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COMPARISON OF THE BIOPHYSICAL PROPERTIES AND SIMULATED PERFORMANCE OF TWO COOLING VESTS

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COMPARISON OF THE BIOPHYSICAL PROPERTIES AND SIMULATED PERFORMANCE OF TWO COOLING VESTS

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14. ABSTRACT

This report provides a quantitative comparison of two different cooling vests and compares simulated performance in two environmental conditions, three metabolic rates, while wearing a chemical protective ensemble. Standard thermal manikin assessments were conducted for a chemical protective ensemble and specifically for two cooling vests: the Air Soldier Environmental Control Vest (ECV) and the Oceanit Laboratories' Liquid Cooling Garment (LCG). Modeling and analysis was conducted using a version of the Heat Strain Decision Aid (HSDA) to compare maximal work times at three work rates (130, 200, 330W), in two environmental conditions warm (35°C, 40%RH) and extreme hot dry (51.7°C, 14%RH). Results: Biophysical testing properties in standard conditions of the ensemble measured the thermal insulation (1.86 clo) and evaporative potential (0.049 im/clo). Based on predictive modeling outcome parameters of lower core temperatures during work and work time to reach critical temperature, the LCG is a better cooling garment than the ECV.

15. SUBJECT TERMS
thermal manikins; biophysics; clothing; predictive modeling; thermoregulation, cooling, TATPE

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EXECUTIVE SUMMARY

Introduction: This work was done in support of requirements from the Product Manager (PM) Air Warrior and the Defense Threat Reduction Agency (DTRA) to support the development of a new cooling vest. This report provides a quantitative comparison of two different cooling vests and compares simulated performance in two environmental conditions, three metabolic rates, while wearing a chemical protective ensemble.

Methods: Standard thermal manikin assessments were conducted for a chemical protective ensemble and specifically for two cooling vests: the Air Soldier Environmental Control Vest (ECV) and the Oceanit Laboratories' Liquid Cooling Garment (LCG). Modeling and analysis was conducted using a version of the Heat Strain Decision Aid (HSDA) to compare maximal work times at three work rates (130, 200, 330W), in two environmental conditions warm (35°C, 40%RH) and extreme hot dry (51.7°C, 14%RH). This extreme case was chosen to align with PM Air Warrior requirements.

Results: Biophysical testing properties in standard conditions of the ensemble measured the thermal insulation (1.86 clo) and evaporative potential (0.049 i_m/clo). The cooling vests provided different levels of maximal heat removal potential (ECV 87.5W and LCG 123.8W) when coupled to the Lightweight Environmental Control System (LWECS) Personal Cooling Unit (PCU). Modeling supported that the LCG possesses more heat removal and an associated longer duration of work in each work rate and environmental condition.

Conclusion: Based on predictive modeling outcome parameters of lower core temperatures during work and work time to reach critical temperature, the LCG is a better cooling garment than the ECV.

INTRODUCTION

This report provides a quantitative comparison of the Air Soldier Environmental Control Vest (ECV) and Oceanit Laboratories' Liquid Cooling Garment (LCG) cooling potentials and predicted ability to reduce thermal strain and prolong work time during physical activity. The capabilities of each system were simulated during three levels of energy expenditure, in two environmental conditions, and wearing a select chemical protective ensemble with body armor.

METHODS

Initially standard thermal manikin assessments were performed for a chemical protective ensemble and additional testing was conducted specifically for the cooling vests with this ensemble. These data were used as inputs into a thermoregulatory model to make predictions for body temperature increase and work time to reach a critical core temperature.

Manikin Tests

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

Standard biophysical assessments for the thermal and evaporative resistances (R_t and R_{et}, respectively) were conducted (ASTM F1291-16 & ASTM F2370-16) [1-2] for three ensembles. These values of (R_t and R_{et}) were converted to total insulation (clo) and a permeability index (i_m). A ratio of clo and i_m (i_m/clo) is used as a measure of the ensembles' evaporative potential [3-4]. 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 [5-8].

Testing of the heat removal and cooling capacity of the two body-worn cooling vests was conducted according to ASTM standard F2371-10 [9]. This test requires a saturated steady-state condition. Each cooling garment was coupled to the Lightweight Environmental Control System (LWECS) Personal Cooling Unit (PCU) and cooling potential was measured at the high cooling setting.

Ensemble Details

1) Tactical Advanced Threat Protective Ensemble (TATPE) Chemical/Biological (CB) suit over nude manikin, Improved Outer Tactical Vest (IOTV) with front back and side plates, Army Combat Helmet (ACH), Cloutier CB gloves, M50 CB mask, and GORE CB tan suede combat boots (TATPE IOTV) (Figure 1).
2) **[ECV]** - Air Soldier Environmental Control Vest (ECV) (Figure 2).
3) **[LCG]** - Oceanit Laboratories' Liquid Cooling Garment (LCG) (Figure 3).

Figure 1. Thermal manikin wearing the Tactical Advanced Threat Protective Ensemble (TATPE) Chemical/Biological (CB) with Body Armor

Figure 2. Air Soldier Environmental Control Vest (ECV)

Figure 3. Oceanit Laboratories' Liquid Cooling Garment (LCG)

Predictive Modeling

Modeling and simulation of predicted human responses were conducted using USARIEM’s Heat Strain Decision Aid (HSDA) [10-13]. Predictions were made for two environmental conditions: an extreme hot-dry (51.7°C; 14% RH) and warm (35°C; 40% RH); both assumed partial sun and 1.0 $m \cdot s^{-1}$ wind velocity. The extreme condition was chosen to align with PM Air Warrior requirements.

For all simulations, inputs for an average sized healthy male Soldier were used (172 cm height, 79 kg weight, and 1.9 m^2 surface area) [14], and individuals were assumed as normally hydrated (-1.24%), fully heat acclimated (12 days exposure to heat), with initial skin and core body temperatures assumed as normal (33 and 37°C). For each simulated environment, modeling was conducted at three working metabolic rates: Very Light (130 W), Light (200 W), and Moderate (330 W). The output variables of interest were predicted core body temperature over time and estimated one-time maximal work duration (minutes) for 120 minutes. The time to reach 38.6°C and time to reach 40°C were specifically identified, as these represent temperature thresholds where there is heightened risk of heat injuries in uncompensable and compensable heat stress conditions, respectively [15,16]. The cooling rate provided by the cooling vests was accounted for by subtracting the net wattage measured during manikin tests from the heat produced at each energy expenditure.

RESULTS

Total thermal insulation (clo) and evaporative potential (i_m/clo) and wind coefficients of the TATPE ensemble are shown in Table 1. Heat removal provided by each cooling vest is presented in Table 2. Manikin testing was only conducted on the "High" PCU setting. Heat removal rates noted for the "Low" and "Medium" settings are calculated values, based upon information from the PCU developer.

Table 1. Total thermal insulation (clo) and evaporative potential (i_m/clo) at 1.0 $m \cdot s^{-1}$ and 0.4 $m \cdot s^{-1}$ wind speeds and wind coefficients for TATPE ensemble.

	0.4 $m \cdot s^{-1}$ Wind (~still air)		1.0 $m \cdot s^{-1}$ Wind		Wind Coefficients (N.D.)	
	clo	i_m /clo	clo	i_m /clo	clo^g	i_m /clo^g
TATPE IOTV	**1.86**	**0.035**	**1.53**	**0.049**	**-0.210**	0.049

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

Table 2. Maximal amount of heat removal (W) provided by each cooling vest and values used for modeling in different settings

	Measured	Off	Low (~52%)	Medium (~80%)	High (100%)
Air Soldier Environmental Control Vest (ECV)	87.5	0	45.5	70.0	87.5
Oceanit Laboratories' Liquid Cooling Garment (LCG)	123.8	0	64.4	99.0	123.8

The predicted times to reach safe core temperature thresholds (38.6 and 40°C) and predicted core temperature at the end of the 120 minute simulation for each condition with the PCU on the high setting are shown in Table 3. For context, Figures 4 and 5 show the predicted rise in core body temperature for both environmental conditions, warm (Fig 4) and hot dry (Fig 5) with no cooling provided. From Figure 4, we see that without cooling in warm conditions an unsafe limit is reached in 55-57 minutes working at 330W, in 91-95 minutes at 200W, and does not get reached at 130W work rate within the 120 minute simulation. Figure 4 shows that the risk of heat stroke is not likely within the 120 minute simulation for any of the three work intensities. Figure 5 shows that without cooling in hot dry conditions and working at 330W an unsafe limit is reached in 39-44 minutes and heat stroke risk in 70-82 minutes. Working at 200W unsafe limits are reached in 59-65 minutes and heat stroke risk in ~115 minutes. Working at 130W unsafe limits are reached at 81-93 minutes and stroke risk is not reached during the 120 minute simulation.

Table 3. Predicted time to reach unsafe thresholds and core temperature at the end of 120 minute simulation wearing TATPE ensemble and PCU on high setting

	Environment	Work Rate	Time (min) to 38.6°C	Time (min) to 40.0°C	Core Temperature at 120 minutes
No Cooling	Warm (35°C, 40%RH)	200W	103	N/A	38.8°C
Air Soldier Environmental Control Vest (ECV)			N/A	N/A	38.1°C
Oceanit Laboratories' Liquid Cooling Garment (LCG)			N/A	N/A	37.9°C
No Cooling	Warm (35°C, 40%RH)	330W	60	N/A	39.8°C
Air Soldier Environmental Control Vest (ECV)			82	N/A	39.1°C
Oceanit Laboratories' Liquid Cooling Garment (LCG)			99	N/A	38.8°C
No Cooling	Hot Dry (51.7°C, 14%RH)	200W	68	N/A	39.7°C
Air Soldier Environmental Control Vest (ECV)			106	N/A	38.8°C
Oceanit Laboratories' Liquid Cooling Garment (LCG)			107	N/A	38.8°C
No Cooling	Hot Dry (51.7°C, 14%RH)	330W	45	83	41.1°C
Air Soldier Environmental Control Vest (ECV)			58	115	40.1°C
Oceanit Laboratories' Liquid Cooling Garment (LCG)			66	N/A	39.7°C

Figure 4. TATPE chemical protective ensemble worn in warm conditions (35°C, 40% RH) with no cooling

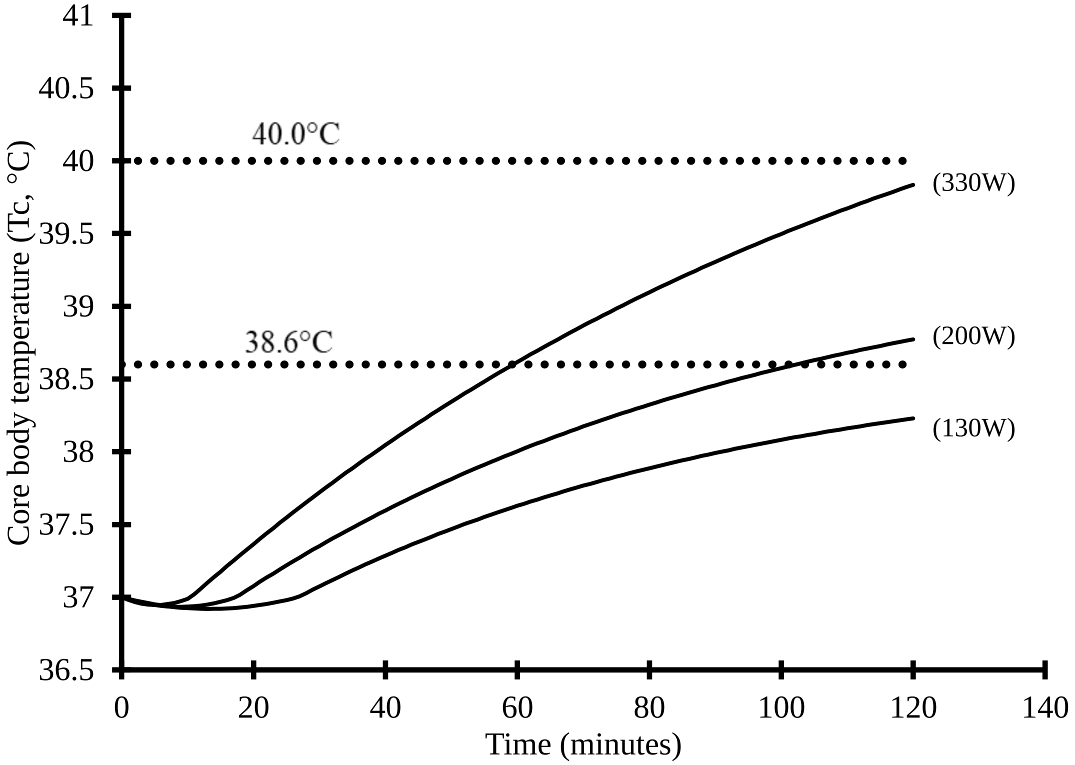
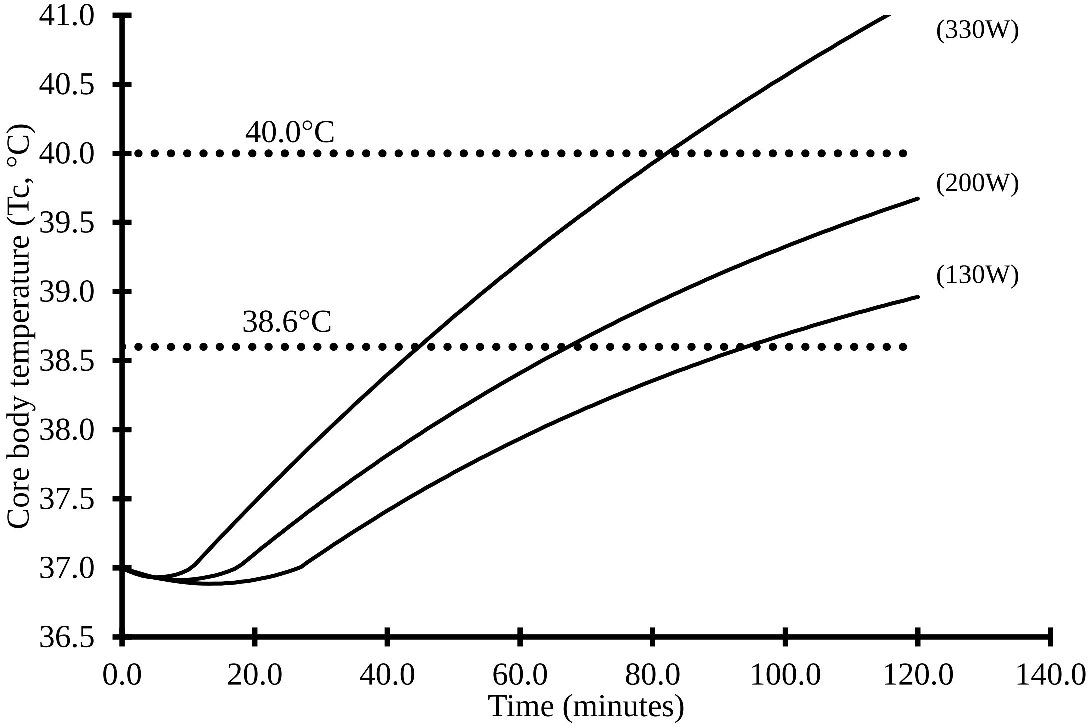


Figure 5. TATPE chemical protective ensemble worn in extreme hot dry conditions (51.7°C, 14% RH) with no cooling



Figures 6-7 show the predicted rise in core body temperature for warm conditions while wearing the TATPE chemical protective ensemble with varied levels of cooling provided by the Air Soldier Environmental Control Vest (ECV) at 200W (Fig. 6) and at 330W (Fig. 7). Figures 8-9 show these same simulations in extreme hot dry conditions for 200W (Fig. 8) and 330W (Fig. 9).

Figures 10-11 show the predicted rise in core body temperature for warm conditions while wearing the TATPE chemical protective ensemble with varied levels of cooling provided by the Oceanit Laboratories' Liquid Cooling Garment (LCG) at 200W (Fig. 10) and 330W (Fig. 11). Figures 12-13 show these same simulations in extreme hot dry conditions for 200W (Fig. 12) and 330W (Fig. 13).

Figures 14 and 15 show a comparison of cooling provided while wearing each vest and the TATPE chemical protective ensemble in warm (Fig. 14) and extreme hot dry (Fig. 15) working at 330W.

Figure 6. Predicted rise in core body temperature working at 200W in warm conditions (35°C, 40% RH) with four levels of cooling wearing the Air Soldier Environmental Control Vest (ECV)

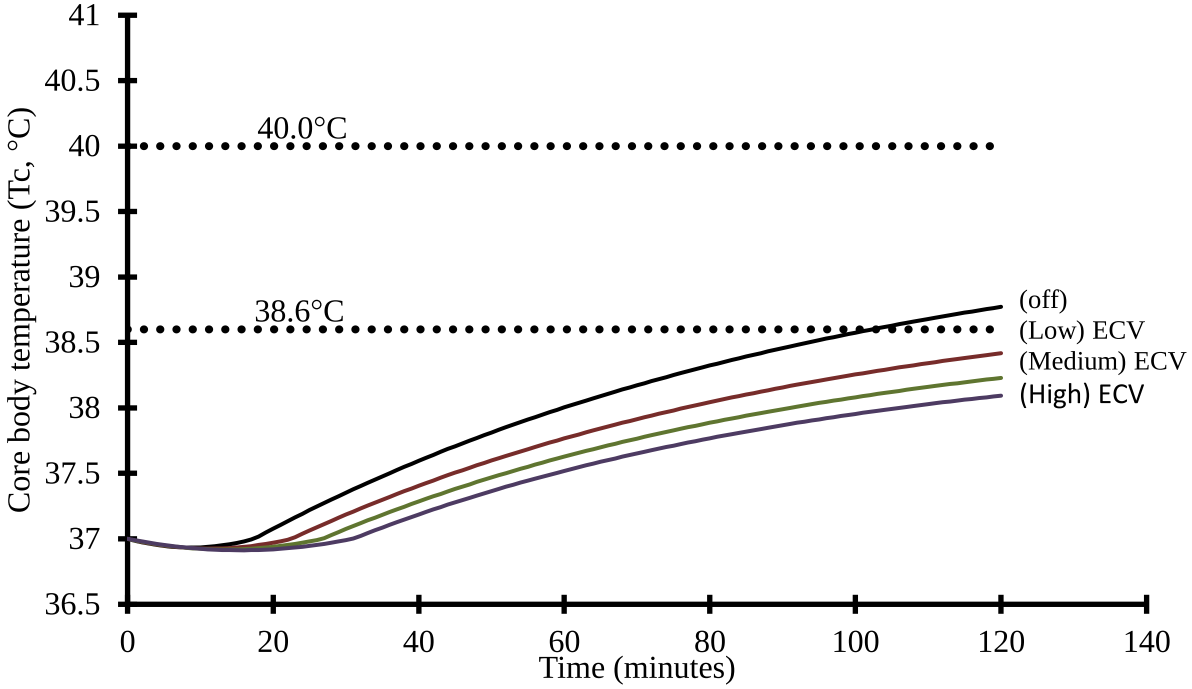


Figure 7. Predicted rise in core body temperature working at 330W in warm conditions (35°C, 40% RH) with four levels of cooling wearing the Air Soldier Environmental Control Vest (ECV)

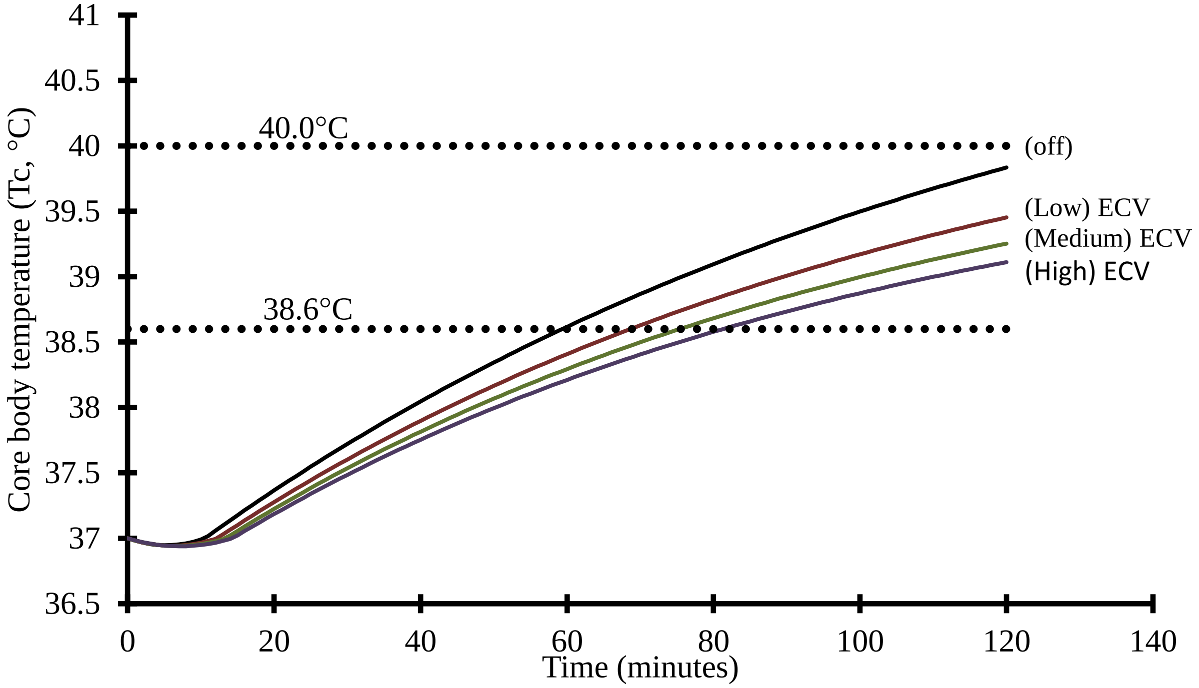


Figure 8. Predicted rise in core body temperature working at 200W in extreme hot dry conditions (51.7°C, 14% RH) with four levels of cooling wearing the Air Soldier Environmental Control Vest (ECV)

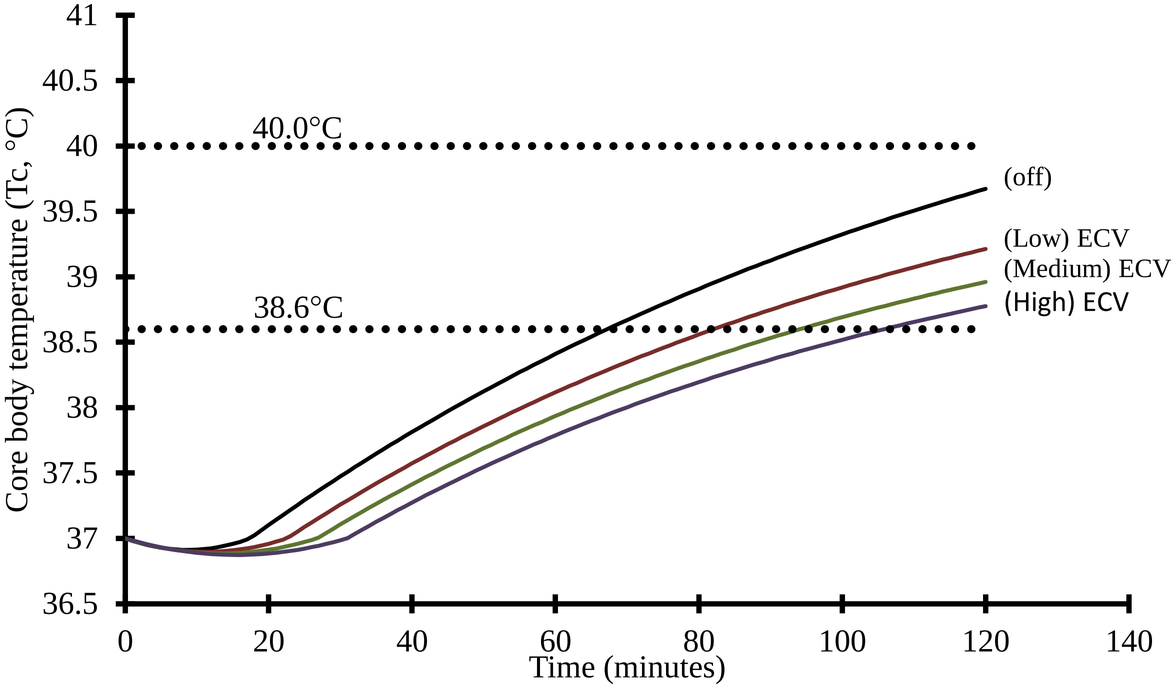


Figure 9. Predicted rise in core body temperature working at 330W in extreme hot dry conditions (51.7°C, 14% RH) with four levels of cooling wearing the Air Soldier Environmental Control Vest (ECV)

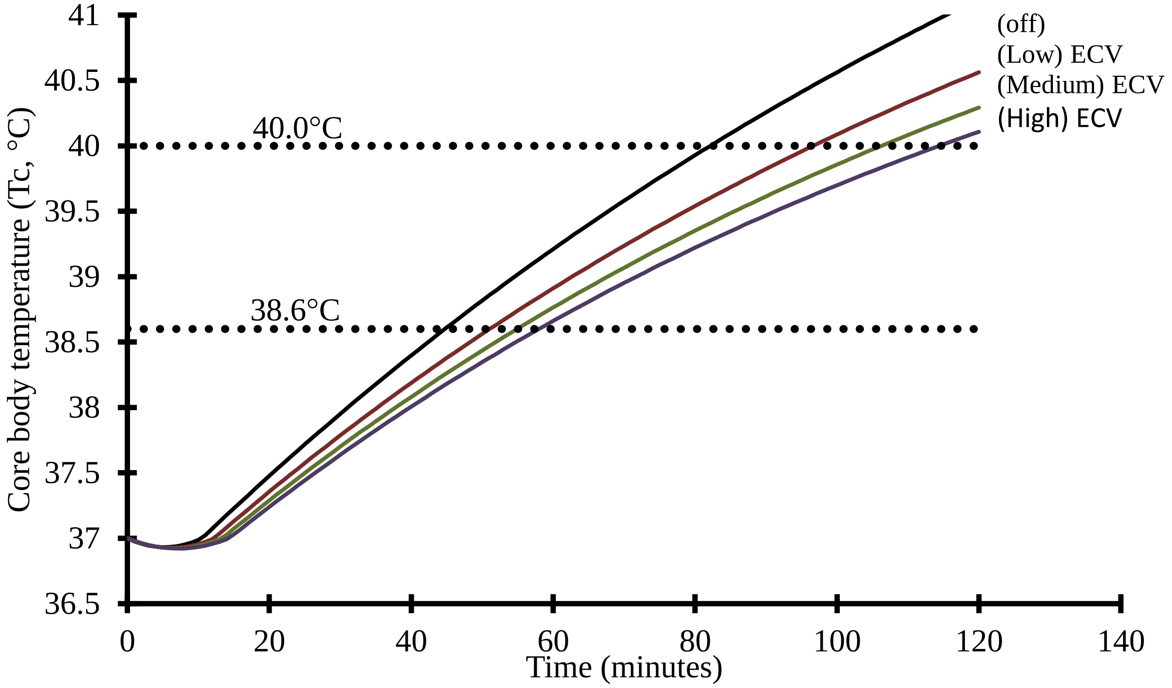


Figure 10. Predicted rise in core body temperature working at 200W in warm conditions (35°C, 40% RH) with four levels of cooling wearing the Oceanit Laboratories' Liquid Cooling Garment (LCG)

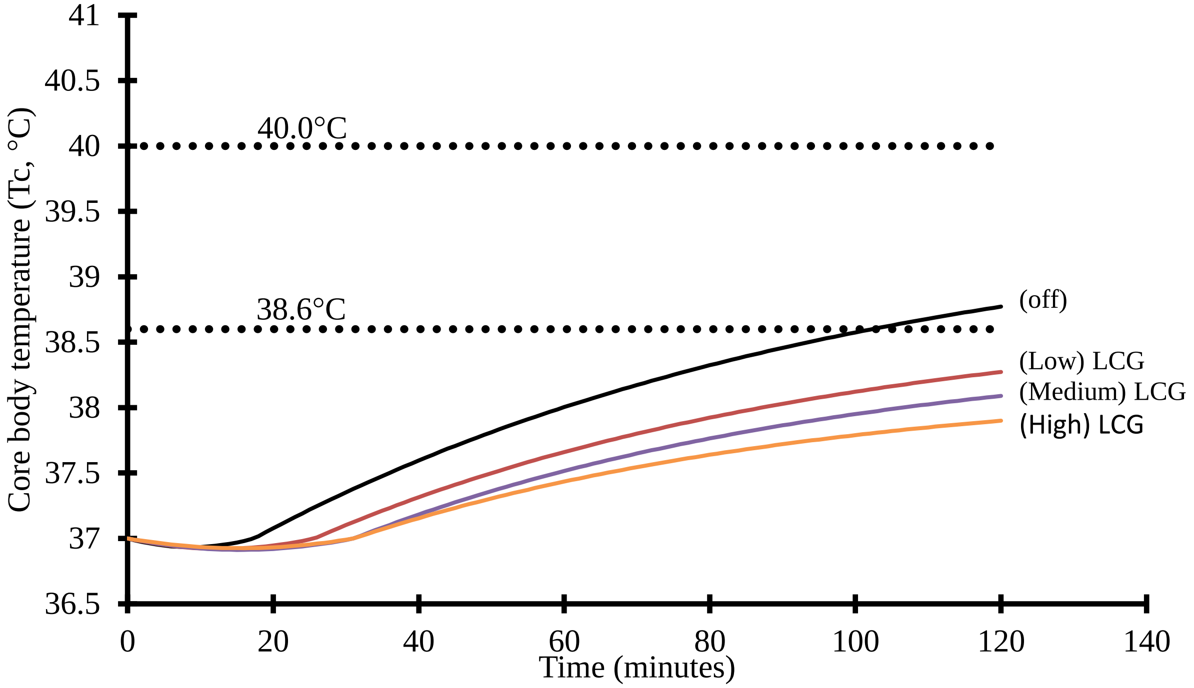


Figure 11. Predicted rise in core body temperature working at 330W in warm conditions (35°C, 40% RH) with four levels of cooling wearing the Oceanit Laboratories' Liquid Cooling Garment (LCG)

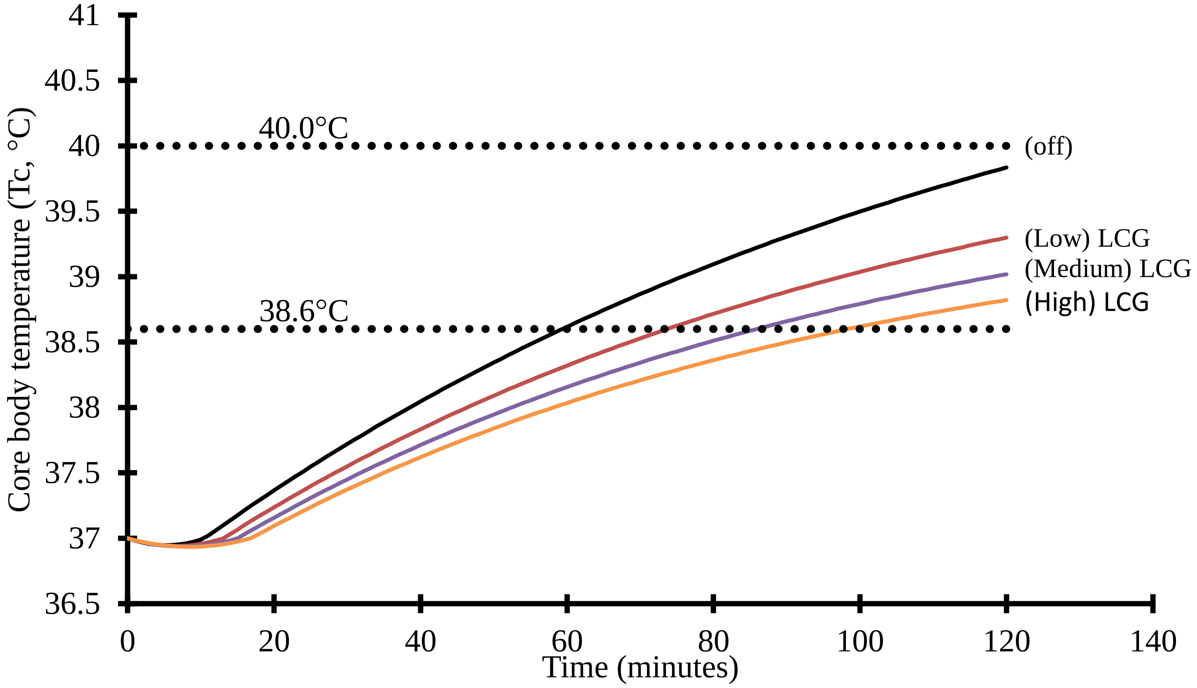


Figure 12. Predicted rise in core body temperature working at 200W in extreme hot dry conditions (51.7°C, 14% RH) with four levels of cooling wearing the Oceanit Laboratories' Liquid Cooling Garment (LCG)

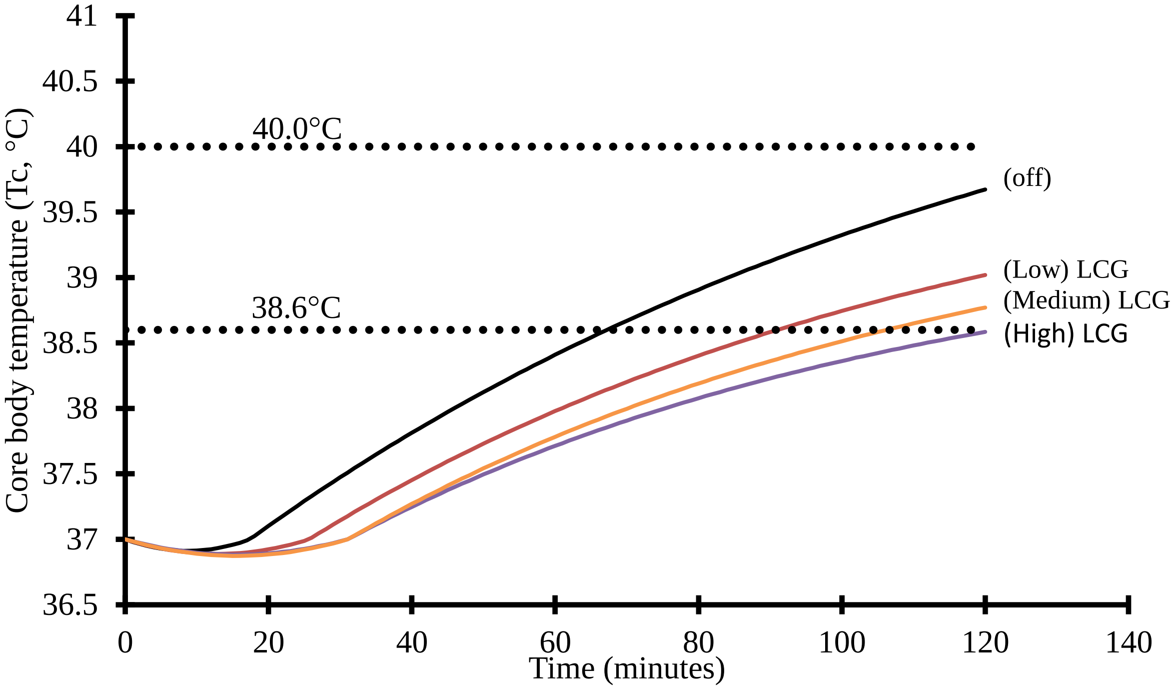


Figure 13. Predicted rise in core body temperature working at 330W in extreme hot dry conditions (51.7°C, 14% RH) with four levels of cooling wearing the Oceanit Laboratories' Liquid Cooling Garment (LCG)

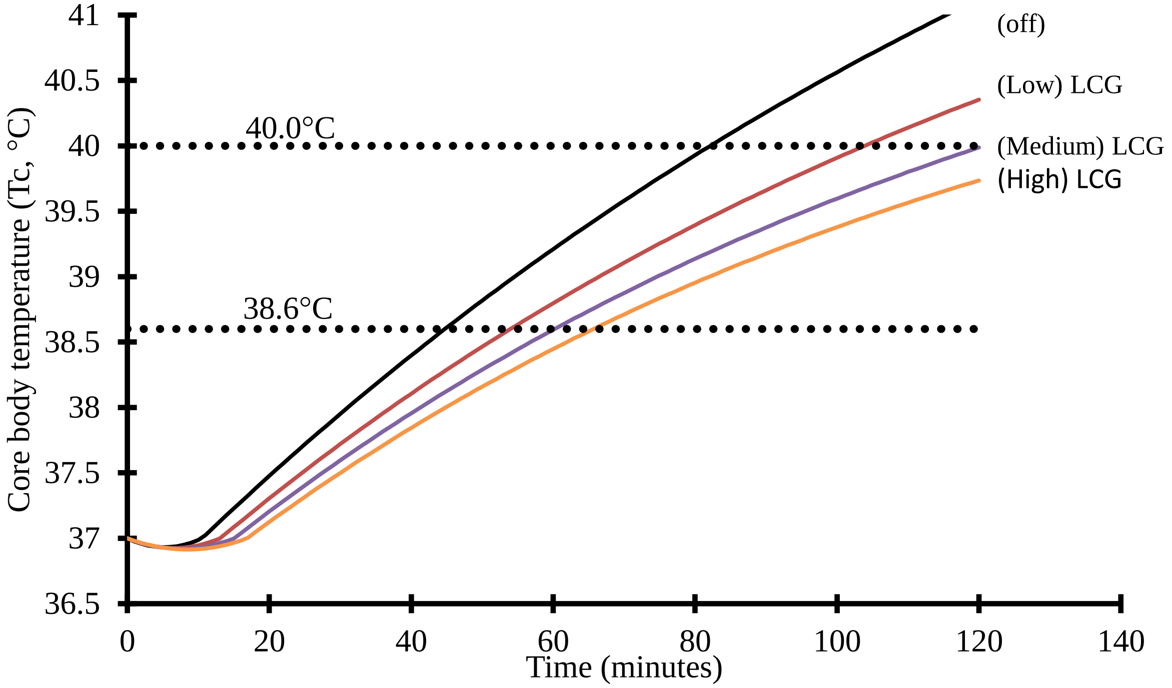


Figure 14. Predicted rise in core body temperature at 330W in warm conditions (35°C, 40% RH) with two levels of cooling wearing the Air Soldier Environmental Control Vest (ECV) and Oceanit Laboratories' Liquid Cooling Garment (LCG)

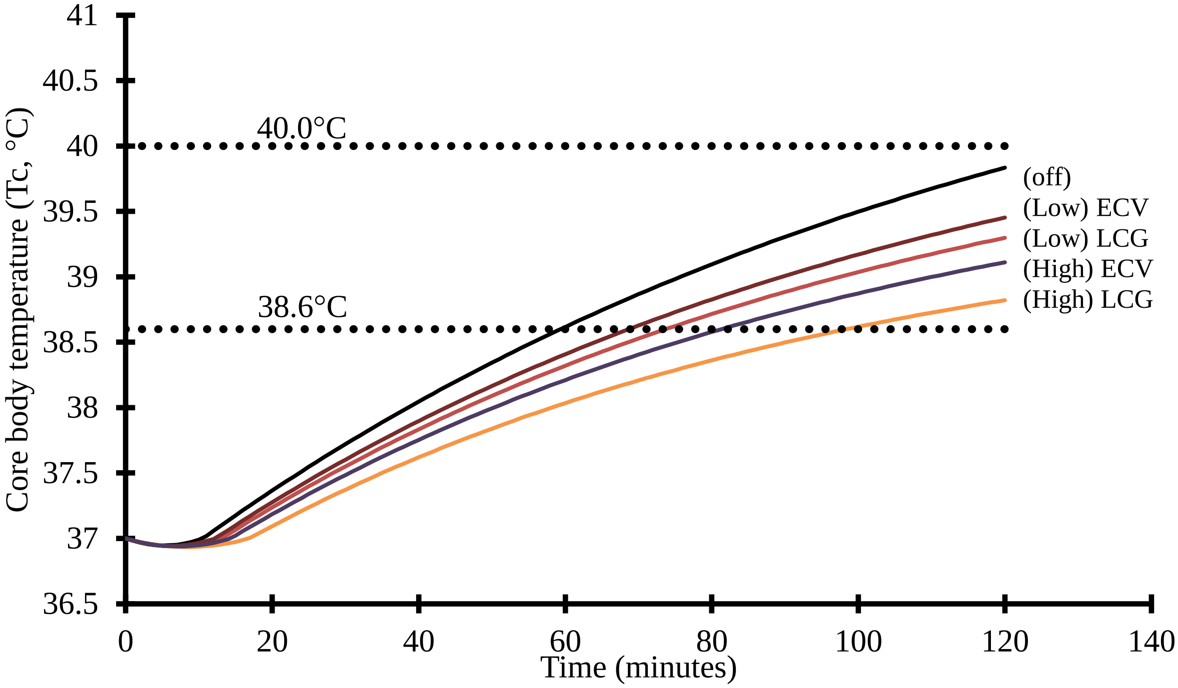
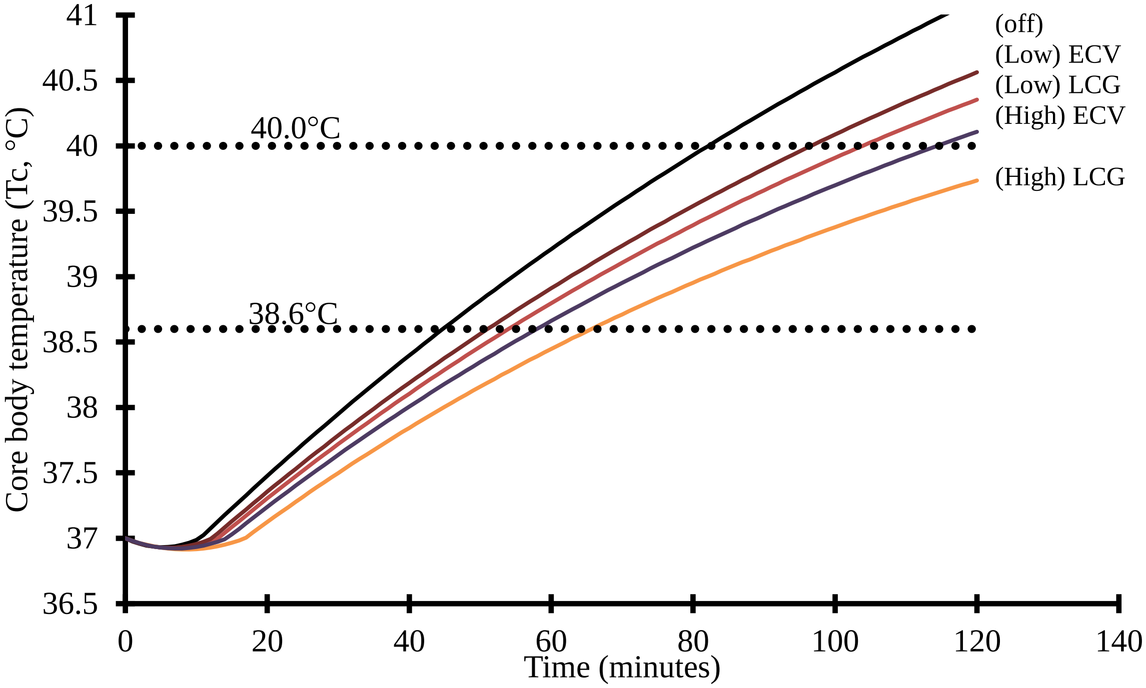


Figure 15. Predicted rise in core body temperature at 330W in hot dry conditions (51.7°C, 14% RH) with two levels of cooling wearing the Air Soldier Environmental Control Vest (ECV) and Oceanit Laboratories' Liquid Cooling Garment (LCG)



DISCUSSION

The modeling and analysis from this report provide quantitative evidence that the LCG is a better cooling garment than the ECV, based on predicted lower core temperatures during work and work time to reach critical temperature. Tables 2 shows the manikin tests results that suggest the LCG provides approximately 42% heat removal advantage over the ECV; while Table 3 and Figures 6-15 show that predictive modeling suggest that LCG allows for longer duration of activities in each assessed work rate and environmental condition. Additionally, wearing the LCG in each of the environments and work rates, resulted in lower average core body temperatures at 60 minutes and 120 minute marks on low (0.11 and 0.18°C respectively) and on high (0.12 and 0.22°C respectively) (Figures 6-15; Table 4).

Table 4. Differences in simulated core body temperatures (°C) at 60 and 120 minutes

Cooling	**Work Rate**	**Warm (35°C, 40%RH)**		**Hot Dry (51.7°C, 14%RH)**	
		60 min	120 min	60 min	120 min
LCG low	200W	37.66°C	38.27°C	37.98°C	39.02°C
ECV low	200W	37.77°C	38.42°C	38.12°C	39.21°C
Delta		**0.11°C**	**0.15°C**	**0.14°C**	**0.19°C**
LCG low	330W	38.32°C	39.30°C	38.80°C	40.35°C
ECV low	330W	38.41°C	39.45°C	38.91°C	40.56°C
Delta		**0.08°C**	**0.19°C**	**0.11°C**	**0.21°C**
LCG high	200W	37.43°C	37.90°C	37.78°C	38.77°C
ECV high	200W	37.52°C	38.09°C	37.79°C	38.78°C
Delta		**0.09°C**	**0.15°C**	**0.00°C**	**0.01°C**
LCG high	330W	38.03°C	38.82°C	38.45°C	39.74°C
ECV high	330W	38.21°C	39.11°C	38.66°C	40.11°C
Delta		**0.18°C**	**0.29°C**	**0.21°C**	**0.37°C**

There are a number of countermeasures that can be used to mitigate the risk of heat strain to include use of simple work-rest cycles as well as more interventional methods such as the use of personal cooling systems. Work-rest management can provide significant benefits by reducing the metabolic demands and allowing for body cooling or by opening up of clothing systems to 'air out'. However, this is often not practical when wearing protective clothing, and therefore cooling systems can be used to provide significant benefits [17]. Extensive research has been conducted to assess biophysical properties and cooling abilities of body-worn systems using thermal manikin and modeling methods [18-19]; while human studies have been conducted to complement and affirm these results for both active and passive cooling [20-26].

Biophysical assessments combined with modeling and simulations provides a quantitative and cost effective approach to clothing and cooling system assessments. However, there are limitations to elements within these modeling and simulations methods that ultimately require human-based studies to fully capture any potential nuances of individual responses of both human factors and physiological differences. This work provides some quantitative evidence regarding the thermal burden imposed by these three CB protective ensemble configurations. The information from this report can be used to inform clothing selection and mission planning related to these specific ensembles and data to make comparisons to different ensembles.

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