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HEAT STRAIN EVALUATION OF U.S. NAVY STEAM SUIT ENSEMBLES

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USARIEM TECHNICAL REPORT T16-13

HEAT STRAIN EVALUATION OF U.S. NAVY STEAM SUIT ENSEMBLES

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14. ABSTRACT

A manikin testing and modeling approach was used to predict the heat strain while wearing a Prototype Steam Suit Ensemble (PSSE) or the current U.S. Navy Submarine Steam Suit Ensemble (SSSE) and working in a steam-filled environment (88ºC, 100% relative humidity) or a training environment (24ºC, 65% relative humidity). Both ensembles were tested on a thermal manikin to measure thermal resistances. Metabolic rates during walking at 1.8 m/s (4 mph) and wearing the PSSE or the SSSE were estimated using an empirical equation. The six cylinder thermoregulatory model (SCTM) was used to simulate human thermal responses and determine the heat endurance times. Results showed that the PSSE performance improves, relative to the SSSE. The PSSE 1) increases thermal resistance by 70%, indicating more protection from external heat load; 2) reduces metabolic rates due to reduction in weight and possibly less hobbling; and 3) increases the predicted heat endurance times to about 33 min in a steam-filled environment. The analysis is limited to heat stress only and excludes all other possible injuries, such as burn injury.

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EXECUTIVE SUMMARY

A manikin testing and modeling approach was used to predict the heat strain while wearing a Prototype Steam Suit Ensemble (PSSE) or the current U.S. Navy Submarine Steam Suit Ensemble (SSSE) and working in a steam-filled environment (88ºC, 100% relative humidity) or a training environment (24ºC, 65% relative humidity). Both ensembles were tested on a thermal manikin to measure thermal resistances. Metabolic rates during walking at 1.8 m/s (4 mph) and wearing the PSSE or the SSSE were estimated using an empirical equation. The six cylinder thermoregulatory model (SCTM) was used to simulate human thermal responses and determine the heat endurance times. Results showed that the PSSE performance improves, relative to the SSSE. The PSSE 1) increases thermal resistance by 70%, indicating more protection from external heat load; 2) reduces metabolic rates due to reduction in weight and possibly less hobbling; and 3) increases the predicted heat endurance times to about 33 min in a steam-filled environment. The analysis is limited to heat stress only and excludes all other possible injuries, such as burn injury.

INTRODUCTION

The U.S. Navy Submarine Steam Suit Ensemble (SSSE) is designed to allow safe entry into a steam-filled compartment for emergency repair or personnel rescue. The Navy Clothing and Textile Research Facility (NCTRF) is currently developing an improved SSSE. NCTRF has already analyzed the material and design of the SSSE, developed a new concept and produced a functional Prototype Steam Suit Ensemble (PSSE). The NCTRF effort aims to significantly enhance human performance of the user while wearing the PSSE, compared to the currently fielded SSSE. A critical requirement is that the PSSE does not increase the level of heat strain while maintaining adequate protection.

At the request of NCTRF and Natick Soldier Research, Development and Engineering Center (NSRDEC), the Biophysics and Biomedical Modeling Division (BBMD) at the U.S. Army Research Institute of Environmental Medicine (USARIEM) evaluated heat strain imposed by the PSSE and SSSE. Using the manikin testing and modeling approach, BBMD evaluated biophysical characteristics and then predicted the potential heat strain that personnel would experience while wearing the PSSE or SSSE for simulated work in both steam-filled and temperate training environments. The steam-filled environment was 88ºC, 100% relative humidity, and the training environment was 24ºC, 65% relative humidity. This report details the findings of this modeling and analysis.

METHODS

Thermal Manikin Testing

The SSSE and PSSE were evaluated on the Nemo thermal manikin (Thermetrics, Seattle, WA; http://www.thermetrics.com/) at NCTRF. The testing configurations are shown in Figures 1 and 2.

The Nemo thermal manikin has 22 independently heated and sweating zones. The manikin is covered with a fabric skin layer to distribute water evenly over its surface. The set points for water flow in each zone are adjusted to keep the manikin skin saturated. A computer program controls, records data and displays real-time numeric data and graphic plots of the zone temperatures. The software also calculates thermal resistances, evaporative resistances and the power input into the manikin.

Thermal resistances for the SSSE and PSSE were measured on Nemo according to the American Society for Testing and Materials (ASTM) standard F1291 (1). The manikin surface temperature was set to 35ºC within a climatic chamber controlled at -5ºC, 50% relative humidity with a 0.4 m/s air velocity. After the manikin reached steady-state, all skin temperatures, power inputs and environmental conditions were recorded for 30 min. Manikin tests were repeated three times with each ensemble. These data were then used to calculate thermal resistances.

Figure 1: Submarine Steam Suit Ensemble (SSSE) on the sweating thermal manikin (Images depict donning sequence of the SSSE)[1]

Front View **Rear View** **Front View** **Final Configuration**

Figure 2: Prototype Steam Suit Ensemble (PSSE) on sweating thermal manikin[2]

Front **Rear**

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[1] Tested configuration did not include fire fighter boots and self-contained breathing apparatus.

[2] Testing configuration did not include self-contained breathing apparatus.

Metabolic Rates

The Pandolf equation was used to estimate metabolic rates from body mass, external load including the clothing weight, walking speed, grade and a terrain coefficient through an empirical equation (13):

$$\dot{M} = 1.5 \cdot BM + 2.0 \cdot (BM + L) \cdot \left(\frac{L}{BM}\right)^2 + \eta \cdot (BM + L) \cdot (1.5 \cdot V^2 + 0.35 \cdot V \cdot G) \qquad \text{(Eq. 1)}$$

where $\dot{M}$ is metabolic rate in Watts, BM is body mass in kilograms; L is external load mass in kilograms; ŋ is the terrain factor; V is walking speed in meters per second and G is uphill grade (%).

Weights of the SSSE and PSSE are 8.6 kg (19 lb) and 5 kg (11 lb), respectively. The weight of the self-contained breathing apparatus (SCBA), gloves and boots are 15 kg (33 lb). Thus the total weights of the SSSE and PSSE are 23.6 kg and 20 kg, respectively.

The predicted metabolic rates were 647 W for the SSSE and 625 W for the PSSE during walking at 1.8 m/s (4 mph) on a flat ground. The walking speed of 1.8 m/s was estimated from the operational scenarios.

Metabolic rates were also measured in a human research study conducted by NSRDEC. Additional details were reported in a separate report. Average height and weight (± standard deviation (SD)) of the five health volunteers were 1.8 m (± 0.11) and 81.0 kg (± 7.1). The measured metabolic rates were 968 W (± 187) for the SSSE and 653 W (± 91) for the PSSE.

Six Cylinder Thermoregulation Model

Thermoregulatory simulations were conducted using the Six Cylinder Thermoregulation Model (SCTM) (21, 23). SCTM is a rational physiological model that represents the human body as six cylinders: the head, torso, arms, hands, legs and feet. Each cylinder consists of core, muscle, fat, skin and clothing layers. Body temperature and skin temperature are regulated by using a rational control system of thermoregulatory mechanisms, including sweating and variable blood flow. SCTM requires input information about the environment, clothing and human parameters. It predicts parameters of thermal responses, such as the body core temperature and local skin temperature. This model has been validated for a wide range of applications, including both heat and cold stress, various exercise intensities and various clothing ensembles (3, 21-22).

Modeling Inputs

The height and weight inputs of 1.8 m and 81 kg respectively represent the mean value of the five participants in the study of metabolic rate measurements. Body fat percentage was estimated to be 23%, which is the mean body fat percentage for a 20-year-old U.S. male with the same height and weight (24). Both measured and estimated metabolic rates were used as inputs.

The assumed operational scenario is a steam-filled environment: ambient temperature 88°C, wall temperature 32°C, relative humidity 100% and wind speed 0.4 m/s. The assumed training scenario is: ambient temperature 24°C, wall temperature 32°C, relative humidity 65%, and wind speed 0.4 m/s

SCTM requires input values for the intrinsic thermal resistance (I_{cl}) and intrinsic permeability index for six body zones; head, torso, arm, hand, leg and foot. I_{cl} is calculated by:

$$I_{cl} = I_t - \frac{I_a}{f_{cl}} \qquad \text{(Eq. 2)}$$

where I_t is the total thermal resistance, and I_a is the resistance measured on the nude manikin. The clothing area factor (f_{cl}) is defined as:

$$f_{cl} = \frac{A_{cl}}{A} \qquad \text{(Eq. 3)}$$

where A is the surface area of the nude manikin and is provided by the manikin manufacturer. A_{cl} is the surface area of the clothing when dressed on the manikin. For simplicity, f_{cl} was assumed to be 1.0.

Permeability index was not measured and thus assumed to be 0.1 (8, 9).

Uncertainty Analysis

Uncertainty analyses were conducted to determine how errors in the permeability indexes and metabolic rates could affect the predicted heat endurance times of the PSSE:

1) In the training scenario, simulations were performed with permeability indexes of 0.2, 0.1 and 0.01, while the rest of the parameters were kept unchanged.
2) For both the operational and training scenarios, the simulations were performed with three variations of the work rates: the measured metabolic rate and measured values plus or minus the standard deviation (SD). The other parameters were kept unchanged.

RESULTS

Ensemble Thermal Resistance

Table 1 shows the total (I_t) and intrinsic thermal resistance (I_{cl}) values of the SSSE and the PSSE. The PSSE increases the I_t of the whole-body by an average of 70% and the I_{cl} of five regions ranging from 24% to 146%; meanwhile, the thermal resistance in the hand region decreases by 4%.

When the SSSE was tested, the boots were too tight to put on the manikin and therefore the boots were not included. This deviation could explain why the thermal resistance of the leg of the SSSE was much lower than the PSSE.

Table 1: Total (I_t) and intrinsic (I_{cl}) thermal resistances of the SSSE and PSSE.

	Total (I_t, clo)		Change (%)	Intrinsic (I_{cl}, clo)	
	SSSE	PSSE		SSSE	PSSE
Head	1.65	2.23	-35.2	1.09	1.69
Torso	5.39	6.67	-23.7	4.79	6.29
Arms	3.20	5.89	-84.1	2.68	5.34
Hands	2.10	2.01	4.3	1.72	1.50
Leg	2.77	6.81	-145.8	2.24	6.21
Feet	0.93	1.52	-63.4	0.42	0.99
Whole body	2.69	4.58	-70.3		

Simulated Thermoregulatory Responses

Heat endurance times, i.e., the time for the core temperature to reach a defined threshold value, is often used as a thermal performance measure of protective ensemble. Endurance time is an approximation of the time that a wearer can work in a warm or hot environment without becoming a heat casualty, and may be expressed, for example, in terms of maximum allowable exposure time (7), the tolerance time (11), or safe exposure times. Those parameters are particularly useful in planning shift changes or rotation for teams working under extreme conditions such as hazardous waste clean-up operations. For this project, a threshold value of 39°C was used for the modeling analysis, and endurance time was defined as the length of the time for the core temperature (T_c) to increases to a temperature of 39°C.

Predicted core temperatures and the associated measured metabolic rates are shown in Figures 3 and 4. The predicted heat endurance times are approximately 33 min for the PSSE and 25 min for the SSSE in a steam-filled environment. In the temperate training environment, the predicted heat endurance times are approximately 40 min for the PSSE and 29 min for the SSSE

Predicted core temperatures and the corresponding estimated metabolic rates in a steam-filled environment are shown in Figure 5. The predicted heat endurance times were 38 min for the PSSE and 35 min for the SSSE. The difference in the predicted heat endurance time is about 3 min.

Figure 3: Predicted core temperatures (T_c) in the steam-filled environment: ambient temperature 88°C, wall temperature 32°C, relative humidity 100% and wind speed 0.4 m/s. Measured metabolic rates: 968 W for SSSE and 653 W for PSSE.

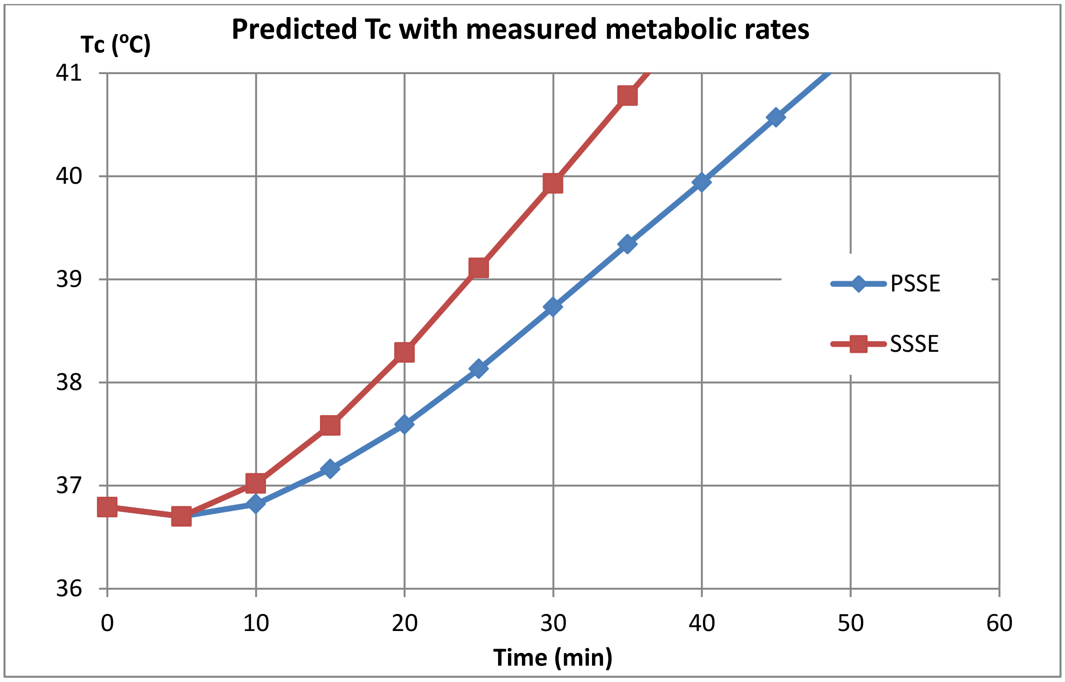


Figure 4: Predicted core temperatures (T_c) in the temperate training environment: ambient temperature 24°C, wall temperature 32°C, relative humidity 65% and wind speed 0.4 m/s. Measured metabolic rates: 968 W for SSSE and 653 W for PSSE.

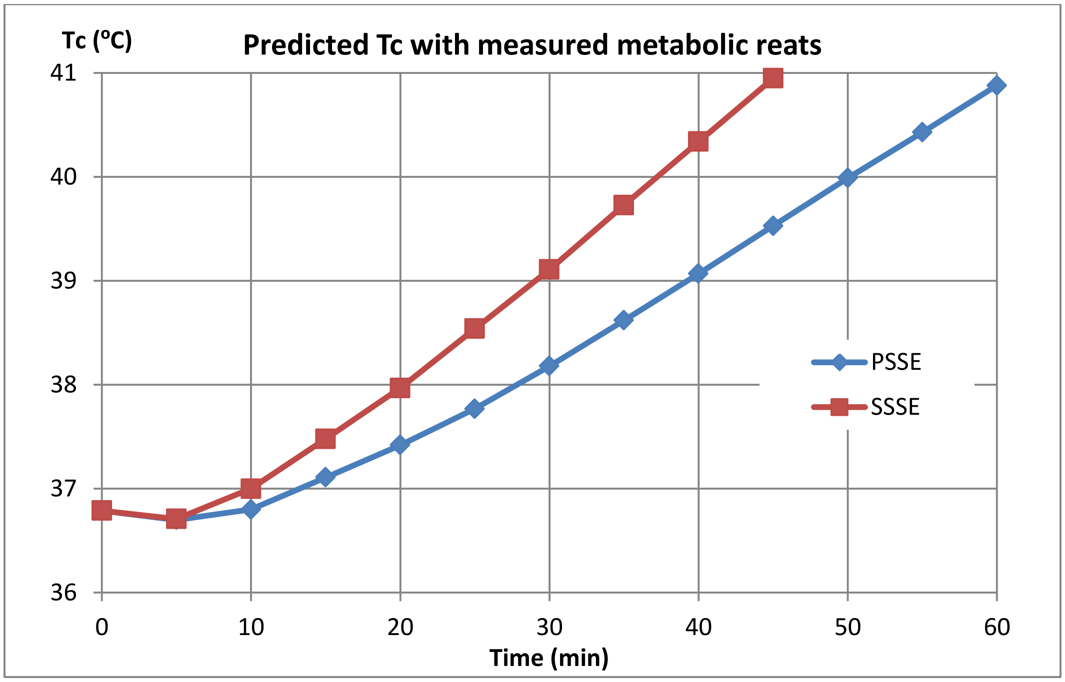
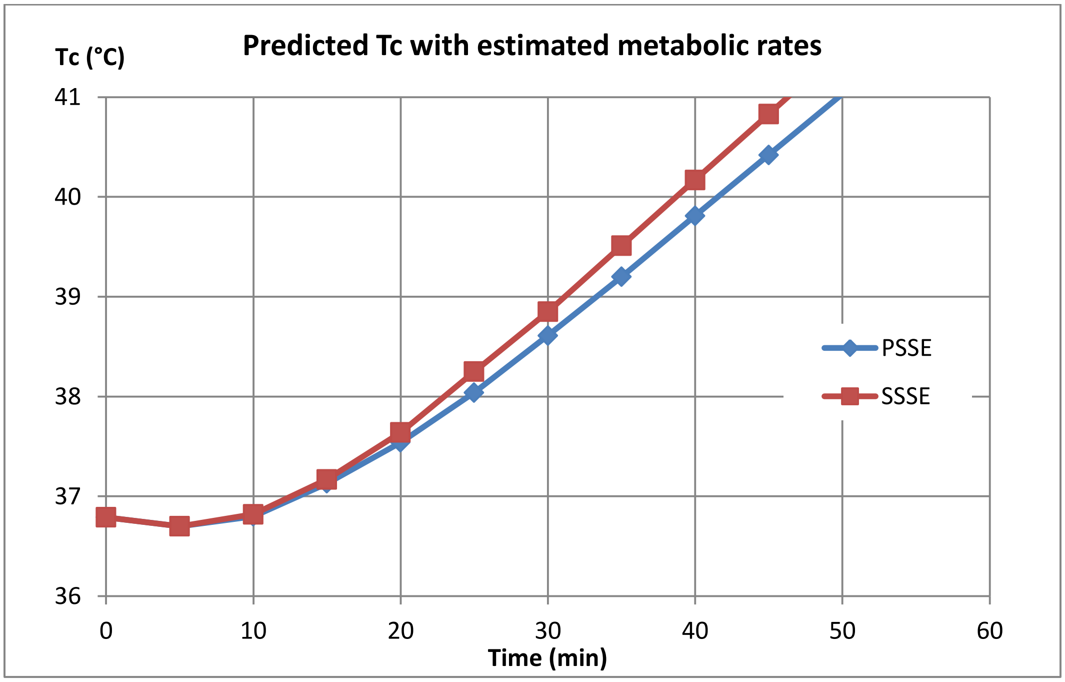


Figure 5: Predicted core temperature (T_c) in the steam-filled environment: ambient temperature 88°C, wall temperature 32°C, relative humidity 100% and wind speed 0.4 m/s. Estimated metabolic rates: 647 W for SSSE and 625 for PSSE.



Uncertainty Analysis Results

As shown in Figure 6, the predicted heat endurance times for the PSSE in the training scenario, was reduced from about 40 min to 37 min when the permeability index was reduced from 0.2 to 0.01. This indicates that the effects of the permeability indexes on the predicted heat endurance times are minimal.

Figure 7 shows the predicted heat endurance times for the PSSE in the steam-filled environment changed from 30 min to 36 min when the metabolic rate changed from 744 W to 562 W (measured value 653 ± 91 W). In the training scenario with the PSSE, the predicted heat endurance times, as shown in Figure 8, changed from 35 min to 45 min when the metabolic rates changed from 744 W to 562 W. This indicates that the predicted heat endurance times, as expected, are sensitive to the metabolic rates.

Figure 6: Predicted core temperatures (T_c) for the PSSE with different permeability indexes at an ambient temperature of 24°C, wall temperature 32°C, relative humidity 65% and wind speed 0.4 m/s.

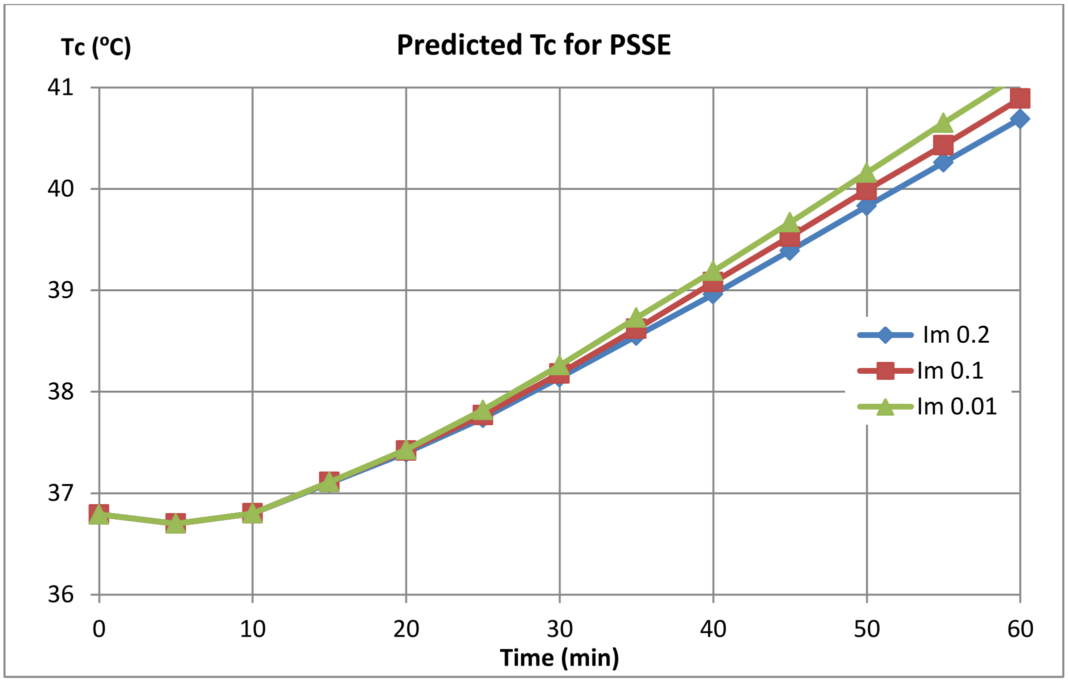


Figure 7: Predicted core temperatures (T_c) for the PSSE with different metabolic rates in a steam-filled environment of ambient temperature 88°C, wall temperature 32°C, relative humidity 100% and wind speed 0.4 m/s

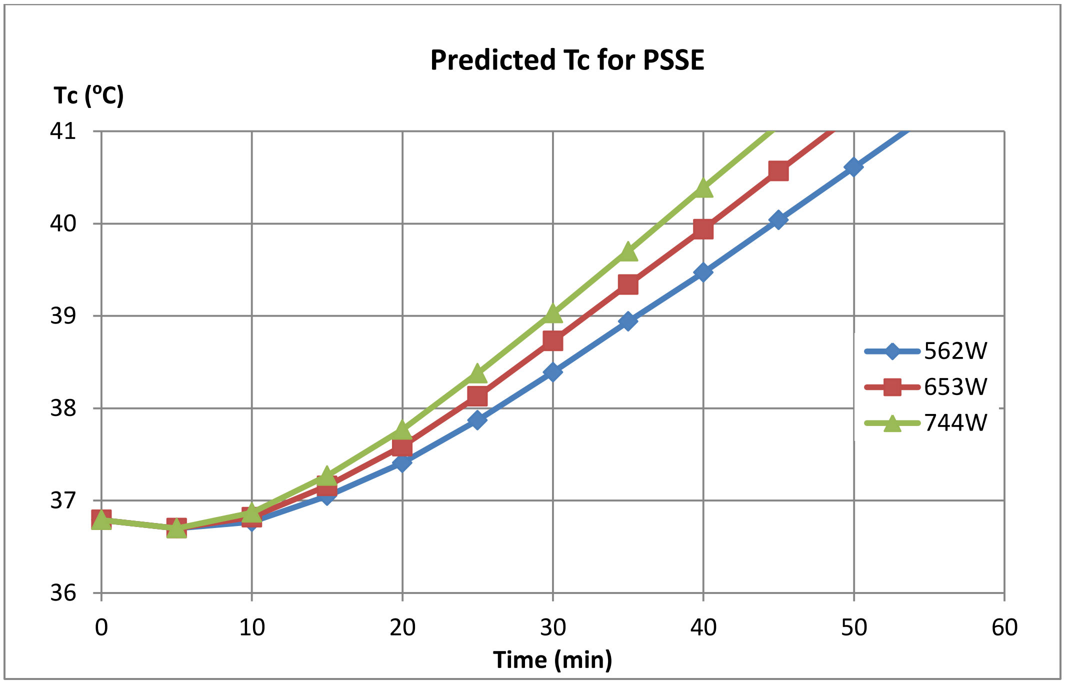
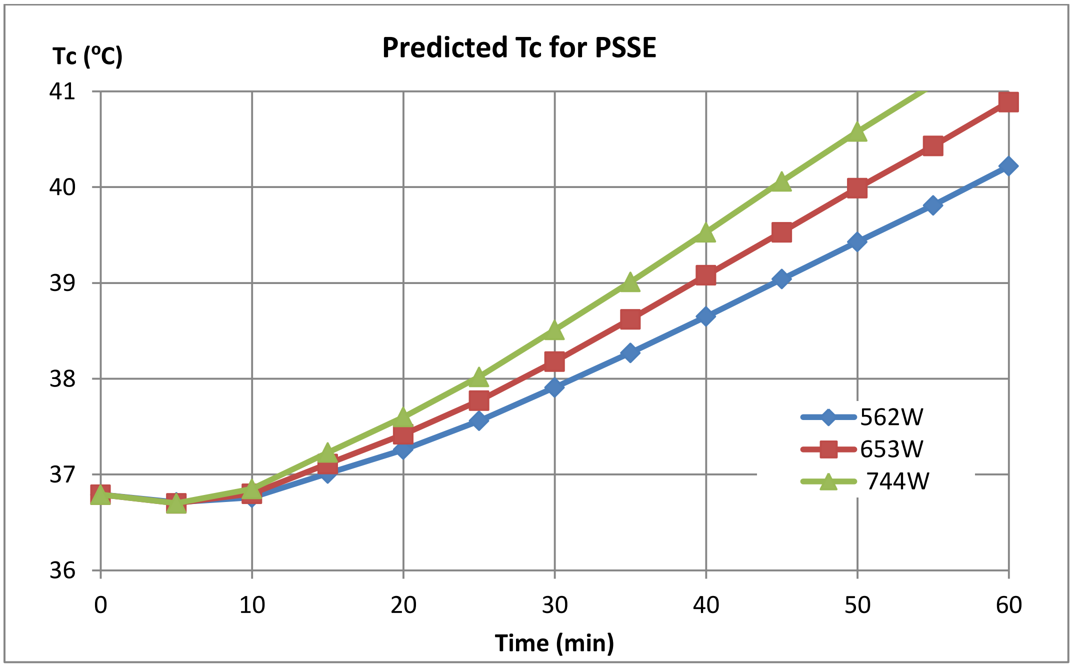


Figure 8: Predicted core temperatures (T_c) for PSSE with different metabolic rates in a training environment of ambient temperature 24°C, wall temperature 32°C, relative humidity 65% and wind speed 0.4 m/s



DISCUSSION

USARIEM has a well-established manikin testing and modeling approach to support the development of new ensembles. This approach consists of two steps. First, the clothing biophysical parameters, i.e., thermal and evaporative resistances, are determined on the thermal manikin in a controlled environment chamber. Second, validated thermoregulatory models are used with the measured resistances as inputs to predict human thermal responses to various activities and environmental conditions. The second step translates the biophysical properties of clothing into human thermal responses and thus allows clothing and material developers to understand how their designs could affect the human physiological responses (12, 14-15, 20, 25). The manikin testing and modeling approach was used to analyze both the SSSE and the PSSE. The results indicate that the PSSE improves the thermal performance in comparison with the SSSE. The PSSE: 1) increases thermal resistance by 70%, indicating more protection from external heat load; 2) reduces metabolic rates due to weight reduction and likely due to less hobbling; and 3) increases the predicted heat endurance times to about 33 min in a steam-filled environment. The analysis is limited to heat stress only and excludes all other possible injury, such as burn injury.

When personnel are exposed to extremely high temperatures, increasing thermal resistance will reduce heat gain from the environments, thus reducing the level of heat stress. With a 70% increase in thermal resistance, the PSSE should reduce the negative effect of the environment on the wearers.

The uncertainty analysis indicates that predicted heat endurance times are sensitive to metabolic rates. This is consistent with previous observations reported in the literature that metabolic rates become a dominant factor that contributes to heat stress when the ensemble thermal resistance values were high (4-5, 17, 25). Therefore, reducing metabolic rate is critical to reduce heat strain. For the PSSE, the measured metabolic rates ranged from 562 W to 744 W, and the estimated metabolic rate of 625 W was in this range. In the steam-filled environments, as shown in Figures 3, 5 and 7, the mean predicted heat endurance times of the PSSE was 33 min, ranging from 30 min to 36 min.

Metabolic rates while wearing personal protective equipment (PPE) during exercising are related to the ensemble weight and design (6, 19). The total weights of the SSSE and the PSSE were 23.6 kg and 20 kg respectively. For walking at 1.8 m/s on flat ground, the estimated metabolic rates were 647 W with the SSSE and 625 W with the PSSE, respectively, a difference of about only 4%. A recent study showed that metabolic rates estimated by the Pandolf equation were low and the metabolic rates increased by 2.7% per kg of clothing weight (6). With this metabolic rate vs. weight relationship, the difference in metabolic rates was expected to be about 10%. This indicates that weight alone cannot explain the 30% difference in the measurement metabolic rates, i.e., 968 W for the SSSE and 653 W for the PSSE. Other factors, such as ensemble configuration, materials and a reduction in hobbling of the PSSE, may contribute to this observed reduction in metabolic rates.

While wearing the SSSE or the PSSE and working at high intensity, the heat strain is uncompensable. Uncompensable heat strain occurs when the individual's evaporative cooling requirements exceed the evaporative cooling capacity, which is determined by the environmental and clothing conditions. Under uncompensable heat stress, the threshold of T_c could be reduced to about 38.5 ºC (10, 16). Recent human studies with explosive ordnance disposal (EOD) system show that the human tests were terminated due to high cardiovascular physiological strain (evidence by high heart rate) instead of heat strain (evidence by high core temperature) (5, 17). Thus, actual tolerance time might be shorter than the predicted heat endurance time due to the cardiovascular strain. Often the metabolic rates of above 500 W is categorized as heavy (16), the measured results when wearing either the SSSE or the PSSE are higher than 500W. This suggests that the cardiovascular physiological strain, related to heavy exercise, rather than heat strain per se, is an additional or even the predominant factor that could limit operation time.

Both metabolic rates and thermal resistances are critical to the modeling analysis. During the metabolic tests, some observed metabolic rates were in the range of about 40-60 $ml \cdot kg^{-1} min^{-1}$, which were in the same range as VO_{2max} values for human study volunteers (2, 3). The reported peak value of metabolic rates with full firefighter ensemble was 3.22 L/min, about 1050 W (18). Exercise at a level close to VO_{2max} is considered unsustainable and can be sustained for only a short amount of time. Considering the significant effects of metabolic rates on human performance and predicted heat endurance times, it is suggested that the metabolic rate testing be expanded to include at least seven to ten subjects, and modified to include VO_{2max} tests and walking at controlled speeds. This would provide an improved data set to support more comprehensive comparison of the differences between the SSSE and PSSE. The USARIEM modeling analysis was based on the thermal resistance values provided by NCTRF, metabolic rates estimated by the Pandolf empirical equation and metabolic rates measured by NSRDEC. Due to lack of the available physiology data, the evaluation outcomes should, to certain degree, be considered theoretical. In addition, the analysis is limited to heat stress only and excludes all other possible injuries, such as burns.

CONCLUSIONS

The manikin testing and modeling approach was used to analyze heat stress of the SSSE and PSSE. The results indicate that the PSSE provides improved thermal performance when compared to the SSSE. The PSSE: 1) increases thermal resistance by 70%, indicating more protection from external heat load; 2) reduces metabolic rates due to weight reduction and a possible reduction in the hobbling effects; and 3) increases the predicted heat endurance times to about 33 min in a hot, steam-filled environment. The analysis is limited to only heat stress and thus excludes all other possible injury, such as burns.

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