions highlighted in yellow correspond to activities that might be similar to those of a person in a refuge alternative.

The University of South Florida conducted research to determine the body size distribution for coal miners and the metabolic heat rate for coal miners occupying a refuge alternative (Bernard, 2016). A height of 1.93 m (6 ft 4 in.) and weight of 124.7 kg (275 lb) were recommended to represent the 95th percentile miner size. A resting metabolic rate (RMR) of 120 W was recommended for a person of that size.

Three different size humans were considered: (1) a standard male with 50th percentile height and weight, 1.75 m (5 ft 9 in.) tall, weighing 78.5 kg (173 lb) with 13 percent body fat, (2) a large male with low body fat, 1.96 m (6 ft 5 in.) tall, weighing 111 kg (245 lb) with 15 percent body fat, and (3) a large male with high body fat, 1.96 m (6 ft 5 in.) tall, weighing 111 kg (245 lb) with 32 percent body fat. The sizes used by the TAITherm HTM were taken from Tilley (2002), which characterizes American anthropometric data sets in terms of percentile. Consequently, a 95th percentile male was one of the largest sizes that could be represented within the software, which corresponded to a 111-kg (245-lb) male with high body fat. An activity level of 0.9 met matched the 120 W RMR of a 95th percentile person, which was recommended by the University of South Florida (Bernard, 2016).

Core temperature and moisture loss metrics

According to the U.S. Army Research Institute of Environmental Medicine (2003), the body's core temperature provides the "best" single physiological measure to estimate physical work capabilities during hot conditions. The same source also defines two categories of heat stress:

- *Compensated heat stress* (CHS): This exists when heat loss occurs at a rate in balance with heat production, so that a steady-state core temperature can be achieved at a sustainable level for a requisite activity. For such environments, the heat stress core temperature threshold is defined as 38.5 °C (101.3 °F).

- *Uncompensated heat stress* (UCHS): This occurs when the individual's evaporative cooling requirements exceed the environment's evaporative cooling capacity. For such environments, the heat stress core temperature threshold is defined as 38 °C (100.4 °F).

The environment inside a typical coal mine refuge alternative tends to be very humid, and the air temperature would be expected to rise within the refuge alternative due to the metabolic heating of the occupants and heat generated by the CO_2 scrubbing system. Because the temperatures within a refuge alternative are continually rising, the UCHS limit is recommended for refuge-alternative occupant evaluations.

In addition to core-temperature rise, moisture loss due to sweating is a serious concern within a refuge alternative. The TAITherm HTM predicts moisture loss due to sweating and respiration, but those losses do not account for all of a person's daily water requirements. Table 2 shows typical ranges for daily water loss and production (Sawka, 2015). The range for sweat loss for an active person is about 0.5 to 3.6 L/d, while the net loss is shown as 1.5 to 6.7 L/d. The total moisture loss could be predicted by adding 0.8 to 2.75 L, equivalent to sedentary net loss minus respiratory loss in Table 2, to the sweat and respiratory losses predicted by the model.

While the model predicts the total sweat rate and the amount of sweat that is evaporated, it does not predict hidromeiosis, which is a decrease in sweat rate that occurs when the skin becomes excessively wet. Hidromeiosis is the body's natural reaction to limit sweat production in hot environments where the sweat cannot be effectively evaporated. According to Candas, Libert and Vogt (1983), high degrees of skin wettedness induce epidermal skin hydration, which is associated with a progressive decrease in sweating. The model predicts skin wettedness as a percentage, with 100 percent being totally wet, or completely covered with a layer of liquid sweat. Figure 3 shows plots of transient total sweat rate and evaporated sweat rate for human subjects in a hot and humid environment. The plots show that for the measured environment, the total sweat rate, m_{sw}, peaked at about 60 min, then started to decline, with the onset of hidromeiosis. The amount of sweat that dripped from the surface of the body, m_{dr}, also decreased after the onset of hidromeiosis. Toward the end of the 140-min exposure, the total sweat rate approached the sweat evaporation rate, E_{sk}. The plots shown in Fig. 3 are for a very hot environment of 48 °C (118.4 °F), which is considerably hotter than a typical mine shelter and the 35 °C (95 °F) limit for apparent temperature.

Results

Human core temperature and moisture loss predictions

Skin and clothing surface temperature predictions can be seen in Fig. 4 for lying (supine) humans with low-resolution and high-resolution surface mesh. Negligible differences in skin and core temperatures were seen between the low- and high-resolution models, which were attributed to a difference in contact area with the floor due to the different arm positions.

Transient core temperature predictions for a 96-hour exposure of a 50th percentile male — 1.75 m (5 ft 9 in.) tall, weighing 78.5 kg (173 lb) — in both the seated and supine (lying) positions are shown in Fig. 5. The air temperature was held constant at 29 °C (85 °F), and the relative humidity was held constant at 95 percent. For one case, the floor temperature was held constant at 29 °C (85 °F). For the other case, the temperature increase of the floor was calculated assuming a siltstone floor, 1.8 m (6 ft) thick, with an initial temperature of 29 °C (85 °F) throughout. The siltstone floor resulted in a slightly greater core temperature rise — 0.036 °F for the supine human — due to the heating of the rock underneath. Given the relatively minor difference in temperature predictions between the two cases, the floor temperature was treated as constant to simplify and reduce model run time.

The plots in Fig. 5 also show that core temperatures tend to stabilize within four to six hours when the body is exposed to steady environmental conditions. Given the large number — approximately 1,000 — of simulated exposures considered in this project, each scenario was consequently assigned a maximum duration of 24 hours.

The core temperature and moisture loss rates for three human sizes and three poses were simulated for a range of apparent temperatures. Air temperature was varied between between 27 and 33 °C (81 and 91 °F) in 1 °F increments, and the relative humidity was held at 95 percent (Steadman apparent temperature between 88.5 and 131.7 °F). The floor temperature was assumed to be constant and equal to the air temperature. The simulations were run for 24 hours using each unique temperature/humidity combination.

Table 3 shows core temperature, moisture loss and metabolic rate as a function of activity level, air temperature, relative humidity and apparent temperature for a 50th percentile male, 1.75 m (5 ft 9 in.) tall, weighing 78.5 kg (173 lb) with 13 percent body fat, and a large male with low body fat, 1.96 m (6 ft 5 in.) tall, weighing 111 kg (245 lb) with 15 percent body fat.

Moisture loss is a combination of sweat and respiratory moisture loss over the 24-hour simulation. The total moisture loss would be 0.8 to 2.75 L greater than the values shown in Table 3 because sedentary losses are not calculated by the TAITherm HTM (see Table 2). The metabolic heat rate value is calculated as a function of the activity level, human body size and core temperature.

The core temperatures at the end of the 24-hour simulations and the predicted moisture losses, consisting of sweat and respiration, over the 24-hour period are also shown in Figs. 6, 7 and 8, along with apparent temperature, which was held constant, on the x-axis.

Figure 6 shows core temperature and moisture loss results for varying poses. The predicted core temperature and moisture loss varied a little between poses due to differences in the amount of contact area with the floor.

Figure 7 shows predicted core temperatures and moisture losses for humans of various body sizes. TAITherm provides a capability to specify the height and weight of the human model in terms of percentiles. For example, the 50^{th} percentile male corresponds to a height of 1.75 m (5 ft 9 in.) and a weight of 78.5 kg (173 lb), while the maximum size, the 95th percentile male, corresponds to a height of 1.96 m (6 ft 5 in.) and a weight of 111 kg (245 lb). The worst case in terms of core temperature and moisture loss is a very large person with low body fat because the metabolic heat rate associated with muscle tissue is greater than that of fat. Therefore, for a given activity level, a person with higher muscle content will have more total metabolic heating than a person with higher fat content despite both having the same total body weight.

Figure 8 shows core temperature and sweat loss results for varying activity levels, or metabolic rates. Higher metabolic rates result in higher core temperature and moisture loss. Based on research by the University of South Florida (Bernard, 2016), it is expected that refuge-alternative occupants would have an activity level of roughly 0.9 to 1.0 met.

Since the TAITherm HTM does not account for hidromeiosis, additional analysis was performed to determine whether hidromeiosis would be likely to occur for the conditions that were simulated. Transient sweat rate plots for two different apparent temperature conditions are shown in Fig. 9. The total sweat is not much greater than the evaporated sweat for the cooler condition — apparent temperature of 106.4 °F — so there would not be much excess sweat on the skin. The predicted skin wettedness was 42.7 percent. For the hot case — apparent temperature of 130.6 °F — the total sweat rate is much greater than the evaporation rate, so the skin would be expected to be wet. The predicted skin wettedness for the hot case was 98.6 percent, so hidromeiosis would be expected to occur. The TAITherm HTM is likely overpredicting the total sweat loss for very hot conditions, because it does not account for hidromeiosis.

Conclusions

The objective of this study was to quantify the effect of temperature and relative humidity on the physiological state of a mine shelter occupant. These findings are meant to inform regulators on whether the current 35 °C (95 °F) apparent temperature limit and water rations are appropriate for coal mine refuge alternatives. Core body temperature and moisture loss metrics were studied to quantify their role in regards to human safety. Apparent temperatures up to 131.7 °F were simulated.

Human body core temperature did not rise above the uncompensated heat stress limit of 38°C (100.4 °F) for any of the simulated conditions. Therefore, moisture loss may be a more critical factor for determining mine shelter occupant safety. Moisture loss due to sweating and respiration increases significantly as the apparent temperature rises above 120 °F, especially for activity levels greater than 1.0 met. The 2.13 L/d (2.25 qt/day) water requirement appears to be sufficient for the current 95 °F apparent temperature regulation. At an apparent temperature of 96.5 °F, the simulations predicted moisture loss, from sweat and respiration, of 1.0 L for both the 78.5-kg (173-lb) and 111-kg (245-lb) humans with high body fat at an activity level of 1.0 met.

The effects of metabolic heat rate (activity level), miner size (height and weight) and pose (sitting or lying) were also examined. Pose affected the final body core temperature by less than 0.2 °F and total moisture loss by less than 1 L for any given apparent temperature. Activity level and body size had more significant effects on body core temperature and moisture loss. At an apparent temperature of 121.8 °F, increasing body weight to 111 kg (245 lb) from 78.5 kg (173 lb) or increasing the activity level to 1.2 met from 0.9 met caused the total moisture loss to double.

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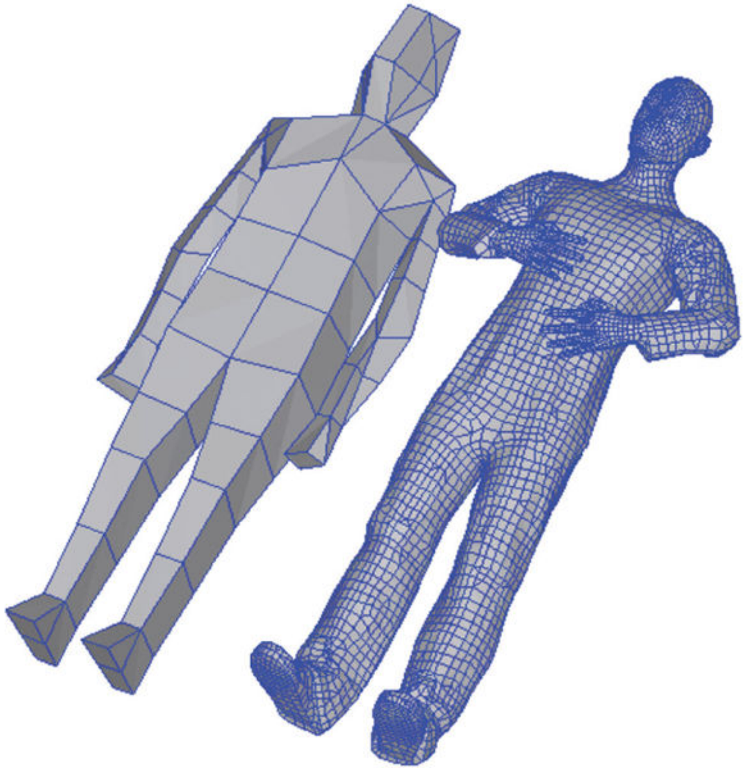

Figure 1.
Supine (lying) humans with low-resolution (left) and high-resolution (right) surface mesh.

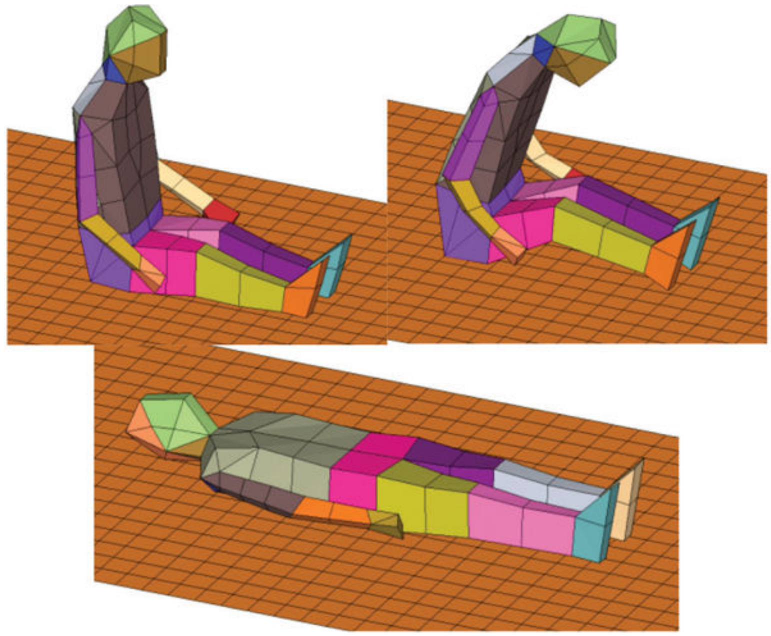

Figure 2.

TAITherm modeling of three human poses: sitting with legs flat, sitting with legs bent, and lying.

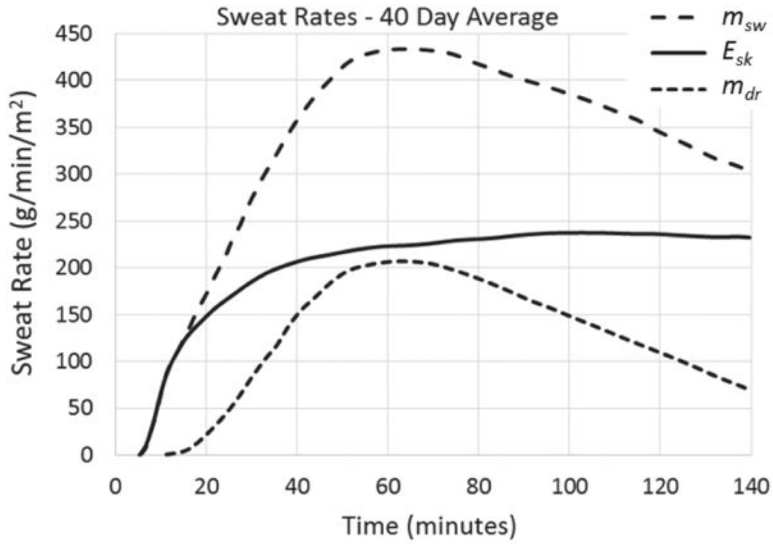

Figure 3.
Transient total sweat and evaporated sweat rates showing effects of hidromeiosis (Candas, Libert and Vogt, 1983).

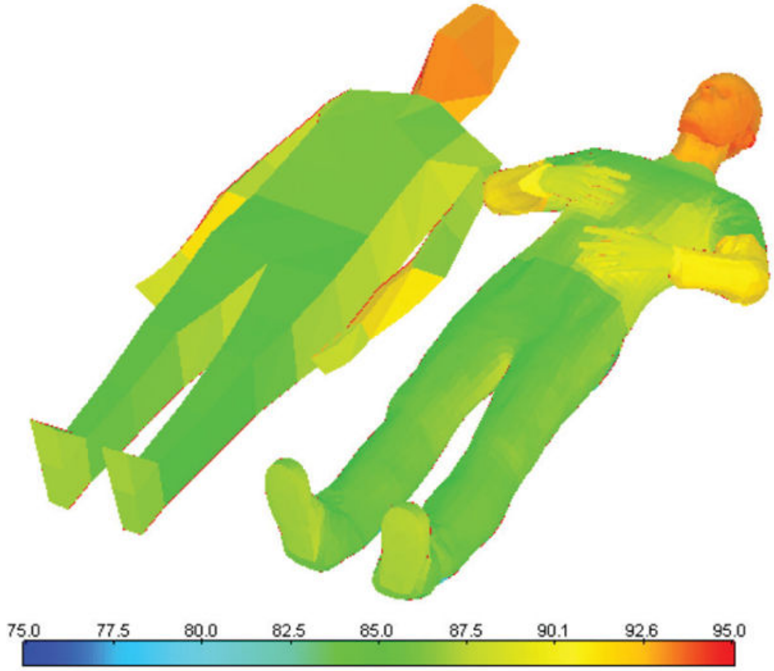

Figure 4.
Low-resolution (left) and high-resolution (right) humans colored by surface temperature.

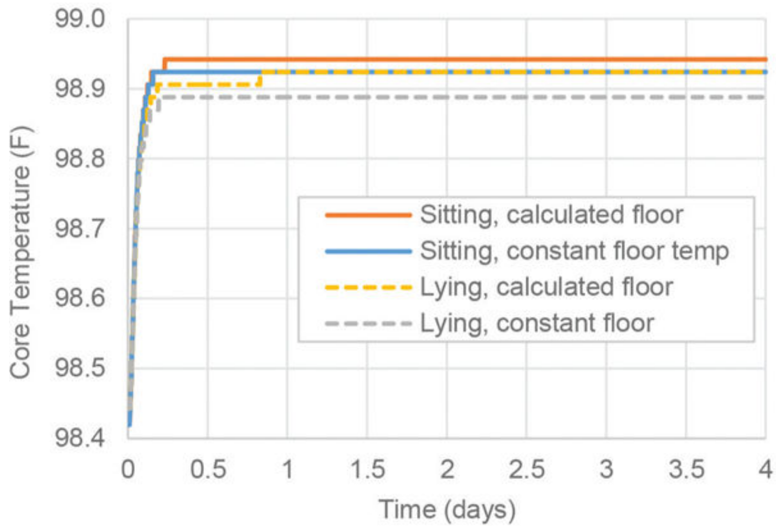

Figure 5.
Predicted core temperature for a human in seated and supine positions with constant and varying (calculated) floor temperatures (85 °F air temperature, 95 percent relative humidity, 104.2 °F apparent temperature).

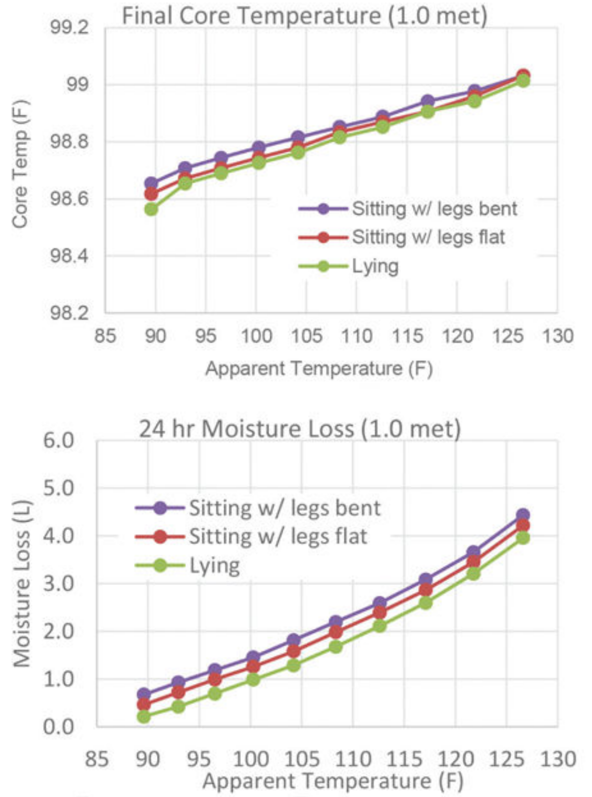

Figure 6.

Final core temperature and moisture (sweat and respiration) loss for three different poses and various apparent temperature environments (5 ft 9 in., 173-lb male, 1.0 met activity level).

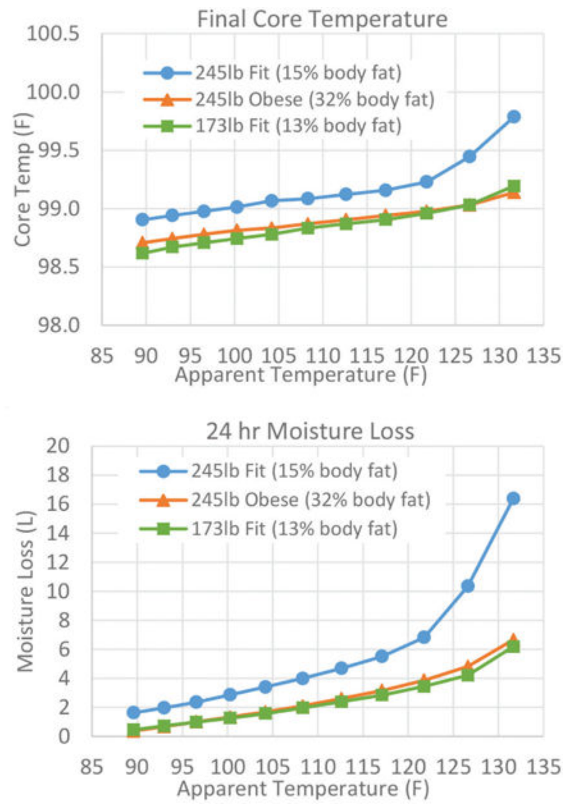

Figure 7.

Final core temperature and moisture (sweat and respiration) loss for three different size humans and various apparent temperature environments (sitting with legs flat, 1.0 met activity level).

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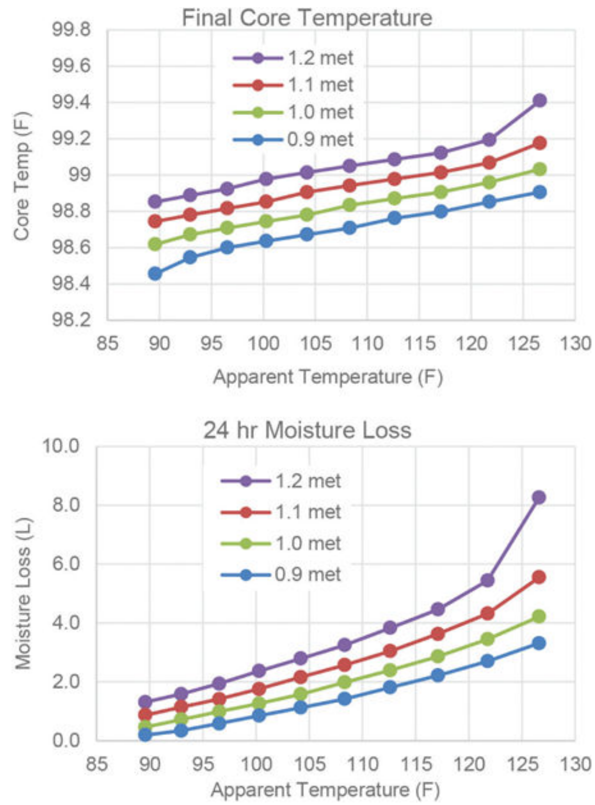

Figure 8.

Final core temperature and moisture (sweat and respiration) loss for four different activity levels and various apparent temperature environments (5 ft 9 in., 173-lb male, sitting with legs flat).

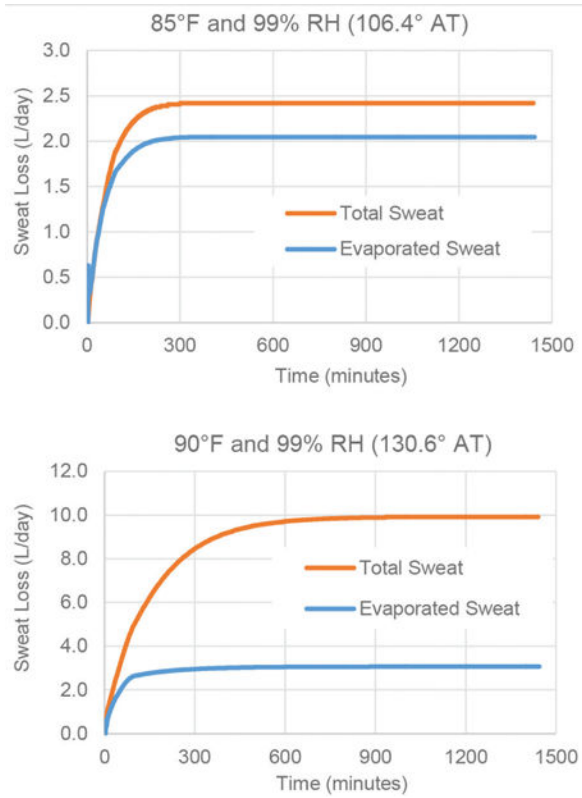

Figure 9.
Total and evaporated sweat plots for two apparent temperature conditions (173-lb male, sitting).

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Table 1

Activity levels for various activities, compiled by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 2005) from various sources (met = metabolic equivalent of task).

Activity	Activity level	
	W/m^2	met
Resting		
Sleeping	40	0.7
Reclining	45	0.8
Seated, quiet	60	1.0
Standing, relaxed	70	1.2
Walking (on level surface)		
3.2 km/h (0.9 m/s)	115	2.0
4.3 km/h (1.2 m/s)	150	2.6
6.4 km/h (1.8 m/s)	220	3.8
Office activities		
Reading, seated	55	1.0
Writing	60	1.0
Typing	65	1.1
Filing, seated	70	1.2
Filing, standing	80	1.4
Walking about	100	1.7

Table 2

Daily water loss and production ranges (Sawka, 2015).

Source	Loss (L/d)	Production (L/d)
Respiratory loss	−0.25 to −0.35	
Urinary loss	−0.50 to −1.0	
Fecal loss	−0.10 to −0.20	
Insensible loss	−0.45 to −1.90	
Metabolic production		+0.25 to +0.35
Total	**−1.30 to −3.45**	**+0.25 to +0.35**
Net loss (sedentary)	−1.05 to −3.10	
Sweat losses, various sports	−0.455 to −3.63	
Net loss (athlete)	−1.55 to −6.73	

Table 3

Summary of temperature and moisture loss results predicted with the TAITherm HTM.

Activity level (met)	Air temperature (°F)	Relative humidity (%)	Apparent temperature (°F)	173 lb, fit (13% body fat)			245 lb, fit (15% body fat)		
				Core temperature (°F)	24-h moisture loss (L)	Metabolic rate (W)	Core temperature (°F)	24-hr moisture loss (L)	Metabolic rate (W)
0.9	81	95	89.6	98.4	0.2	102.1	98.8	1.0	151.1
0.9	82	95	93.0	98.5	0.3	102.6	98.8	1.3	151.4
0.9	83	95	96.5	98.6	0.6	102.9	98.9	1.7	151.6
0.9	84	95	100.3	98.6	0.8	103.1	98.9	2.0	151.9
0.9	85	95	104.2	98.7	1.1	103.3	98.9	2.5	152.2
0.9	86	95	108.3	98.7	1.4	103.5	99.0	3.0	152.5
0.9	87	95	112.6	98.8	1.8	103.8	99.0	3.6	152.8
0.9	88	95	117.1	98.8	2.2	104	99.1	4.3	153.1
0.9	89	95	121.8	98.9	2.7	104.2	99.1	5.2	153.4
0.9	90	95	126.6	98.9	3.3	104.5	99.2	6.6	153.9
0.9	91	95	131.7	99.0	4.2	104.8	99.5	11.0	155.7
1	81	95	89.6	98.6	0.5	114.3	98.9	1.6	168.5
1	82	95	93.0	98.7	0.7	114.6	98.9	2.0	168.7
1	83	95	96.5	98.7	1.0	114.8	99.0	2.4	169
1	84	95	100.3	98.7	1.3	115	99.0	2.9	169.3
1	85	95	104.2	98.8	1.6	115.2	99.1	3.4	169.6
1	86	95	108.3	98.8	2.0	115.5	99.1	4.0	169.9
1	87	95	112.6	98.9	2.4	115.7	99.1	4.7	170.1
1	88	95	117.1	98.9	2.9	115.9	99.2	5.5	170.4
1	89	95	121.8	99.0	3.4	116.1	99.2	6.8	170.8
1	90	95	126.6	99.0	4.2	116.4	99.4	10.3	172.2
1	91	95	131.7	99.2	6.2	117.1	99.8	16.4	174.3