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THERMAL MODELING AND ANALYSES FOR THE UNIFORM INTEGRATED PROTECTION ENSEMBLE (UIPE) FAMILY OF SYSTEMS (FOS) – GENERAL PURPOSE (GP) PROGRAM

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14. ABSTRACT
This effort applies modeling and analysis of predicted thermal burdens for a set of ensembles, predicting core body temperatures (Tc) to assist in determining safe working times within a range of work rates and environmental conditions. The US Army Research Institute of Environmental Medicine (USARIEM) Heat Strain Decision Aid (HSDA) is an empirically developed model for prediction of core temperature (Tc) during military activities. In 2012, the Chemical, Biological, Radiological and Nuclear (CBRN) Test and Evaluation (T&E) Executive approved HSDA for thermal burden assessments across the Chemical Biological Defense Program (CBDP) Enterprise; while HSDA also received accreditation for use in the Uniform Integrated Protection Ensemble Aircrew program (UIPE-Air and GP) in 2022. The UIPE Family of Systems (FoS) program office has requested continued use of HSDA simulations to meet their needs for thermal burden assessment. This work focused on evaluation of selected General Purpose (GP) ensembles.

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EXECUTIVE SUMMARY - INTRODUCTION

Thermal modeling allows for the assessment of thermal burden associated with protective clothing and equipment. While experience and intuition can generally describe potential thermal strain or perceived differences in heat stress; thermal modeling provides quantitative insights related to the complex interactions between variables. These complex interactions can be simulated in wide ranges of conditions that would be impractical to directly assess with human subjects research. The US Army Research Institute of Environmental Medicine (USARIEM) Heat Strain Decision Aid (HSDA) is an empirically developed model for prediction of core temperature (Tc) during military activities (1). HSDA has been widely used to develop heat stress management guidelines for training and operational settings and has previously been used to guide acquisition of protective ensembles (2-4). Recent validation studies have shown the HSDA acceptably predicts core body temperature in individuals wearing chemical and biological (CB) protective clothing during exercise and recommended its use by military and civilian planners to predict core body temperature rise and resulting thermal strain over time for young healthy individuals needing to perform work in CB protective gear (2, 4). In 2012 the Chemical, Biological, Radiological and Nuclear (CBRN) Test and Evaluation (T&E) Executive approved HSDA for thermal burden assessments across the Chemical Biological Defense Program (CBDP) Enterprise; while HSDA also received accreditation for use in the Uniform Integrated Protection Ensemble Aircrew program (UIPE-Air and GP) in 2022 (5, 6). The UIPE Family of Systems (FoS) program office has requested continued use of HSDA simulations to meet their needs for thermal burden assessment. This work focused on evaluation of selected General Purpose (GP) ensembles.

Objective

This effort applies modeling and analysis of predicted thermal burdens for a set of ensembles, predicting core body temperatures (T_c) to assist in determining safe working times within a range of work rates and environmental conditions. The Navy Clothing and Textile Research Facility (NCTRF) conducted biophysical analyses of select clothing and provided data to USARIEM for modeling and analyses using HSDA. Each ensemble included standardized (basic cotton) socks, (basic cotton) underwear, JSLIST block 2 gloves with cotton liners, and Alternative Footwear Solutions ground boot. The specific ensembles include, six different ensemble configurations, half of which included armor, in the form of the Modular Scalable Vest (MSV) with side plates and integrated head protection system (IHPS) helmet, are as follows:

1. Configuration 1 – UIPE FoS GP Chemical, Biological Duty Uniform (CBDU)
2. Configuration 2 – CBDU with armor
3. Configuration 3 – JSLIST
4. Configuration 4 – JSLIST with armor
5. Configuration 5 – JSLIST and Army Combat Uniform (ACU)
6. Configuration 6 – JSLIST and ACU with armor

METHODS

A summary of clothing values and meanings reported by NCTRF have been re-summarized for this report (7).

Thermal modeling using HSDA, was applied to each clothing ensemble. Modeling provided estimated times until T_c reached or exceeded 38.5 and 39°C for each ensemble in twelve environments (six daytime; six nighttime), each characterized by air temperature, relative humidity, solar load, and wind speed, and at three work rates to produce 36 total simulated conditions for each ensemble. Simulated environments include a standard set of characterization conditions (temperate, hot-humid, and hot-dry), with three work rates (light, moderate, and heavy work), and has been expanded for additional resolution to twelve total conditions to better reflect potential use cases for the ensembles.

Inputs for air temperature, mean radiant temperature (MRT), relative humidity (RH%), and wind speed (m/s) are summarized in Table 1 for full sun and Table 2 for nighttime conditions. Each set of conditions will be used as inputs to the HSDA model for full sun and nighttime conditions. For full sun conditions MRT is air temperature plus 40°C; while for nighttime conditions, MRT is set equal to air temperature.

Table 1. Inputs to HSDA for full sun conditions.

Work rate (W)	Air Temperature (°C, °F)	Mean Radiant Temperature (°C) for Full Sun	Relative Humidity (%)	Wind Speed (m/s)
Light 250W	21.1, 70	61.1	20	2
	21.1, 70	61.1	95	
	29.4, 85	69.4	50	
	35, 95	75	35	
	35, 95	75	75	
	48.9, 120	88.9	20	
Moderate 425W	21.1, 70	61.1	20	2
	21.1, 70	61.1	95	
	29.4, 85	69.4	50	
	35, 95	75	35	
	35, 95	75	75	
	48.9, 120	88.9	20	
Heavy 600W	21.1, 70	61.1	20	2
	21.1, 70	61.1	95	
	29.4, 85	69.4	50	
	35, 95	75	35	
	35, 95	75	75	
	48.9, 120	88.9	20	

Table 2. Inputs to HSDA for nighttime conditions.

Work rate (W)	Air Temperature (°C, °F)	Mean Radiant Temperature (°C) for Nighttime	Relative Humidity (%)	Wind Speed (m/s)
Light 250W	21.1, 70	21.1	20	2
	21.1, 70	21.1	95	
	29.4, 85	29.4	50	
	35, 95	35	35	
	35, 95	35	75	
	48.9, 120	48.9	20	
Moderate 425W	21.1, 70	21.1	20	2
	21.1, 70	21.1	95	
	29.4, 85	29.4	50	
	35, 95	35	35	
	35, 95	35	75	
	48.9, 120	48.9	20	
Heavy 600W	21.1, 70	21.1	20	2
	21.1, 70	21.1	95	
	29.4, 85	29.4	50	
	35, 95	35	35	
	35, 95	35	75	
	48.9, 120	48.9	20	

Human inputs in this modeling:

Inputs for HSDA include weather / environmental information, individual human information, and mission information (work rate and clothing ensemble properties). Inputs for the human assume a healthy male (height 172 cm, weight 70 kg), fully heat acclimatized, hydrated, with normal initial skin (33°C) and core body (37°C) temperatures.

Each combination of uniform and weather were simulated for three work rates expressed in total watts (W); light (250 W), moderate (425 W) and heavy (600 W). These corresponding work rates can be associated to a range of different activities. For example, we use a progressive increase in walking speed and added load carriage for reference; where a slow walk (1.1 m/s; 2.5 mph) carrying minimal external load (~5 kg) corresponds to light work rate (250W); a faster pace (1.4 m/s; 3.1 mph) carrying additional external load (~25 kg) for moderate work rate (425W); and even faster pace (1.7 m/s; 3.8 mph) carrying additional external load (~30 kg) corresponds to heavy work rate (600W) (8-14).

Predicted endurance times (up to 5 hours) until body $T_c \geq 38.5$ and 39°C and these timepoints are provided for each of the scenarios. Differences in endurance time between ensembles are also reported for each scenario.

Thermal manikin data inputs in this modeling:

Biophysical data provided from NCTRF was used for thermal modeling. This data includes standard test values (at 0.4 m/s) for dry (Rct) and evaporative (Ret) resistance values converted into units of clo (dry thermal resistance) and a vapor permeability index (i_m) and then into values to allow for wind effects (^{g}) into the model (at 1 m/s) (Table 3) (15-16).

Table 3. Biophysical properties of clothing configurations and calculated values for modeling inputs.

Clothing configuration	Measured values at 0.4 m/s					Converted to 1 m/s for model			
	Rct	***clo***	***Ret***	***i_m***	***i_m/clo***	***clo***	***clo^g***	***im/clo***	***im/clo^g***
CBDU	0.285	1.84	80.44	0.215	0.12	1.59	-0.15	0.13	0.19
CBDU+Armor	0.295	1.9	89.19	0.200	0.11	1.65	-0.14	0.12	0.18
JSLIST	0.268	1.73	85.31	0.191	0.11	1.53	-0.14	0.12	0.19
JSLIST+Armor	0.284	1.83	98.14	0.175	0.10	1.62	-0.13	0.10	0.17
ACU+JSLIST	0.307	1.98	96.16	0.194	0.10	1.72	-0.13	0.10	0.17
ACU+JSLIST+Armor	0.333	2.15	108.71	0.186	0.09	1.86	-0.11	0.09	0.16

RESULTS

Tables 4 (full sun) and 5 (nighttime) show the time, in minutes, until predicted T_c reaches 38.5 and 39°C for each ensemble, environment, and work rate. For all the scenarios examined here, wearers of the CBDU baseline ensemble without armor were able to perform exercise as long or longer than wearers of the JSLIST or ACU+JSLIST baseline ensembles prior to HSDA predicted T_c reaching 38.5 and 39°C, with one exception. In the added armor conditions, the CBDU+Armor allowed for longer or the same amount of time working as the other two with nine exceptions.

Tables 6-8 (full sun) and 9-11 (nighttime) show the differences in time to reach the 38.5 and 39°C thresholds. Table 6 (light intensity 250W in full sun) shows the one exception for the baseline CBDU ensemble vs. ACU+JSLIST, where the ACU+JSLIST allows for one additional minute to reach 39°C in the hottest dry environment (120°F (48.9°C), 20%RH, MRT: 88.9°C). Table 6 also shows four exceptions where ACU+JSLIST+Armor allows for an additional minute to reach 38.5°C and an additional 1-2 minutes to reach 39°C for the hottest humid and hottest dry conditions (hot humid: 95°F (35°C), 75%RH, MRT: 75.0°C; hot dry: 120°F (48.9°C), 20%RH, MRT: 88.9°C)).

Table 7 (moderate work 425W in full sun) shows two exceptions where ACU+JSLIST+Armor allows for an additional minute to reach 38.5 and 39°C for the hottest dry condition (120°F (48.9°C), 20%RH, MRT: 88.9°C)); while Table 8 (heavy work 600W in full sun) shows three exceptions where ACU+JSLIST+Armor allows for an additional minute to reach 39°C in the hottest humid condition (hot humid: 95°F (35°C), 75%RH, MRT: 75.0°C) and to reach 38.5 and 39°C in the hottest dry condition (hot dry: 120°F (48.9°C), 20%RH, MRT: 88.9°C)).

Table 4. Times (in minutes) to reach 38.5 and 39°C during full sun conditions for each ensemble configuration at light (250 W), moderate (425 W), and heavy (600 W) work intensity.

Full Sun Conditions	Clothing configuration	250W		425W		600W	
		38.5°C	39°C	38.5°C	39°C	38.5°C	39°C
70°F (21.1°C), 20%RH Mean radiant temperature (MRT): 61.1°C	CBDU	143	-	65	92	44	59
	CBDU+Armor	130	-	62	88	42	57
	JSLIST	136	-	64	90	43	58
	JSLIST+Armor	121	272	60	85	41	55
	ACU+JSLIST	122	275	60	85	41	55
	ACU+JSLIST+Armor	112	212	58	80	39	52
70°F (21.1°C), 95%RH MRT: 61.1°C	CBDU	111	209	58	80	39	52
	CBDU+Armor	106	188	57	78	38	50
	JSLIST	109	200	58	80	39	52
	JSLIST+Armor	103	176	56	77	37	49
	ACU+JSLIST	103	176	56	76	37	49
	ACU+JSLIST+Armor	98	161	54	74	36	47
85°F (29.4°C), 50%RH MRT: 69.4°C	CBDU	89	136	52	70	34	45
	CBDU+Armor	86	130	51	69	33	43
	JSLIST	86	131	51	69	33	43
	JSLIST+Armor	84	124	50	67	32	42
	ACU+JSLIST	84	126	50	68	32	42
	ACU+JSLIST+Armor	83	122	49	66	31	41
95°F (35°C), 35%RH MRT: 75.0°C	CBDU	78	112	48	64	30	39
	CBDU+Armor	76	109	47	63	29	37
	JSLIST	76	108	47	62	29	37
	JSLIST+Armor	74	105	46	61	28	36
	ACU+JSLIST	75	108	47	62	28	37
	ACU+JSLIST+Armor	75	106	46	61	28	36
95°F (35°C), 75%RH MRT: 75.0°C	CBDU	67	92	42	55	24	30
	CBDU+Armor	67	92	42	55	24	30
	JSLIST	66	90	41	54	23	30
	JSLIST+Armor	66	91	42	54	24	30
	ACU+JSLIST	67	92	42	55	24	30
	ACU+JSLIST+Armor	68	93	42	55	24	31
120°F (48.9°C), 20%RH MRT: 88.9°C	CBDU	59	78	36	47	19	24
	CBDU+Armor	59	78	36	46	19	24
	JSLIST	58	76	35	45	19	23
	JSLIST+Armor	58	76	35	45	19	23
	ACU+JSLIST	59	79	36	47	19	24
	ACU+JSLIST+Armor	60	80	37	47	20	25

Note: A dash (-) symbol is used in scenarios that do not reach a given threshold within the simulation period.

Table 5. Times (in minutes) to reach 38.5 and 39°C during nighttime conditions (no sun) for each ensemble configuration at light (250 W), moderate (425 W), and heavy (600 W) work intensity.

Nighttime conditions (no sun)	Clothing configuration	250W		425W		600W	
		38.5°C	39°C	38.5°C	39°C	38.5°C	39°C
70°F (21.1°C), 20%RH Mean radiant temperature (MRT): 21.1°C	CBDU	-	-	75	112	49	66
	CBDU+Armor	245	-	71	104	46	63
	JSLIST	-	-	74	110	48	65
	JSLIST+Armor	206	-	69	100	45	61
	ACU+JSLIST	197	-	68	98	45	61
	ACU+JSLIST+Armor	158	-	64	91	43	57
70°F (21.1°C), 95%RH MRT: 21.1°C	CBDU	174	-	66	94	44	59
	CBDU+Armor	154	-	64	90	42	57
	JSLIST	172	-	66	94	44	59
	JSLIST+Armor	147	-	63	88	42	56
	ACU+JSLIST	143	-	62	87	41	55
	ACU+JSLIST+Armor	128	-	60	83	40	53
85°F (29.4°C), 50%RH MRT: 29.4°C	CBDU	116	234	58	80	39	51
	CBDU+Armor	110	202	56	78	37	49
	JSLIST	113	219	57	79	38	50
	JSLIST+Armor	106	186	55	76	36	48
	ACU+JSLIST	106	186	55	76	36	48
	ACU+JSLIST+Armor	100	167	54	73	35	46
95°F (35°C), 35%RH MRT: 35.0°C	CBDU	96	155	53	72	35	45
	CBDU+Armor	92	146	52	70	33	44
	JSLIST	94	149	52	71	34	44
	JSLIST+Armor	89	138	51	69	32	42
	ACU+JSLIST	90	140	51	69	33	43
	ACU+JSLIST+Armor	87	133	50	68	32	41
95°F (35°C), 75%RH MRT: 35.0°C	CBDU	79	114	47	62	28	36
	CBDU+Armor	78	113	47	62	28	36
	JSLIST	78	113	47	62	28	36
	JSLIST+Armor	77	112	46	62	28	36
	ACU+JSLIST	78	112	47	62	28	36
	ACU+JSLIST+Armor	77	111	46	62	28	36
120°F (48.9°C), 20%RH MRT: 48.9°C	CBDU	67	92	41	54	23	29
	CBDU+Armor	67	91	41	54	23	29
	JSLIST	66	89	40	53	22	28
	JSLIST+Armor	65	88	40	52	22	28
	ACU+JSLIST	66	91	41	53	23	29
	ACU+JSLIST+Armor	67	91	41	54	23	29

Note: A dash (-) symbol is used in scenarios that do not reach a given threshold within the simulation period.

Table 6. Differences in safe work times between UIPE ensemble (CBDU) and other configuration with and without armor at light intensity work (250 W) in full sun.

250W	Threshold	CBDU vs. JSLIST	CBDU vs. ACU+JSLIST	CBDU+Armor vs. JSLIST+Armor	CBDU+Armor vs. ACU+JSLIST+Armor
70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 61.1°C	38.5°C	5%	17%	7%	16%
	39°C	0%	9%	10%	42%
70°F (21.1°C), 95%RH MRT: 61.1°C	38.5°C	2%	8%	3%	8%
	39°C	11%	19%	7%	17%
85°F (29.4°C), 50%RH MRT: 69.4°C	38.5°C	3%	6%	2%	4%
	39°C	5%	8%	5%	7%
95°F (35°C), 35%RH MRT: 75.0°C	38.5°C	3%	4%	3%	1%
	39°C	3%	4%	4%	3%
95°F (35°C), 75%RH MRT: 75.0°C	38.5°C	2%	0%	2%	-1% *
	39°C	0%	0%	1%	-1% *
120°F (48.9°C), 20%RH MRT: 88.9°C	38.5°C	2%	0%	2%	-2% *
	39°C	0%	-1% *	3%	-3% #

* difference relates to 1 minute
\# difference relates to 2 minutes

Table 7. Differences in safe work times between UIPE ensemble (CBDU) and other configuration with and without armor at moderate intensity work (425 W) in full sun.

425W	Threshold	CBDU vs. JSLIST	CBDU vs. ACU+JSLIST	CBDU+Armor vs. JSLIST+Armor	CBDU+Armor vs. ACU+JSLIST+Armor
70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 61.1°C	38.5°C	2%	8%	3%	7%
	39°C	2%	8%	4%	10%
70°F (21.1°C), 95%RH MRT: 61.1°C	38.5°C	0%	4%	2%	6%
	39°C	0%	5%	1%	5%
85°F (29.4°C), 50%RH MRT: 69.4°C	38.5°C	2%	4%	2%	4%
	39°C	1%	3%	3%	5%
95°F (35°C), 35%RH MRT: 75.0°C	38.5°C	2%	2%	2%	2%
	39°C	3%	3%	3%	3%
95°F (35°C), 75%RH MRT: 75.0°C	38.5°C	2%	0%	0%	0%
	39°C	2%	0%	2%	0%
120°F (48.9°C), 20%RH MRT: 88.9°C	38.5°C	3%	0%	3%	-3% *
	39°C	4%	0%	2%	-2% *

* difference relates to 1 minute

Table 8. Differences in safe work times between UIPE ensemble (CBDU) and other configuration with and without armor at heavy intensity work (600 W) in full sun.

600W	Threshold	CBDU vs. JSLIST	CBDU vs. ACU+JSLIST	CBDU+Armor vs. JSLIST+Armor	CBDU+Armor vs. ACU+JSLIST+Armor
70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 61.1°C	38.5°C	2%	7%	2%	8%
	39°C	2%	7%	4%	10%
70°F (21.1°C), 95%RH MRT: 61.1°C	38.5°C	0%	5%	3%	6%
	39°C	0%	6%	2%	6%
85°F (29.4°C), 50%RH MRT: 69.4°C	38.5°C	3%	6%	3%	6%
	39°C	5%	7%	2%	5%
95°F (35°C), 35%RH MRT: 75.0°C	38.5°C	3%	7%	4%	4%
	39°C	5%	5%	3%	3%
95°F (35°C), 75%RH MRT: 75.0°C	38.5°C	4%	0%	0%	0%
	39°C	0%	0%	0%	-3% *
120°F (48.9°C), 20%RH MRT: 88.9°C	38.5°C	0%	0%	0%	-5% *
	39°C	4%	0%	4%	-4% *

* difference relates to 1 minute

Table 9. Differences in safe work times between UIPE ensemble (CBDU) and other configuration with and without armor at light intensity work (250 W) in nighttime (no sun).

250W	Threshold	CBDU vs. JSLIST	CBDU vs. ACU+JSLIST	CBDU+Armor vs. JSLIST+Armor	CBDU+Armor vs. ACU+JSLIST+Armor
70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 21.1°C	38.5°C	0%	52%	19%	55%
	39°C	0%	0%	0%	0%
70°F (21.1°C), 95%RH MRT: 21.1°C	38.5°C	1%	22%	5%	20%
	39°C	0%	0%	0%	0%
85°F (29.4°C), 50%RH MRT: 29.4°C	38.5°C	3%	9%	4%	10%
	39°C	16%	26%	9%	21%
95°F (35°C), 35%RH MRT: 35.0°C	38.5°C	2%	7%	3%	6%
	39°C	6%	11%	6%	10%
95°F (35°C), 75%RH MRT: 35.0°C	38.5°C	1%	2%	1%	2%
	39°C	1%	2%	1%	2%
120°F (48.9°C), 20%RH MRT: 48.9°C	38.5°C	2%	2%	3%	0%
	39°C	1%	1%	3%	0%

Table 10. Differences in safe work times between UIPE ensemble (CBDU) and other configuration with and without armor at moderate intensity work (425 W) in nighttime (no sun).

425W	Threshold	CBDU vs. JSLIST	CBDU vs. ACU+JSLIST	CBDU+Armor vs. JSLIST+Armor	CBDU+Armor vs. ACU+JSLIST+Armor
70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 21.1°C	38.5°C	1%	10%	3%	11%
	39°C	2%	14%	4%	14%
70°F (21.1°C), 95%RH MRT: 21.1°C	38.5°C	0%	6%	2%	7%
	39°C	0%	8%	2%	8%
85°F (29.4°C), 50%RH MRT: 29.4°C	38.5°C	2%	5%	2%	4%
	39°C	1%	5%	3%	7%
95°F (35°C), 35%RH MRT: 35.0°C	38.5°C	2%	4%	2%	4%
	39°C	1%	4%	1%	3%
95°F (35°C), 75%RH MRT: 35.0°C	38.5°C	0%	0%	2%	2%
	39°C	0%	0%	0%	0%
120°F (48.9°C), 20%RH MRT: 48.9°C	38.5°C	3%	0%	3%	0%
	39°C	2%	2%	4%	0%

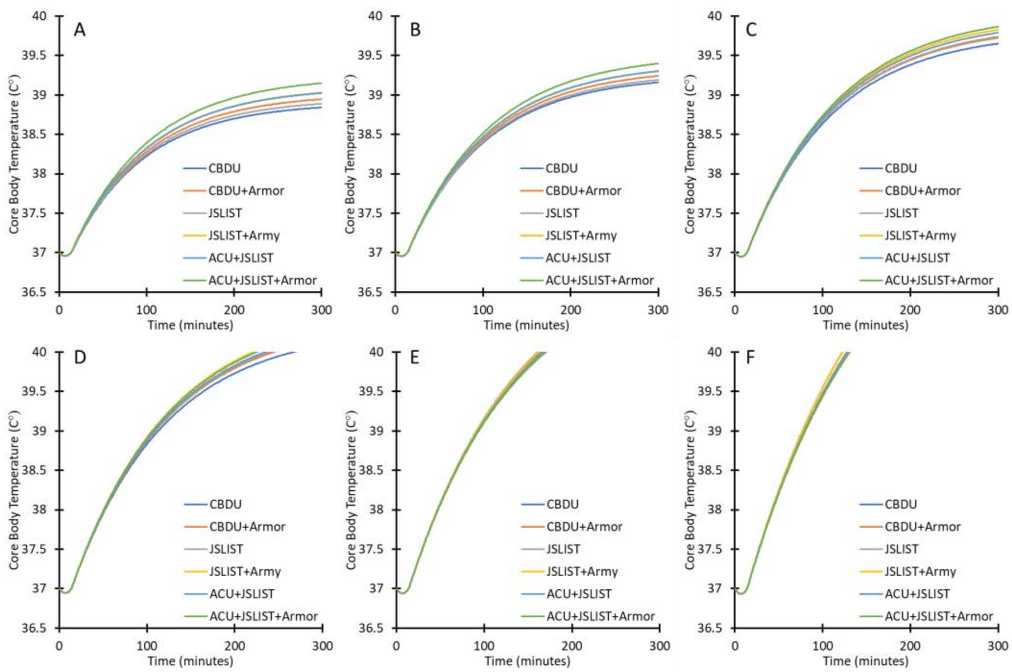
Table 11. Differences in safe work times between UIPE ensemble (CBDU) and other configuration with and without armor at heavy intensity work (600 W) in nighttime (no sun).

600W	Threshold	CBDU vs. JSLIST	CBDU vs. ACU+JSLIST	CBDU+Armor vs. JSLIST+Armor	CBDU+Armor vs. ACU+JSLIST+Armor
70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 21.1°C	38.5°C	2%	9%	2%	7%
	39°C	2%	8%	3%	11%
70°F (21.1°C), 95%RH MRT: 21.1°C	38.5°C	0%	7%	0%	5%
	39°C	0%	7%	2%	8%
85°F (29.4°C), 50%RH MRT: 29.4°C	38.5°C	3%	8%	3%	6%
	39°C	2%	6%	2%	7%
95°F (35°C), 35%RH MRT: 35.0°C	38.5°C	3%	6%	3%	3%
	39°C	2%	5%	5%	7%
95°F (35°C), 75%RH MRT: 35.0°C	38.5°C	0%	0%	0%	0%
	39°C	0%	0%	0%	0%
120°F (48.9°C), 20%RH MRT: 48.9°C	38.5°C	5%	0%	5%	0%
	39°C	4%	0%	4%	0%

Figures 1-3 show predicted T_c for all ensembles and environments for light (250 W) (Figure 1), moderate (425W) (Figure 2), and heavy work (600W) (Figure 3) during full sun conditions. Data corresponding to these figures is shown in Tables 4, 6, 7, and 8.

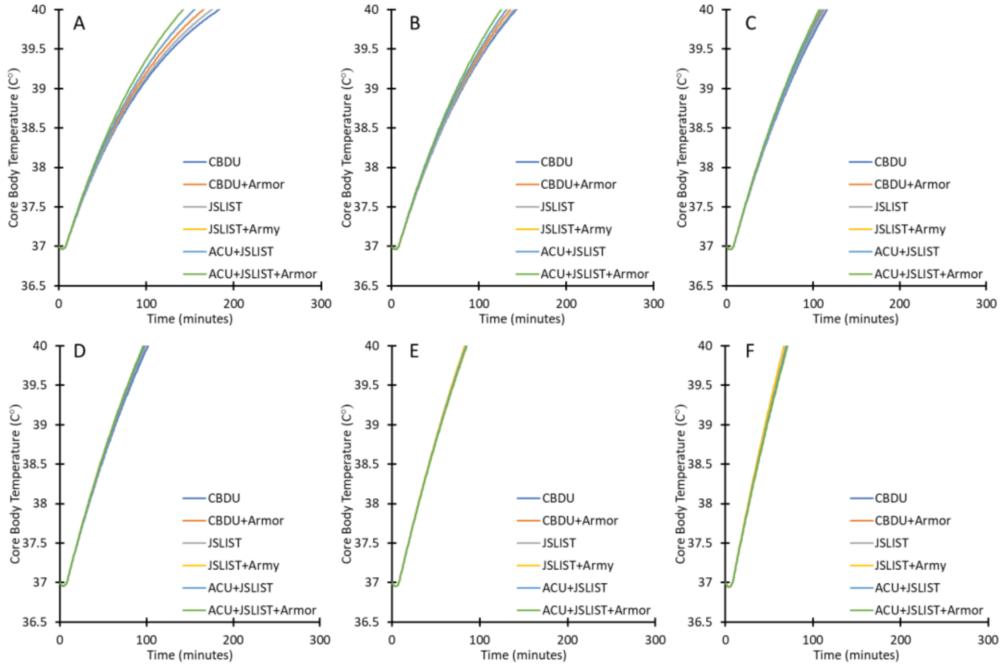
Figures 4-6 show predicted T_c for all ensembles and environments for light (250 W) (Figure 4), moderate (425W) (Figure 5), and heavy work (600W) (Figure 5) during nighttime conditions (no added solar). Data corresponding to these figures is shown in Tables 5, 9, 10, and 11.

Figure 1. Predicted core body temperature rise in full sun conditions during light work (250W).



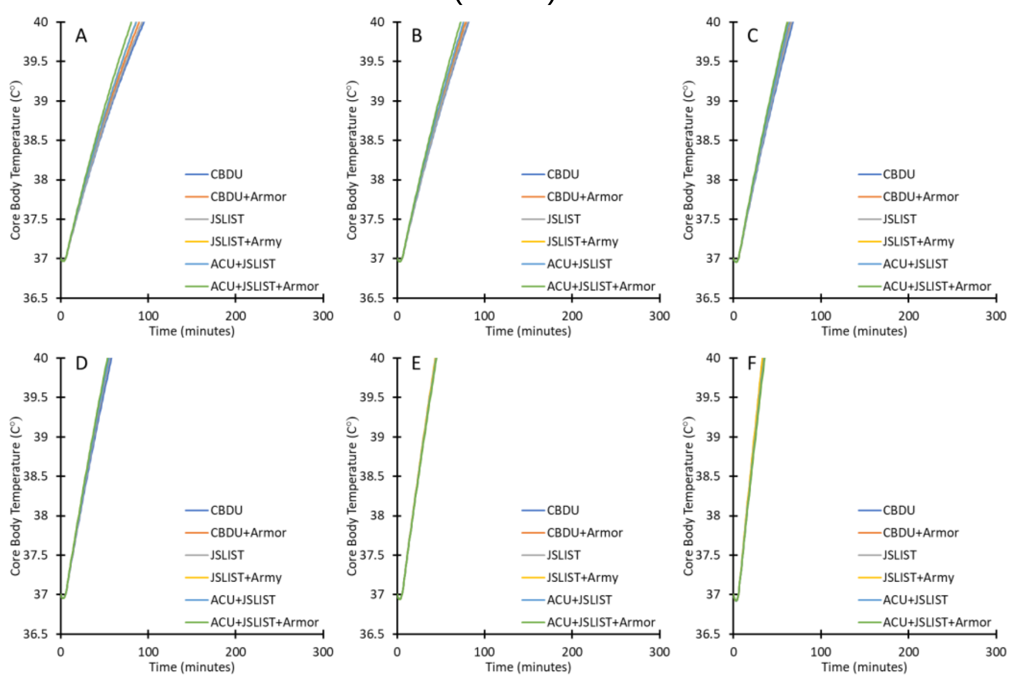
Note: A) 70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 61.1°C; **B)** 70°F (21.1°C), 95%RH, MRT: 61.1°C; **C)** 85°F (29.4°C), 50%RH, MRT: 69.4°C, **D)** 95°F (35°C), 35%RH, MRT: 75.0°C; **E)** 95°F (35°C), 75%RH, MRT: 75.0°C; **F)** 120°F (48.9°C), 20%RH, MRT: 88.9°C

Figure 2. Predicted core body temperature rise in full sun conditions during moderate work (425W).



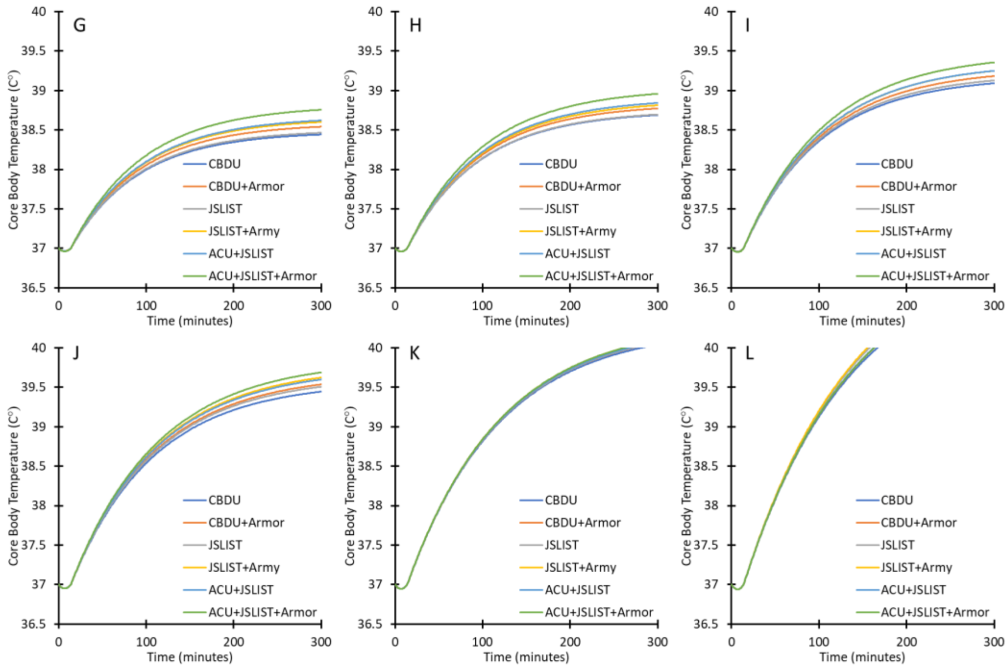
Note: A) 70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 61.1°C; **B)** 70°F (21.1°C), 95%RH, MRT: 61.1°C; **C)** 85°F (29.4°C), 50%RH, MRT: 69.4°C, **D)** 95°F (35°C), 35%RH, MRT: 75.0°C; **E)** 95°F (35°C), 75%RH, MRT: 75.0°C; **F)** 120°F (48.9°C), 20%RH, MRT: 88.9°C

Figure 3. Predicted core body temperature rise in full sun conditions during heavy work (600W).



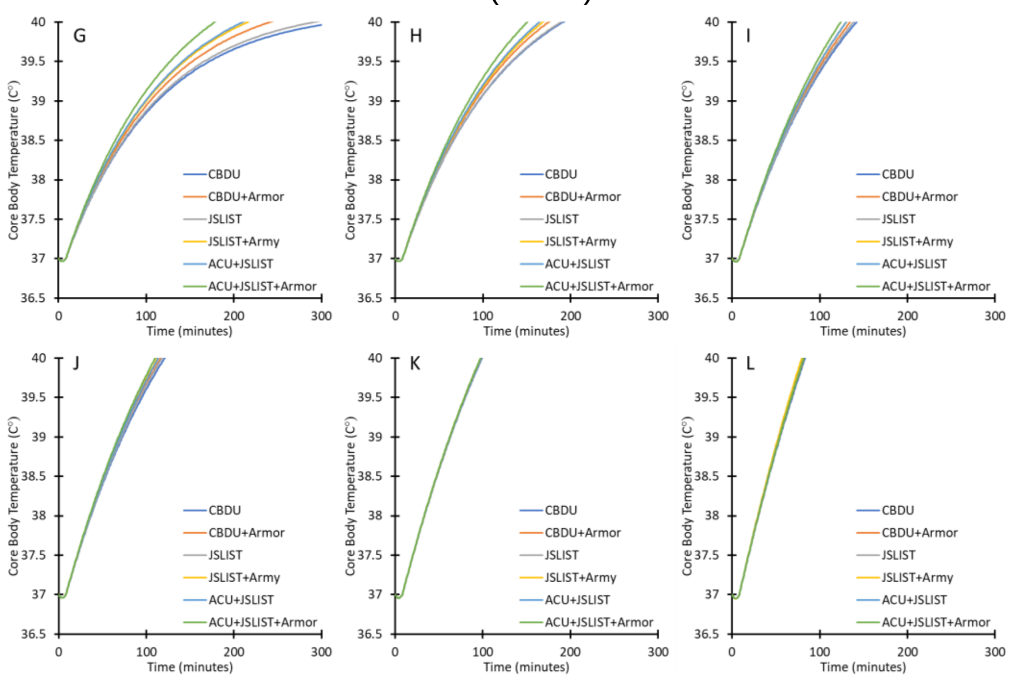
Note: A) 70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 61.1°C; **B)** 70°F (21.1°C), 95%RH, MRT: 61.1°C; **C)** 85°F (29.4°C), 50%RH, MRT: 69.4°C, **D)** 95°F (35°C), 35%RH, MRT: 75.0°C; **E)** 95°F (35°C), 75%RH, MRT: 75.0°C; **F)** 120°F (48.9°C), 20%RH, MRT: 88.9°C

Figure 4. Predicted core body temperature rise in nighttime conditions during light work (250W).



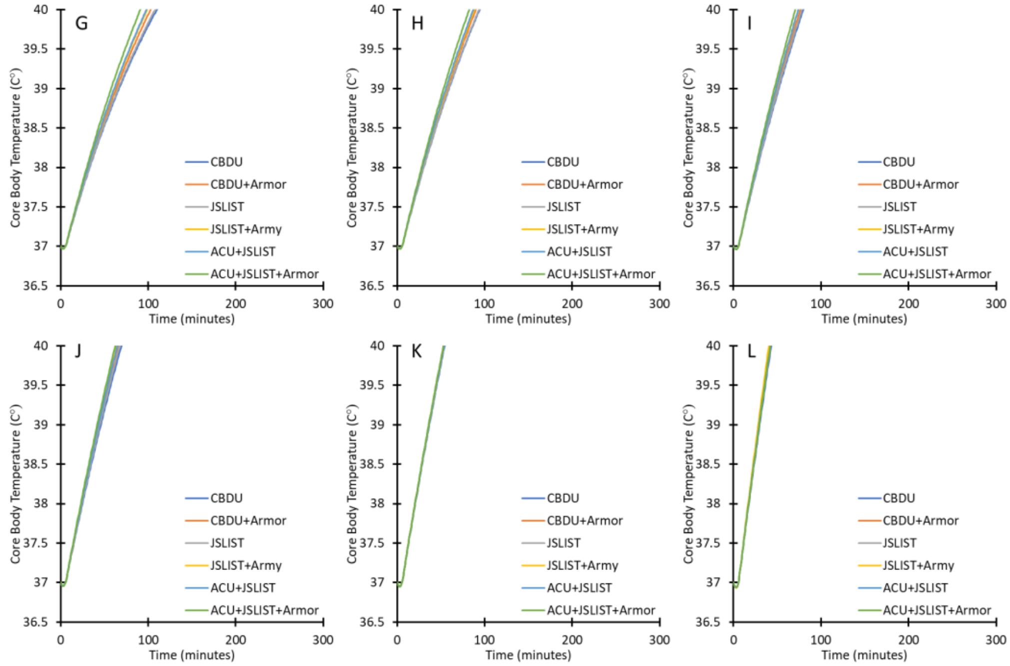
Note: G) 70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 21.1°C; **H)** 70°F (21.1°C), 95%RH, MRT: 21.1°C; **I)** 85°F (29.4°C), 50%RH, MRT: 29.4°C, **J)** 95°F (35°C), 35%RH, MRT: 35.0°C; **K)** 95°F (35°C), 75%RH, MRT: 35.0°C; **L)** 120°F (48.9°C), 20%RH, MRT: 48.9°C

Figure 5. Predicted core body temperature rise in nighttime conditions during moderate work (425W).



Note: G) 70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 21.1°C; **H)** 70°F (21.1°C), 95%RH, MRT: 21.1°C; **I)** 85°F (29.4°C), 50%RH, MRT: 29.4°C, **J)** 95°F (35°C), 35%RH, MRT: 35.0°C; **K)** 95°F (35°C), 75%RH, MRT: 35.0°C; **L)** 120°F (48.9°C), 20%RH, MRT: 48.9°C

Figure 6. Predicted core body temperature rise in nighttime conditions during heavy work (600W).



Note: G) 70°F (21.1°C), 20%RH, Mean radiant temperature (MRT): 21.1°C; **H)** 70°F (21.1°C), 95%RH, MRT: 21.1°C; **I)** 85°F (29.4°C), 50%RH, MRT: 29.4°C, **J)** 95°F (35°C), 35%RH, MRT: 35.0°C; **K)** 95°F (35°C), 75%RH, MRT: 35.0°C; **L)** 120°F (48.9°C), 20%RH, MRT: 48.9°C

Total times (in minutes) across each scenario are shown in Table 12. Collectively the UIPE CBDU ensemble with and without armor performs better than the other two baseline comparison ensembles. Table 13 shows the total time differences for each ensemble with the addition of body armor.

Table 12. Total endurance times (minutes) for each ensemble across all simulated conditions

	Times to reach		Difference to 38.5°C and:		Difference to 39°C and:	
	38.5°C	**39°C**	**JSLIST**	**ACU+JSLIST**	**JSLIST**	**ACU+JSLIST**
CBDU	2,181	3,213	-37 min	-236 min	-62 min	-208 min
JSLIST	2,144	3,151				
ACU+JSLIST	1,945	3,005				
			JSLIST +Armor	**ACU+JSLIST +Armor**	**JSLIST +Armor**	**ACU+JSLIST +Armor**
CBDU+Armor	2,043	3,100	-92 min	-201 min	-109 min	-247 min
JSLIST+Armor	1,951	2,991				
ACU+JSLIST+Armor	1,842	2,853				

Table 13. Total endurance times (minutes) for each ensemble with the addition of body armor

Change with addition of Armor	**No Armor**	**+Armor**	**Difference**	**No Armor**	**+Armor**	**Difference**
	38.5°C		**Δ 38.5°C**	**39°C**		**Δ 39°C**
CBDU	2,181	2,043	-138 min	3,213	3,100	-113 min
JSLIST	2,144	1,951	-193 min	3,151	2,991	-160 min
ACU+JSLIST	1,945	1,842	-103 min	3,005	2,853	-152 min

Table 14 shows the same total time differences as Table 12 separated out by different work intensity levels (light 250W, moderate 425W, and heavy 600W).

Table 14. Total endurance times (minutes) for each ensemble across all simulated conditions broken down by work intensity rates (low 250W, moderate 425W, and heavy 600W)

		Times to reach		**Difference to 38.5°C and:**		**Difference to 39°C and:**	
		38.5°C	**39°C**	**JSLIST**	**ACU+JSLIST**	**JSLIST**	**ACU+JSLIST**
Light work 250W	CBDU	1379	2122	-25 min	-189 min	-47 min	-137 min
	JSLIST	1270	2049				
	ACU+JSLIST	1354	2075				
Moderate work 425W	CBDU	641	882	-9 min	-26 min	-13 min	-44 min
	JSLIST	632	869				
	ACU+JSLIST	615	838				
Heavy work 600W	CBDU	408	535	-8 min	-26 min	-10 min	-26 min
	JSLIST	400	525				
	ACU+JSLIST	387	509				
		38.5°C	**39°C**	**Difference to 38.5°C and:**		**Difference to 39°C and:**	
				JSLIST +Armor	**ACU+JSLIST +Armor**	**JSLIST +Armor**	**ACU+JSLIST +Armor**
Light work 250W	CBDU+Armor	1270	2049	-74 min	-157 min	-81 min	-173 min
	JSLIST+Armor	1196	1968				
	ACU+JSLIST+Armor	1113	1876				
				JSLIST +Armor	**ACU+JSLIST +Armor**	**JSLIST +Armor**	**ACU+JSLIST +Armor**
Moderate work 425W	CBDU+Armor	626	857	-13 min	-25 min	-21 min	-43 min
	JSLIST+Armor	613	836				
	ACU+JSLIST+Armor	601	814				
				JSLIST +Armor	**ACU+JSLIST +Armor**	**JSLIST +Armor**	**ACU+JSLIST +Armor**
Heavy work 600W	CBDU+Armor	394	519	-8 min	-15 min	-13 min	-25 min
	JSLIST+Armor	386	506				
	ACU+JSLIST+Armor	379	494				

Tables 15 and 16 provide additional comparisons as a metric of overall predicted performance; where each section shows a relative calculation for the rate of T_c rise by the time to reach a given threshold (38.5 and 39°C); where a larger rate of increase indicates a higher thermal strain. The calculation for each is based on the change in T_c from baseline divided by the time to reach a threshold. From these tables it shows that overall, the CBDU without and with armor provides lower thermal strain across the majority of cases. Table 17 shows the average rates of change for each base ensemble, where the CBDU shows collectively lower thermal strain than the other compared ensembles.

Table 15. Calculated rates of increase in T_c to reach thresholds of 38.5 and 39°C in full sun conditions

Full Sun Conditions	Clothing configuration	250W		425W		600W	
		38.5°C	39°C	38.5°C	39°C	38.5°C	39°C
70°F (21.1°C), 20%RH Mean radiant temperature (MRT): 61.1°C	CBDU	0.010	-	0.023	0.022	0.034	0.034
	CBDU+Armor	0.012	-	0.024	0.023	0.036	0.035
	JSLIST	0.011	-	0.023	0.022	0.035	0.034
	JSLIST+Armor	0.012	0.007	0.025	0.024	0.037	0.036
	ACU+JSLIST	0.012	0.007	0.025	0.024	0.037	0.036
	ACU+JSLIST+Armor	0.013	0.009	0.026	0.025	0.038	0.038
70°F (21.1°C), 95%RH MRT: 61.1°C	CBDU	0.014	0.010	0.026	0.025	0.038	0.038
	CBDU+Armor	0.014	0.011	0.026	0.026	0.039	0.040
	JSLIST	0.014	0.010	0.026	0.025	0.038	0.038
	JSLIST+Armor	0.015	0.011	0.027	0.026	0.041	0.041
	ACU+JSLIST	0.015	0.011	0.027	0.026	0.041	0.041
	ACU+JSLIST+Armor	0.015	0.012	0.028	0.027	0.042	0.043
85°F (29.4°C), 50%RH MRT: 69.4°C	CBDU	0.017	0.015	0.029	0.029	0.044	0.044
	CBDU+Armor	0.017	0.015	0.029	0.029	0.045	0.047
	JSLIST	0.017	0.015	0.029	0.029	0.045	0.047
	JSLIST+Armor	0.018	0.016	0.030	0.030	0.047	0.048
	ACU+JSLIST	0.018	0.016	0.030	0.029	0.047	0.048
	ACU+JSLIST+Armor	0.018	0.016	0.031	0.030	0.048	0.049
95°F (35°C), 35%RH MRT: 75.0°C	CBDU	0.019	0.018	0.031	0.031	0.050	0.051
	CBDU+Armor	0.020	0.018	0.032	0.032	0.052	0.054
	JSLIST	0.020	0.019	0.032	0.032	0.052	0.054
	JSLIST+Armor	0.020	0.019	0.033	0.033	0.054	0.056
	ACU+JSLIST	0.020	0.019	0.032	0.032	0.054	0.054
	ACU+JSLIST+Armor	0.020	0.019	0.033	0.033	0.054	0.056
95°F (35°C), 75%RH MRT: 75.0°C	CBDU	0.022	0.022	0.036	0.036	0.063	0.067
	CBDU+Armor	0.022	0.022	0.036	0.036	0.063	0.067
	JSLIST	0.023	0.022	0.037	0.037	0.065	0.067
	JSLIST+Armor	0.023	0.022	0.036	0.037	0.063	0.067
	ACU+JSLIST	0.022	0.022	0.036	0.036	0.063	0.067
	ACU+JSLIST+Armor	0.022	0.022	0.036	0.036	0.063	0.065
120°F (48.9°C), 20%RH MRT: 88.9°C	CBDU	0.025	0.026	0.042	0.043	0.079	0.083
	CBDU+Armor	0.025	0.026	0.042	0.043	0.079	0.083
	JSLIST	0.026	0.026	0.043	0.044	0.079	0.087
	JSLIST+Armor	0.026	0.026	0.043	0.044	0.079	0.087
	ACU+JSLIST	0.025	0.025	0.042	0.043	0.079	0.083
	ACU+JSLIST+Armor	0.025	0.025	0.041	0.043	0.075	0.080

Table 16. Calculated rates of increase in T_c to reach thresholds of 38.5 and 39°C in nighttime conditions

Nighttime conditions (no sun)	Clothing configuration	250W		425W		600W	
		38.5°C	39°C	38.5°C	39°C	38.5°C	39°C
70°F (21.1°C), 20%RH Mean radiant temperature (MRT): 21.1°C	CBDU	0.005	-	0.020	0.018	0.031	0.030
	CBDU+Armor	0.006	-	0.021	0.019	0.033	0.032
	JSLIST	0.005	-	0.020	0.018	0.031	0.031
	JSLIST+Armor	0.007	-	0.022	0.020	0.033	0.033
	ACU+JSLIST	0.008	-	0.022	0.020	0.033	0.033
	ACU+JSLIST+Armor	0.009	-	0.023	0.022	0.035	0.035
70°F (21.1°C), 95%RH MRT: 21.1°C	CBDU	0.009	-	0.023	0.021	0.034	0.034
	CBDU+Armor	0.010	-	0.023	0.022	0.036	0.035
	JSLIST	0.009	-	0.023	0.021	0.034	0.034
	JSLIST+Armor	0.010	-	0.024	0.023	0.036	0.036
	ACU+JSLIST	0.010	-	0.024	0.023	0.037	0.036
	ACU+JSLIST+Armor	0.012	-	0.025	0.024	0.038	0.038
85°F (29.4°C), 50%RH MRT: 29.4°C	CBDU	0.013	0.009	0.026	0.025	0.038	0.039
	CBDU+Armor	0.014	0.010	0.027	0.026	0.041	0.041
	JSLIST	0.013	0.009	0.026	0.025	0.039	0.040
	JSLIST+Armor	0.014	0.011	0.027	0.026	0.042	0.042
	ACU+JSLIST	0.014	0.011	0.027	0.026	0.042	0.042
	ACU+JSLIST+Armor	0.015	0.012	0.028	0.027	0.043	0.043
95°F (35°C), 35%RH MRT: 35.0°C	CBDU	0.016	0.013	0.028	0.028	0.043	0.044
	CBDU+Armor	0.016	0.014	0.029	0.029	0.045	0.045
	JSLIST	0.016	0.013	0.029	0.028	0.044	0.045
	JSLIST+Armor	0.017	0.014	0.029	0.029	0.047	0.048
	ACU+JSLIST	0.017	0.014	0.029	0.029	0.045	0.047
	ACU+JSLIST+Armor	0.017	0.015	0.030	0.029	0.047	0.049
95°F (35°C), 75%RH MRT: 35.0°C	CBDU	0.019	0.018	0.032	0.032	0.054	0.056
	CBDU+Armor	0.019	0.018	0.032	0.032	0.054	0.056
	JSLIST	0.019	0.018	0.032	0.032	0.054	0.056
	JSLIST+Armor	0.019	0.018	0.033	0.032	0.054	0.056
	ACU+JSLIST	0.019	0.018	0.032	0.032	0.054	0.056
	ACU+JSLIST+Armor	0.019	0.018	0.033	0.032	0.054	0.056
120°F (48.9°C), 20%RH MRT: 48.9°C	CBDU	0.022	0.022	0.037	0.037	0.065	0.069
	CBDU+Armor	0.022	0.022	0.037	0.037	0.065	0.069
	JSLIST	0.023	0.022	0.038	0.038	0.068	0.071
	JSLIST+Armor	0.023	0.023	0.038	0.038	0.068	0.071
	ACU+JSLIST	0.023	0.022	0.037	0.038	0.065	0.069
	ACU+JSLIST+Armor	0.022	0.022	0.037	0.037	0.065	0.069

Table 17. Overall comparison of rates of T_c change for each base ensemble

Conditions	Clothing configuration	250W		425W		600W		Total Average
		38.5°C	39°C	38.5°C	39°C	38.5°C	39°C	
Full Sun Conditions	CBDU	0.0178	0.0182	0.0312	0.0310	0.0513	0.0528	0.0337*
	JSLIST	0.0183	0.0184	0.0315	0.0315	0.0523	0.0543	0.0344
	ACU+JSLIST	0.0185	0.0184	0.0317	0.0315	0.0523	0.0545	0.0345
Nighttime conditions (no sun)	CBDU	0.0140	0.0155	0.0277	0.0268	0.0442	0.0453	0.0289*
	JSLIST	0.0145	0.0160	0.0282	0.0275	0.0457	0.0463	0.0297
	ACU+JSLIST	0.0142	0.0155	0.0280	0.0270	0.0450	0.0462	0.0293

Limitations / Discussion:

Choosing a T_c limit is not a precise process. Heat acclimatization, physical fitness, natural selection, and lower skin temperatures all affect individual tolerance for higher T_c prior to heat exhaustion (17). Since T_c thresholds of both 38.5 and 39°C are not absolute markers for when heat exhaustion or heat stroke will occur, these graphs provide a broader picture of relative thermal burden associated with these ensembles. Additionally, improvements to methodology continue, there are still several limitations to HSDA. More inclusive data is currently being sought within a military context; specifically to improve upon previously underrepresented samples of females, differences in ages, body morphologies, or for different fitness levels (18-30). More advancements to methods or more sophisticated models (31-38) like these can have larger future implications specific to climate change and increased risks of thermal injuries (39-45).

Conclusions

For the environments and work rates used as inputs to these HSDA simulations, the UIPE CBDU with and without armor provides less thermal burden than the comparison ensembles (JSLIST and ACU+JSLIST with and without armor). The UIPE CBDU compared to others had 1 time out of 144 scenarios (36 simulations for each threshold 38.5 and 39.0°C both full sun and nighttime (36 x 2 x 2)) where it performed 1 minute less than the ACU+JSLIST (representing 0.7% of these scenarios), 40 times where it was the same predicted time (representing 27.8% of occurrences), and the remaining 103 (71.5%) performing better. The CBDU+Armor compared to others had 8 times out of the 144 where it performed 1 minute less than the ACU+JSLIST+Armor (representing 5.6% of these scenarios), one time where it performed 2 minutes less than the ACU+JSLIST+Armor (representing 0.7% of these scenarios), 24 times (16.7%) where it was the same predicted time, and 111 (77.1%) where it performed better. It is important to note that these small differences (e.g., 1-2 minutes) can be seen as less operationally significant. These results indicate the UIPE CBDU, in both armored and non-armored configurations, can be expected to impose a lower thermal burden than that of either JSLIST or ACU+JSLIST.

The CBDU uniform meets the threshold requirement for UIPE FoS General Purpose KSA #4. **The UIPE FoS General Purpose Key System Attribute (KSA) #4 for physiological performance states:** *"…The UIPE FoS GP will reduce the wearer's physiological load compared to JSLIST (T), equal to the standard duty uniform (O) when worn in Mission-Oriented Protective Posture (MOPP) 2/MOPP 3 (Afloat) and MOPP 4 (with and without body armor and helmet)…".*

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