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QUANTITATIVE COMPARISON OF TWO CHEMICAL BIOLOGICAL PROTECTIVE SUITS: THE JOINT SERVICE LIGHTWEIGHT INTEGRATED SUIT TECHNOLOGY (JSLIST) AND THE TACTICAL ADVANCED THREAT PROTECTIVE ENSEMBLE (TATPE)

United States Army
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14. ABSTRACT
This report provides a quantitative assessment and comparison of the biophysical properties of the Joint Service Lightweight Integrated Suit Technology (JSLIST) Chemical Biological (CB) Protective suit (JSLSIT); the Tactical Advanced Threat Protective Ensemble (TATPE) Chemical Biological (CB) Protective suit (TATPE); the JSLIST CB suit plus the Improved Outer Tactical Vest (IOTV) body armor with front, back and side plates (JSLIST IOTV); and the TATPE CB suit plus the IOTV body armor with front, back and side plates (TATPE IOTV). Thermal and evaporative resistances (Rt and Ret) were conducted (ASTM F1291-16 & ASTM F2370-16). Modeling was used to make predictions of human responses for three work intensities (120 (Rest), 150, 250, 350, and 425 W) in three environmental conditions, desert, jungle, and temperate. Biophysical testing found increased thermal insulation (clo) and slight change in evaporative potential (im/clo) for each additional level of clothing, JSLIST (1.76 clo, 0.18 im/clo), JSLIST with IOTV (2.07 clo, 0.15 im/clo), TATPE (1.30 clo, 0.04 im/clo), TATPE with IOTV (1.69 clo, 0.05 im/clo) at 0.4 m•s-1 wind speeds

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EXECUTIVE SUMMARY

Introduction: This report provides a quantitative assessment and comparison of the biophysical properties of the Joint Service Lightweight Integrated Suit Technology (JSLIST) Chemical Biological (CB) Protective suit (JSLSIT); the Tactical Advanced Threat Protective Ensemble (TATPE) Chemical Biological (CB) Protective suit (TATPE); the JSLIST CB suit plus the Improved Outer Tactical Vest (IOTV) body armor with front, back and side plates (JSLIST IOTV); and the TATPE CB suit plus the IOTV body armor with front, back and side plates (TATPE IOTV). This work provides quantitative comparisons of the thermal properties of these four ensembles as well as predicted human thermal responses for each of them at five work intensities and in three environmental conditions. **Methods:** Standard tests for the thermal and evaporative resistances (R_t and R_{et}) were conducted (ASTM F1291-16 & ASTM F2370-16) for four ensembles. Modeling methods were used to make predictions of human responses for three work intensities (120 (Rest), 150, 250, 350, and 425 W) in three environmental conditions, desert (48.89°C; 20% RH), jungle (35°C; 75% RH), and temperate (25°C; 50% RH). **Results:** Biophysical testing found increased thermal insulation (clo) and slight change in evaporative potential (i_m/clo) for each additional level of clothing, JSLIST (1.76 clo, 0.18 i_m/clo), JSLIST with IOTV (2.07 clo, 0.15 i_m/clo), TATPE (1.30 clo, 0.04 i_m/clo), TATPE with IOTV (1.69 clo, 0.05 i_m/clo) at 0.4 m•s^{-1} wind speeds. Predicted maximal work times were reduced for each level of ensemble based on work intensity and environmental condition.

INTRODUCTION

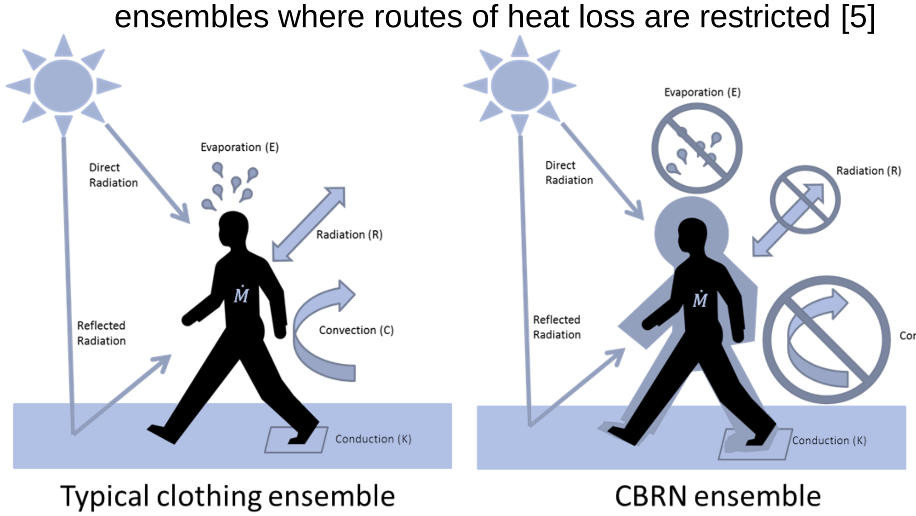
Personal protective clothing and equipment (PPE) are an essential part of military operational equipment. Chemical, biological, radiological, and nuclear (CBRN) PPE are designed to provide individual protection from CBRN threats; while body armor PPE are designed to increase survivability from ballistic threats. The increased weight and design of these systems compromise mobility, agility, situational awareness, and impede heat loss/dissipation [1-5]. Developing systems that optimize these protective elements while minimizing impediments is a top goal of material developers.

Humans regulate body by generating or dissipating heat. Thermoregulatory balance or storage (S) is determined by heat generation (via natural metabolic heat production or from external work (M and W) and the four heat dissipation pathways - radiation (R), convection (C), conduction (K), and evaporation (E). The heat balance equation is expressed as:

$$S = M \pm W \pm R \pm C \pm K - E \; [\mathrm{W/m^2}]$$

The balance of heat loss and gained translates to decreases or increases in body temperature. The protective features of PPE add insulation and vapor impermeability to the garment, which impede heat loss (Figure 1) [5]. Newer designs attempt to achieve a balance between chemical and ballistic protection and the imposed insulative and vapor impermeability to create equipment suitable for law enforcement [6-7], military [8], and healthcare responder [9-11] work situations; but design improvements are still needed to optimize performance capabilities.

Figure 1. Heat exchange in typical clothing ensembles compared to personal protective ensembles where routes of heat loss are restricted [5]



This report provides a quantitative assessment of the biophysical properties of the Joint Service Lightweight Integrated Suit Technology (JSLIST) Chemical Biological (CB) Protective suit; the JSLIST plus the Improved Outer Tactical Vest (IOTV) body armor with front, back and side plates; the Tactical Advanced Threat Protective Ensemble (TATPE) CB suit; and the TATPE CB suit plus the IOTV body armor. This work also provides quantitative comparisons of the thermal properties of these four ensembles as well as predicted human thermal responses when worn at five work intensities (120 (Rest), 150, 250, 350, and 425W) and in three environmental conditions representing desert (hot – dry), jungle (hot – humid), and temperate conditions.

METHODS

Standard thermal manikin assessments were conducted for three ensembles. These biophysical properties were then entered into a thermoregulatory model to make predictions for maximal work times in various environments at different work intensities.

Biophysical Manikin Tests

Testing was conducted using a 20-zone sweating thermal manikin (Thermetrics, Seattle, WA http://www.thermetrics.com/) located in a climatically controlled environmental chamber (USARIEM, Natick, MA, room 232C).

Standard biophysical assessments for the thermal and evaporative resistances (R_t and R_{et}) were conducted (ASTM F1291-16 & ASTM F2370-16) [12-13] for three ensembles. These values of (R_t and R_{et}) were converted to total insulation (clo), a permeability index (i_m) [14-16]. A ratio of clo and i_m (i_m/clo) is used as a measure of the ensembles evaporative potential [14-16]. Testing for R_t and R_{et} measurements were conducted at three wind velocities (*V*) to enable the calculation of coefficient (gamma) values (^{g}) to describe the change in insulation and evaporative potential with increasing wind speeds [5,17-18].

Ensemble Details

1) **JSLIST**: JSLIST CB suit over standard issue cotton briefs, wicking t-shirt, and cotton socks; M50 CB mask without hood; JB1GU CB gloves; AFS CB socks; and desert tan suede combat boots (Figure 2a).

2) **JSLIST IOTV**: JSLIST CB suit over standard issue cotton briefs, wicking t-shirt, and cotton socks; IOTV with front back and side plates; ACH; M50 CB mask without hood; JB1GU CB gloves; AFS CB socks; and desert tan suede combat boots (Figure 2b).

3) **TATPE**: TATPE CB suit over nude manikin; ACH, Cloutier CB gloves, M50 CB mask, and GORE CB tan suede combat boots (Figure 3a).

4) **TATPE IOTV**: TATPE CB suit over nude manikin; IOTV with front back and side plates; ACH; Cloutier CB gloves; SCBA TATPE Pack; M50 CB mask; and GORE CB tan suede combat boots (Figure 3b).

Figure 2. Thermal manikin wearing the JSLIST (a) and JSLIST with IOTV (b).

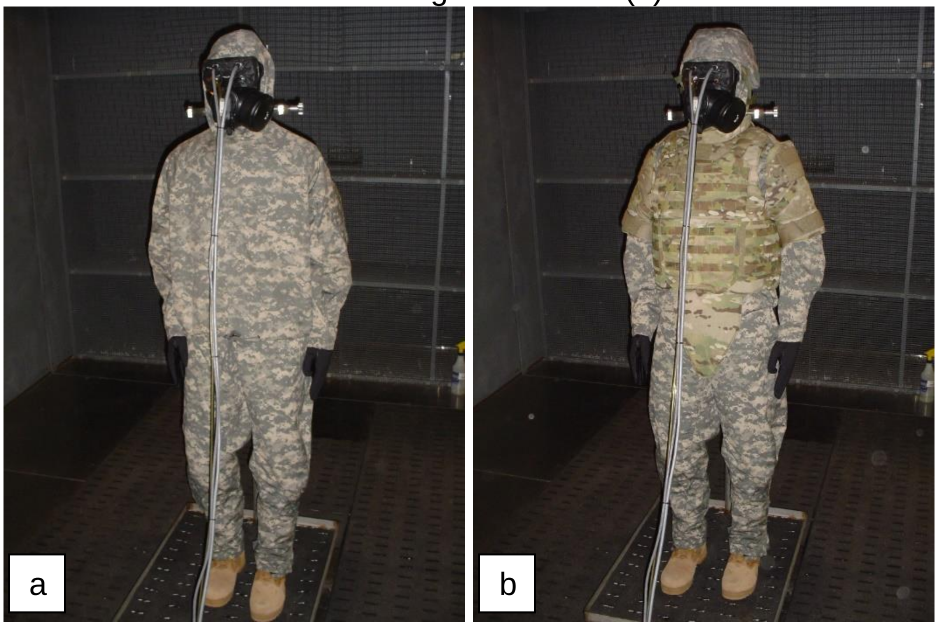
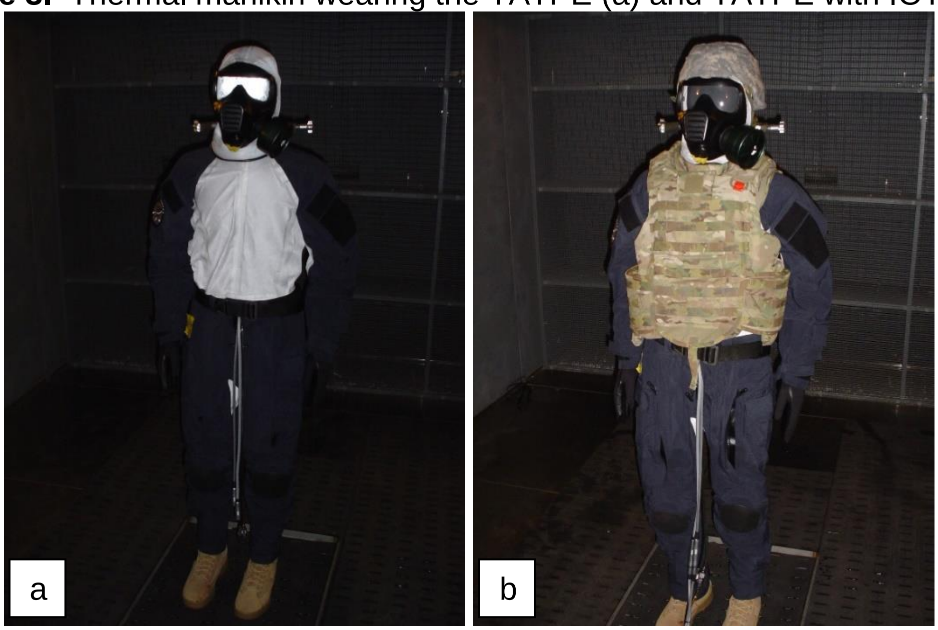


Figure 3. Thermal manikin wearing the TATPE (a) and TATPE with IOTV (b).



Predictive Modeling

Modeling and simulation of predicted human responses were conducted using USARIEM's Heat Strain Decision Aid (HSDA) [19-22]. The c code variant of HSDA (HSDAC, version 8) was used to make predictions in three environmental conditions: Desert (48.89°C; 20% RH), Jungle (35°C; 75% RH), and Temperate (25°C; 50% RH). For each of these environments, the model was run at three working metabolic rates: Very Light (150 W), Light (250 W), and Moderate (425 W). Additionally, minute-by-minute predictions of core body temperature rise were modeled using a version of

HSDA in mathematical long-form [19] for each of the above environmental conditions while the simulated Soldier was walking at approximately 3.5mph (1.34m•s^{-1}) (350W) and while at rest (120W).

Modeling assumptions: A 'Standard male' was used for each simulation, and all modeling assumed the conditions of full sun and 1.0 m•s^{-1} wind speed, with the wearer at normal hydration (-1.24%), 12 days of heat acclimation, and utilizing a standard man (176 cm height, 76 kg weight, and 1.9 m^2 surface area). The c code model was used to predict a one-time maximum work duration (minutes) (based on the time for core temperature to reach 39°C), for a maximum of 300 minutes; while minute-by-minute predictions of core temperature rise are for 120 minutes.

RESULTS

Biophysical Assessments

The total thermal insulation (clo) and evaporative potential (i_m/clo) for each configuration measured at different wind velocities are shown in Figures 4 and 5 as well as in Table 1. Testing showed the JSLIST configurations have a higher thermal insulation (clo) compared to the TATPE configurations (Figure 4); where higher clo values indicate more dry heat will be retained within the clothing. However, testing showed the JSLIST configurations also had higher evaporative potential (i_m/clo) values than the TATPE configurations (Figure 5); where they are allow for more evaporative heat exchange through the ensemble (e.g., from sweat).

Figure 4. Total thermal insulation (clo) for the 4 ensemble configurations.

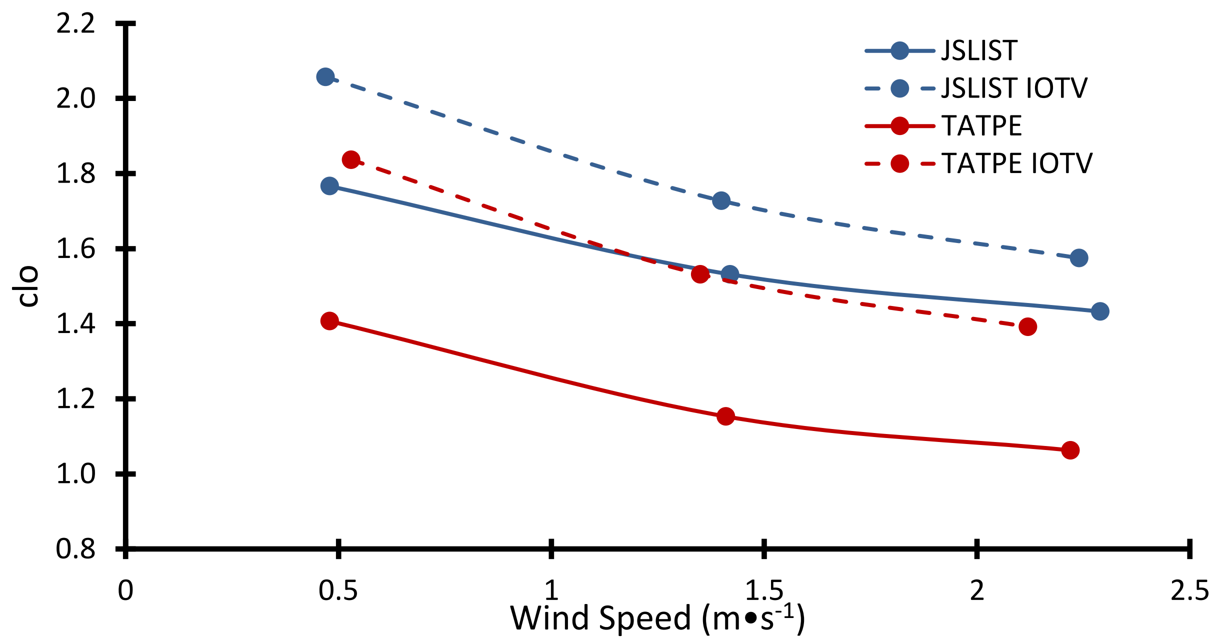


Figure 5. Evaporative potential (i_m/clo) for the 4 ensemble configurations.

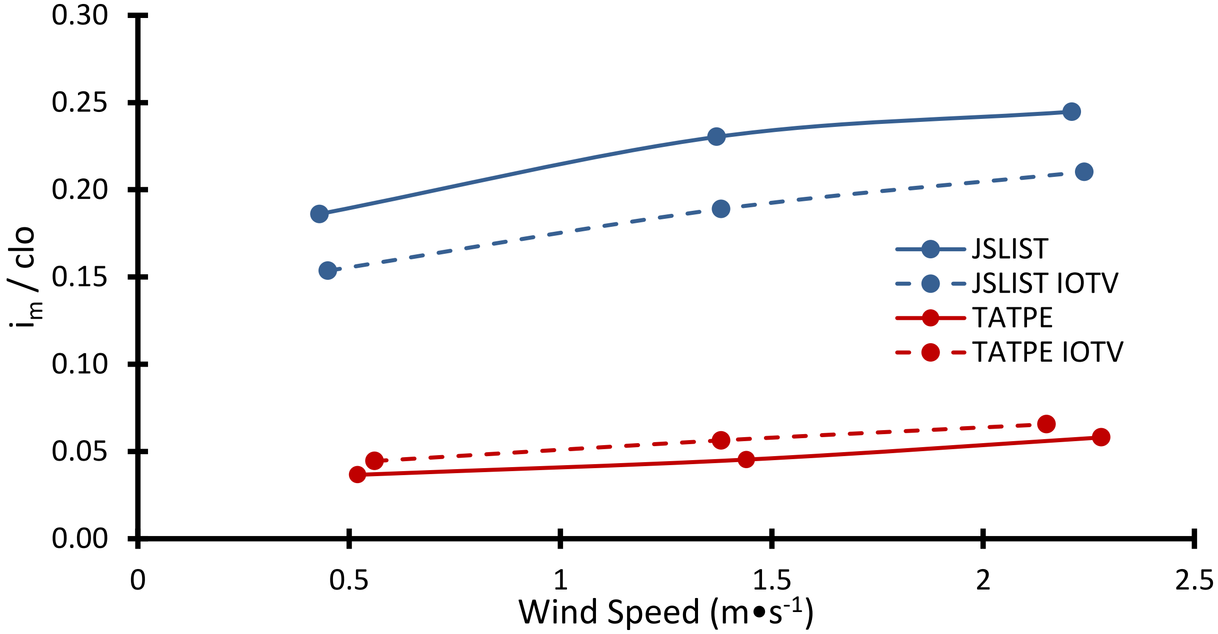


Table 1. Total thermal insulation (clo) and evaporative potential (i_m/clo) at 1.0 m•s^{-1} and 0.4 m•s^{-1} wind speeds for 4 ensembles tested.

	0.4 m•s^{-1} Wind (Still air)		1.0 m•s^{-1} Wind	
	clo	i_m /clo	clo	i_m /clo
JSLIST	1.761	0.185	1.552	0.216
JSLIST IOTV	2.069	0.150	1.764	0.179
TATPE	1.547	0.033	1.299	0.044
TATPE IOTV	2.041	0.040	1.690	0.052

Note: lower clo = less thermal resistance, higher i_m/clo = better evaporative potential.

The added thermal burden imposed by body armor is of significant interest to the military [23-27]. This is of particular interest in CB operations because of the already high vapor impermeable nature of these clothing ensembles. Table 2 presents the relative impact of wearing body armor over JSLIST and TATPE on heat transfer resistance and evaporative potential.

Predictive Modeling

Table 3 shows the predicted results for maximal work time (minutes), based on the time for core body temperature to reach 39°C. Figures 6 – 9 show the predicted core body temperature rise for each clothing configuration during work (350W) in each environmental condition (desert, jungle, and temperate). From these figures minor (expected) differences in increased rate of rise in core body temperature can be observed in the JSLIST and JSLIST IOTV ensembles within each environment (Figures 6-7).

Table 2. Predicted Results for One Time Maximum Work Duration in Minutes for core temperature to reach 39°C, for a maximum of 300 minutes.

		T_a (°C)	RH%	Work (watts)	Max Work (min) Time to reach 39°C
JSLIST	Desert	48.89	20	150	101
				250	58
				425	35
	Jungle	35.00	75	150	161
				250	65
				425	38
	Temperate	25.00	50	150	300
				250	300
				425	60
JSLIST IOTV	Desert	48.89	20	150	100
				250	57
				425	35
	Jungle	35.00	75	150	152
				250	64
				425	37
	Temperate	25.00	50	150	300
				250	300
				425	55
TATPE	Desert	48.89	20	150	52
				250	37
				425	21
	Jungle	35.00	75	150	79
				250	51
				425	32
	Temperate	25.00	50	150	300
				250	80
				425	42
TATPE IOTV	Desert	48.89	20	150	60
				250	42
				425	25
	Jungle	35.00	75	150	89
				250	54
				425	33
	Temperate	25.00	50	150	300
				250	81
				425	42

Figure 6. Predicted core body temperature rise wearing JSLIST in jungle, desert, and temperate conditions working at 350W.

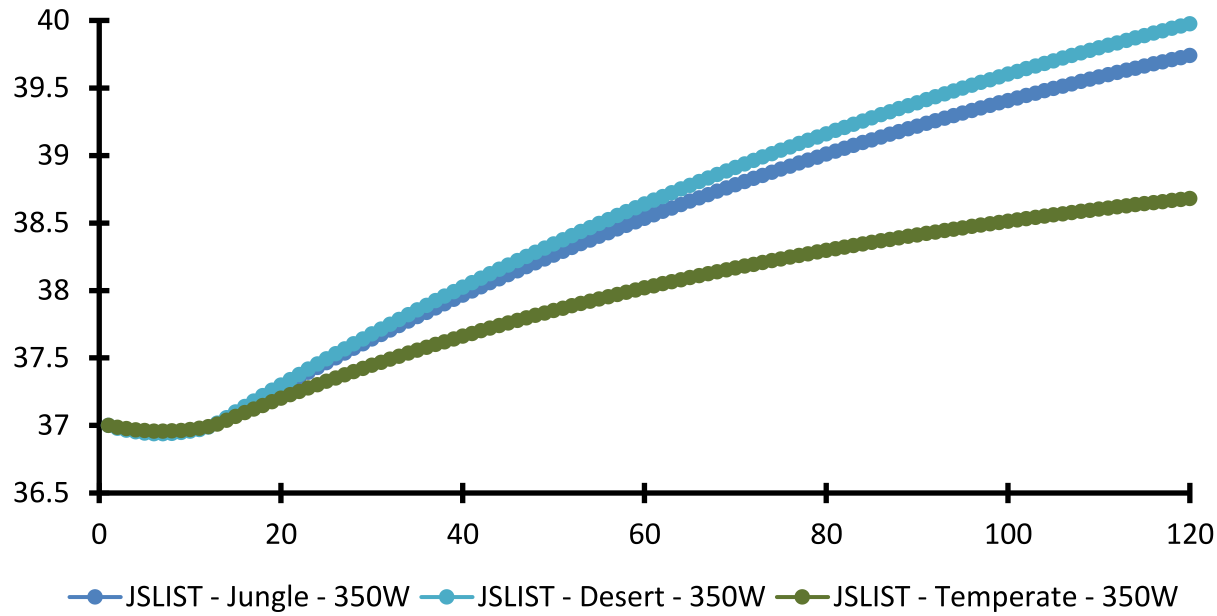
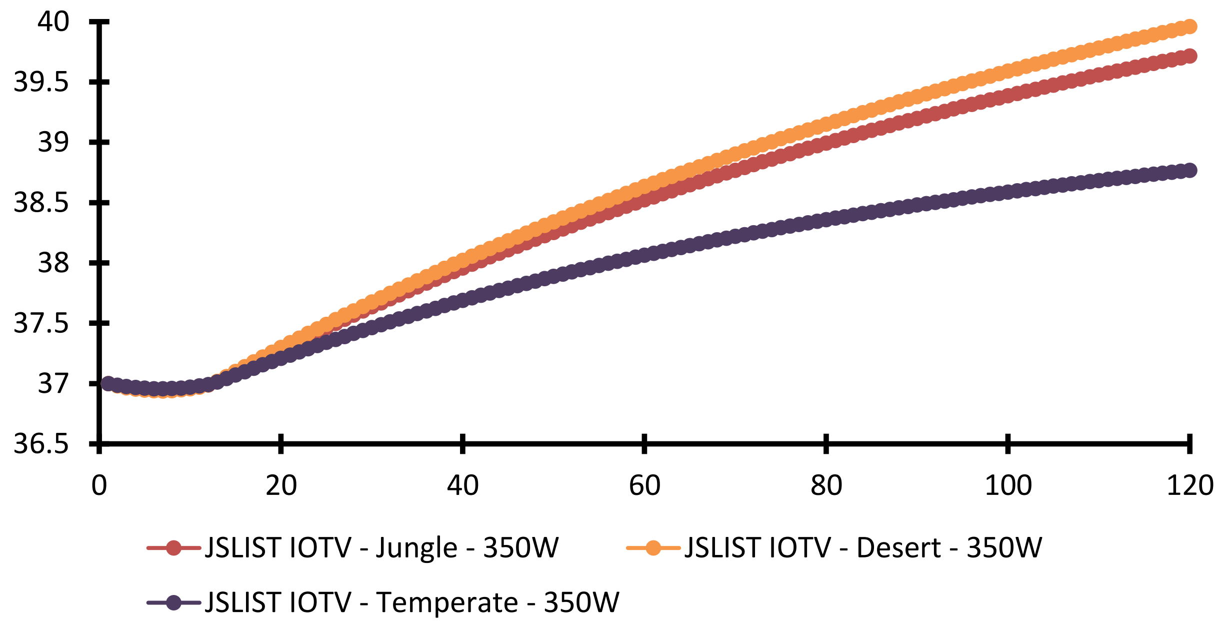


Figure 7. Predicted core body temperature rise wearing JSLIST with IOTV in jungle, desert, and temperate conditions working at 350W.



In contrast to the JSLIST expected differences, we see a steep increase in the rate of rise for the TATPE and TATPE IOTV ensembles in response to desert conditions (Figures 8-9). This steep increase in the TATPE compared to the JSLIST ensembles can be directly contributed to the lower i_m/clo values (worse) in the TATPE configurations.

Figure 8. Predicted core body temperature rise wearing TATPE in jungle, desert, and temperate conditions working at 350W.

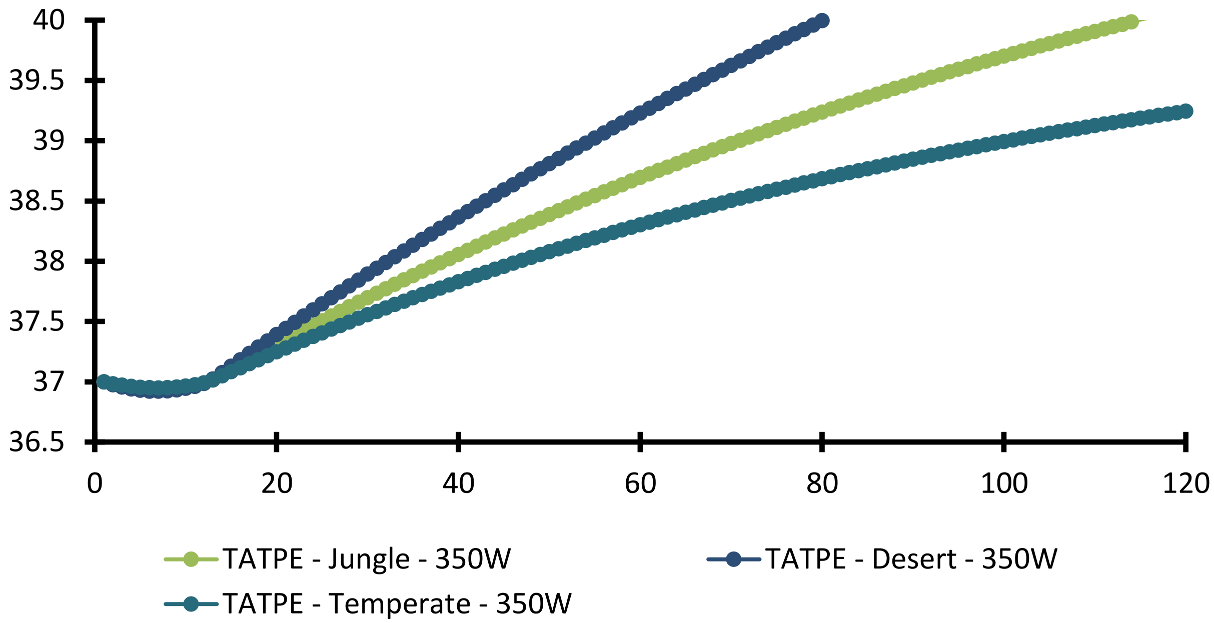
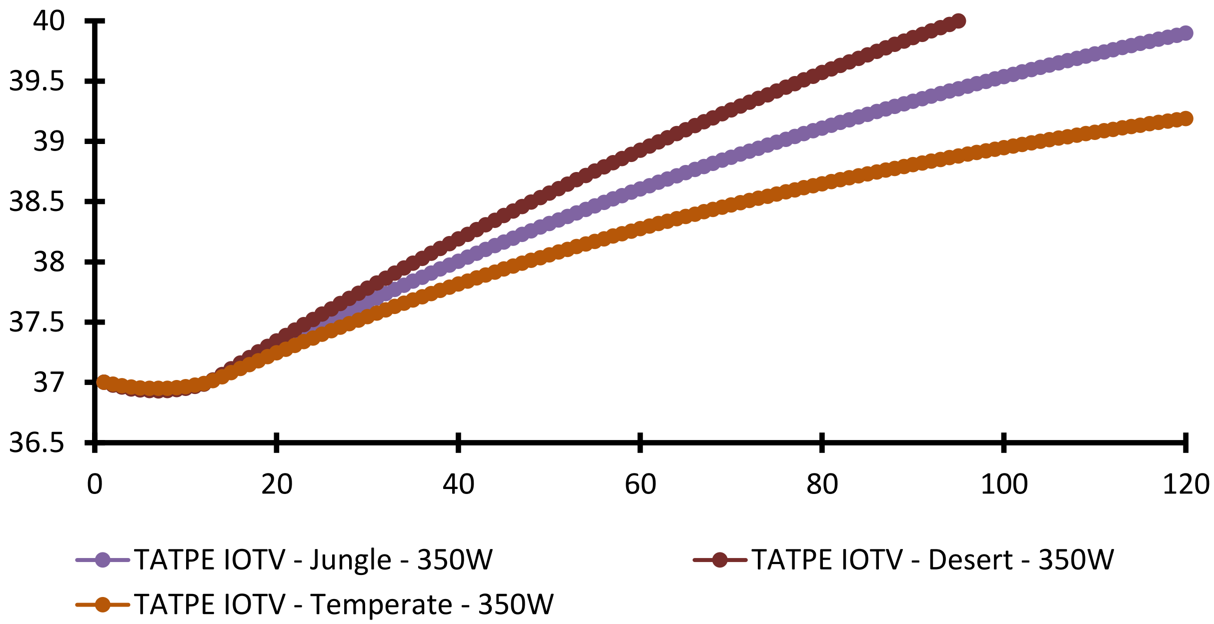


Figure 9. Predicted core body temperature rise wearing TATPE with IOTV in jungle, desert, and temperate conditions working at 350W.



Figures 10-12 show comparisons between ensembles, conditions, and with and without IOTV. The lowest deviations between configurations in response to working are seen in in jungle conditions (Figure 10); while slightly more can be observed in temperate conditions (Figure 12). More pronounced differences can be observed from working in desert conditions (Figure 11).

Figure 10. Predicted core body temperature rise in jungle conditions working at 350W.

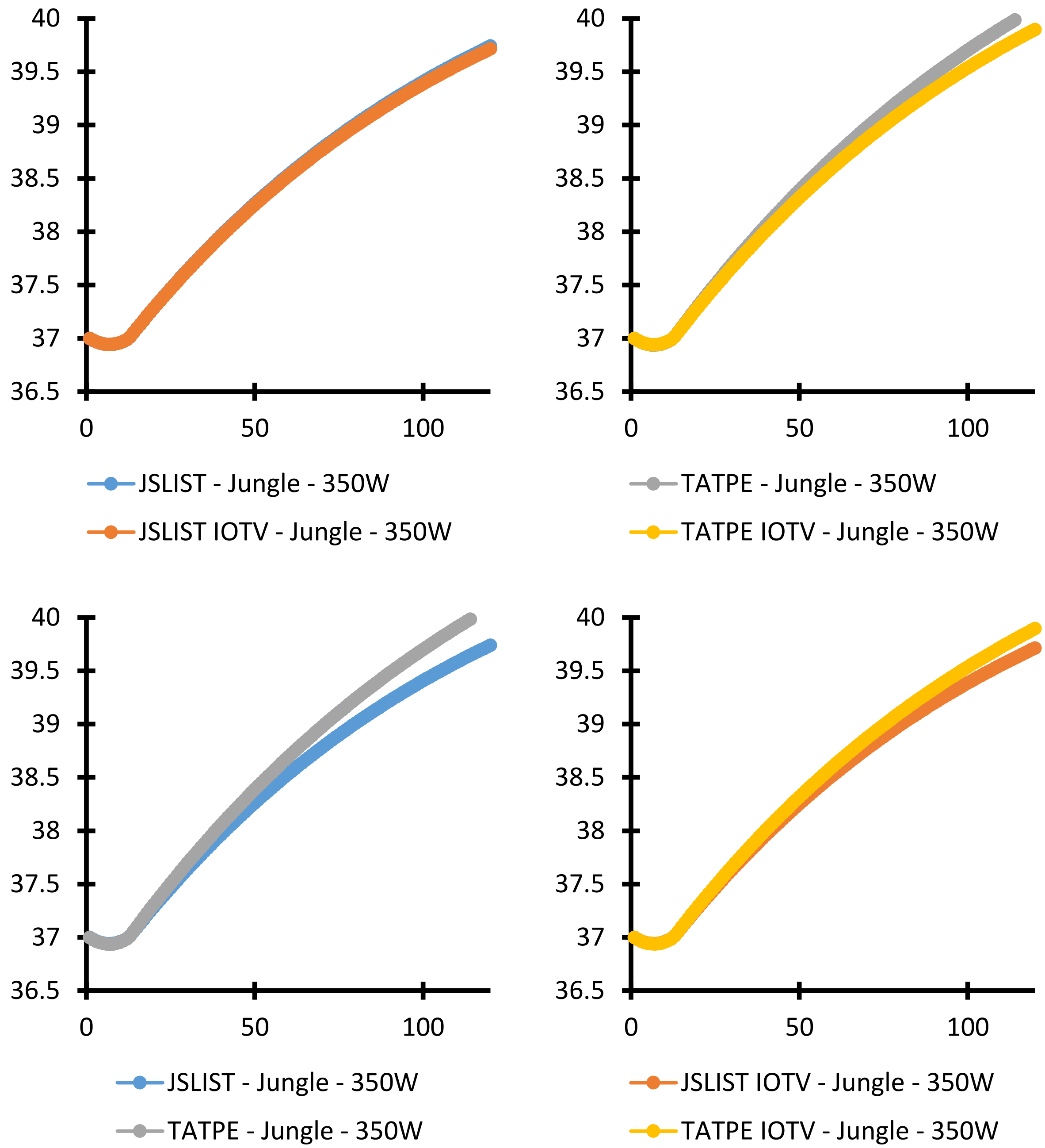


Figure 11. Predicted core body temperature rise in desert conditions working at 350W.

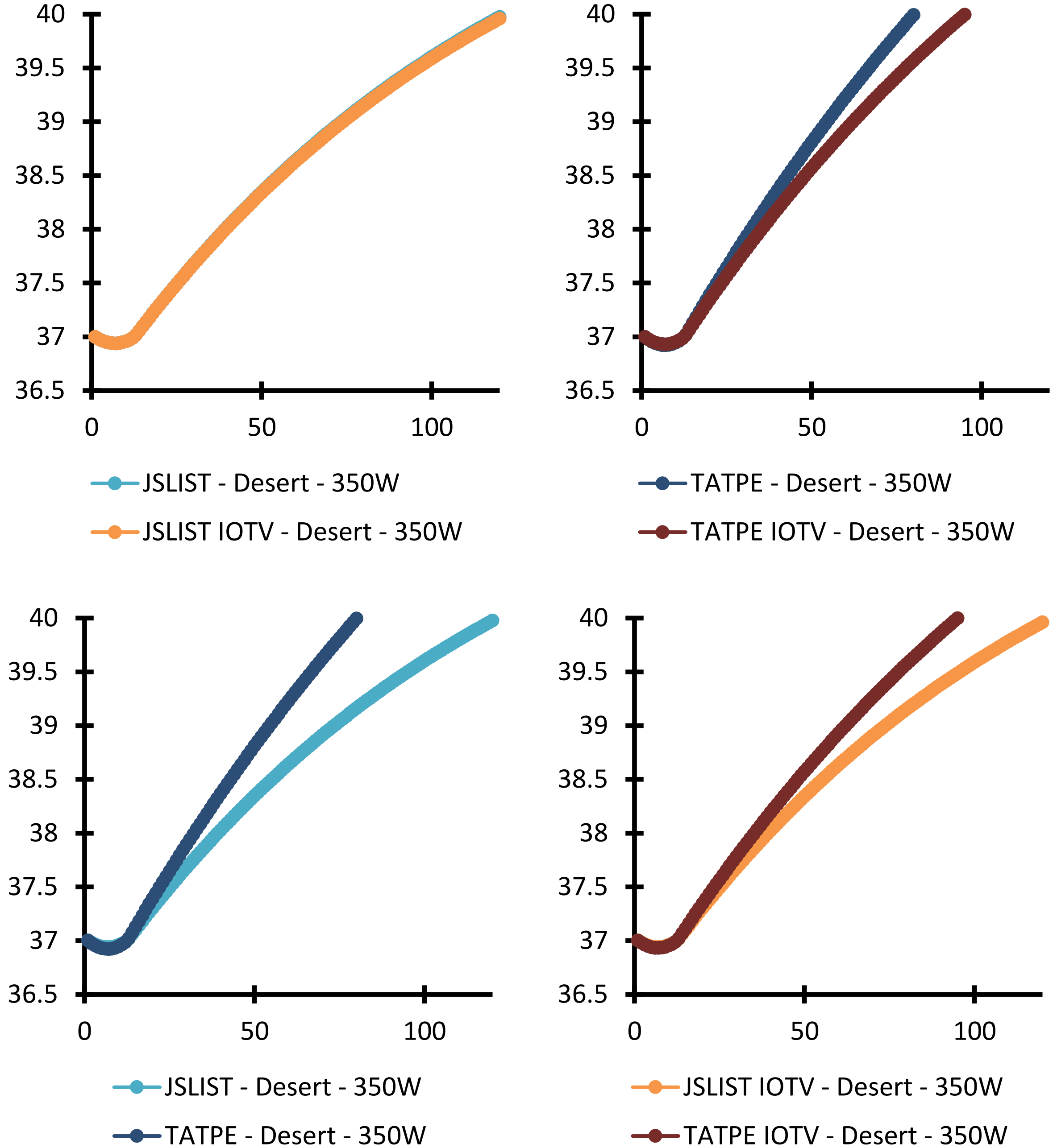
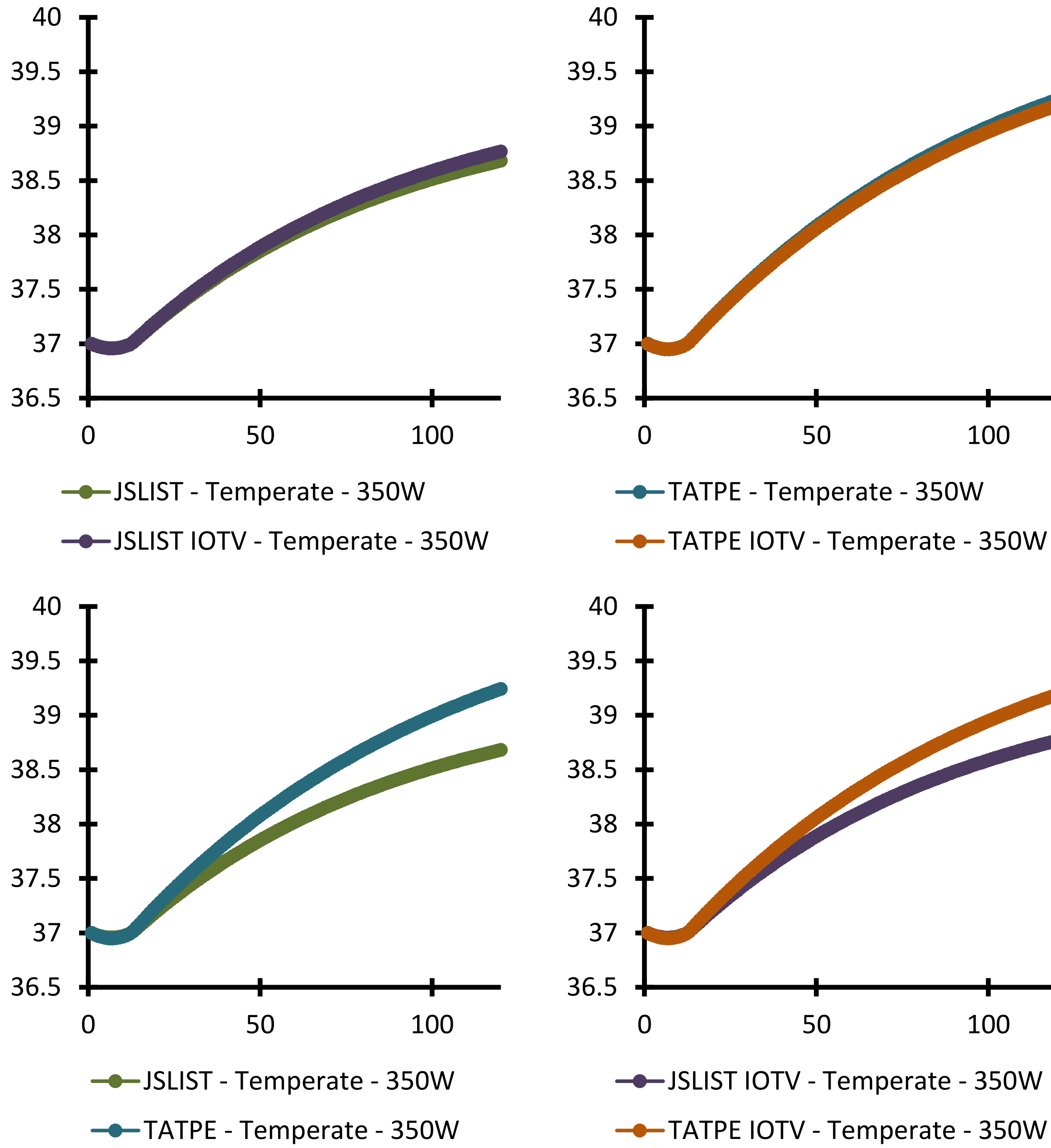


Figure 12. Predicted core body temperature rise in temperate conditions working at 350W.



Figures 13-14 show predicted increases in core body temperatures in response to environmental conditions while at rest. Figure 13 shows in a side-by-side comparison of JSLIST and TATPE responses to rest in each environment; while Figure 14 shows this same comparison with the addition of IOTV. Figures 13 and 14 both show that at rest there is a steeper rate of rise in core body temperature wearing the TATPE.

Figure 13. Predicted core body temperature rise at rest (120W) in jungle, desert, and temperate conditions for JSLIST and TATPE ensembles.

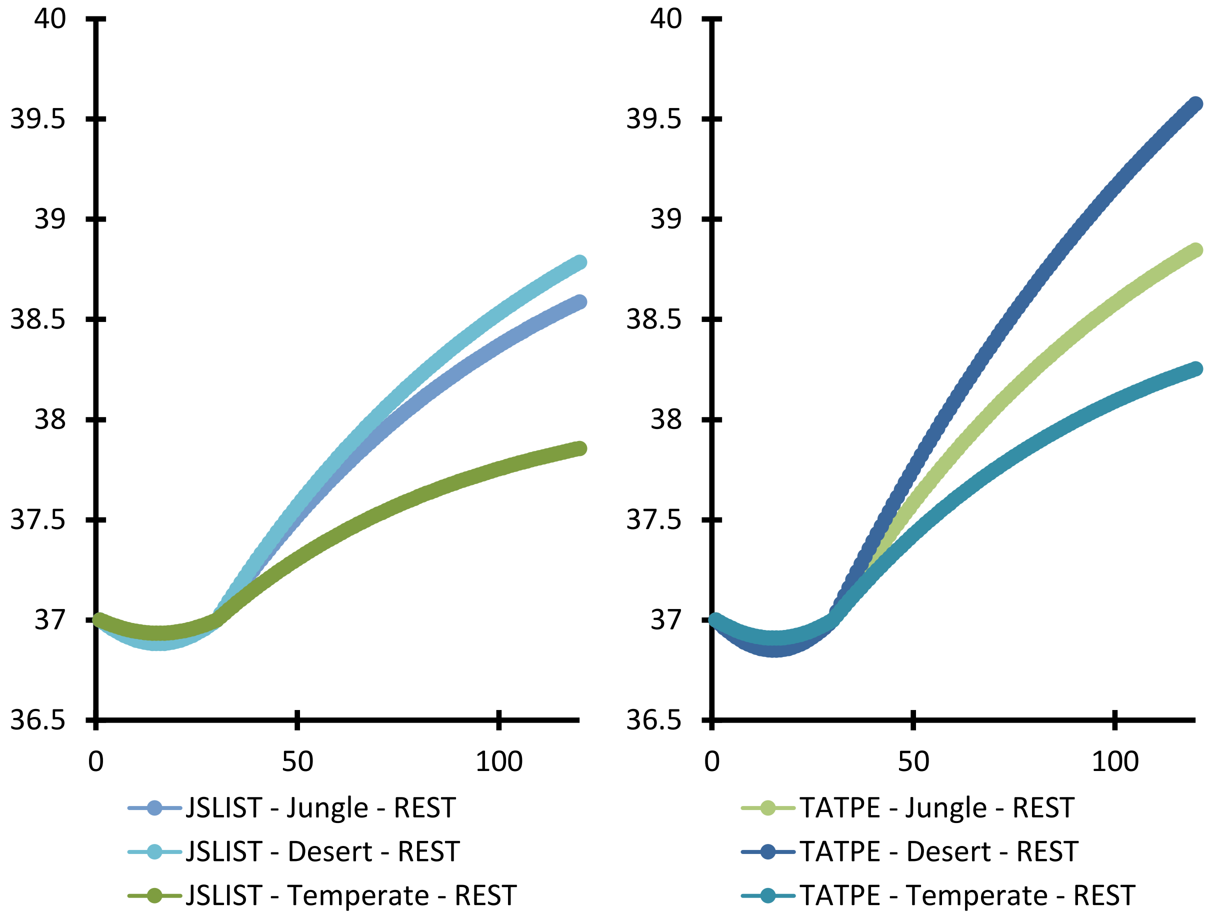
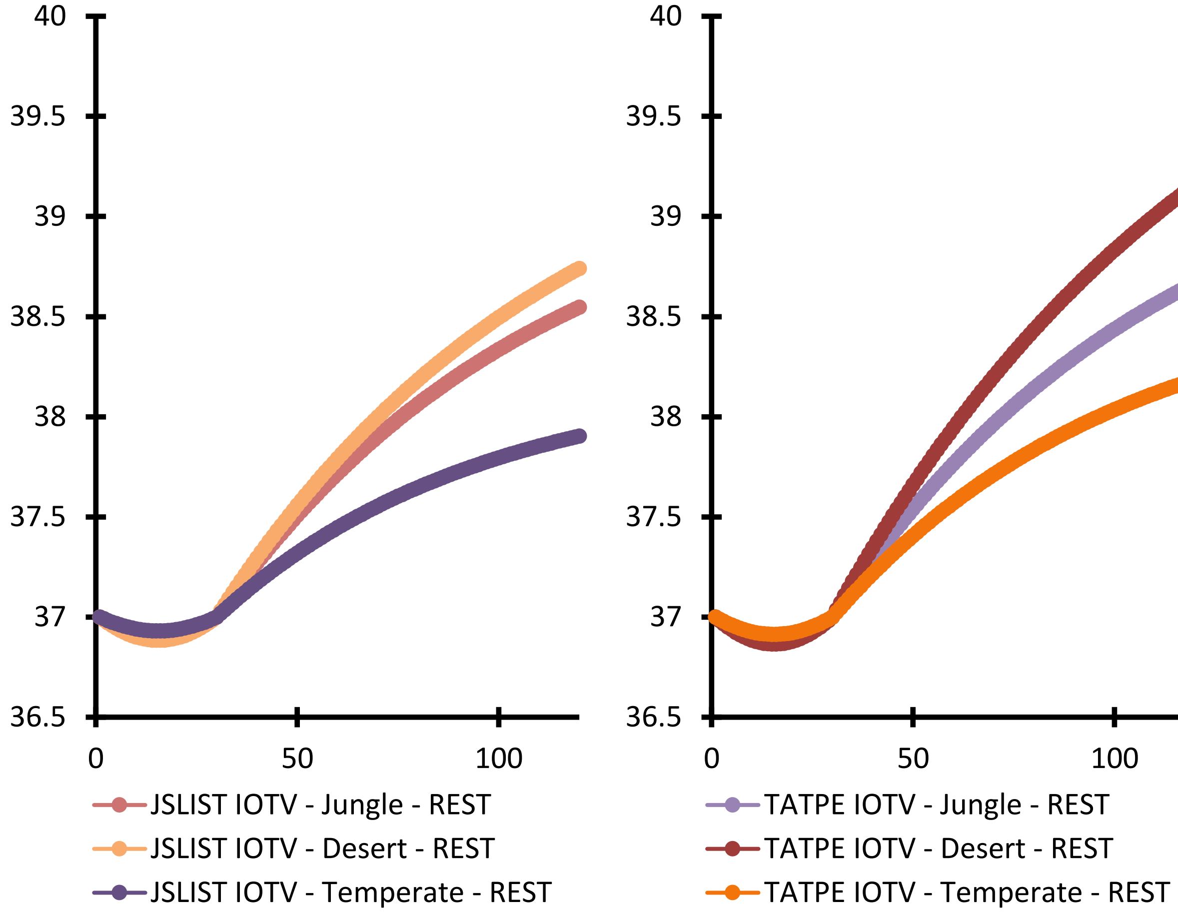


Figure 14. Predicted core body temperature rise at rest (120W) in jungle, desert, and temperate conditions for JSLIST IOTV and TATPE IOTV ensembles.



DISCUSSION

Hazmat suits are garments worn to protect from hazardous materials including chemicals, biological agents, and radioactive materials. The JSLIST is the sole hazmat suit used by all military services for both combat and cleanup operations. The TATPE suit is being considered by the military for use in non-combat hazmat cleanup operations.

The JSLIST is a lightweight, two-piece, front-opening suit with a laminated selectable permeable layer plus a carbon layer that both filters and absorbs contaminants while allowing for water vapor permeability. The TATPE suit is an impermeable whole-body garment worn as protection during hazmat cleanup operations. Both suits can be worn as an overgarment or as a primary suit over underwear. Once opened, the JSLIST maintains is PPE properties for 120 days, can be worn continuously for 45 days, and can be laundered six times. The TATPE suit can be reused up to ten times, if not damaged exposed or contaminated and laundered twice.

To evaluate the two suits worn alone or with body armor, a combination of biophysical testing and mathematical modeling were used to provide quantitative comparisons of these ensemble configurations. A primary finding is that the TATPE possess much lower vapor permeability, and this property is predicted to impose a greater thermal burden in temperate temperatures with moderate humidity and when worn in hot temperatures with low humidity; both situations where sweat evaporation is the primary means of dissipating body heat. The effect was less apparent in the high humidity jungle condition where differences in vapor permeability would be less of a liability. The TATPE is also predicted to substantially shorten time to reach 39°C. At 250W, maximal work time was shortened 21-73% compared to JSLIST. Likewise, at 425W, maximal work time was 16-40% shorter. At both work intensities the magnitude of impairment was greatest in the lower humidity conditions.

This report provides measured and predicted impacts from the addition of body armor (IOTV). The biophysical measures show an increase in thermal insulation (clo) for both the JSLIST (3.2%) and TATPE (6.5%) when IOTV is added to the clothing worn. The addition of body armor to the JSLIST decreased evaporative potential (i_m/clo) (4.7%). In contrast, the addition of body armor to the TATPE slightly increased evaporative potential (-4.5%). Previous work has shown that the change in air layer (i.e., space between layers) caused by increasing layers or addition of body armor can cause a decrease in insulation due to the shrinking of total air volume [28]. However, this change creates less predictable changes in permeability. The modest changes in vapor permeability in the two conditions modeled, had negligible effects when translated to the predicted physiological responses to graded increases in ambient temperature, or workload. The addition of body armor to JSLIST produced essentially equivalent thermal strain as the ambient temperatures and humidity were manipulated. Likewise, IOTV added to TATPE appeared to have minimal impact when worn in the jungle and temperate conditions (Figures 10-12), with modest decrease in thermal strain in desert conditions (Figure 11).

This effort combined thermal manikin assessments with predictive modeling to provide a quantitative and cost effective approach to the assessment of clothing ensembles. Manikin assessments provide direct measures that can be used for comparisons; while predictive modeling offers a simulated response to the human wearer. While the underlying algorithms used for the modeling have been validated or developed using appropriate scientific design, there are limitations to the accuracy of the predictive simulations. As such, in order to fully capture the impact on human wearers, human factors assessments and human field studies should still be considered a required test for completely studying the influences of clothing systems.

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