



**U.S. Army
Research Institute of
Environmental Medicine**

Natick, Massachusetts

TECHNICAL REPORT NO. T23-009

DATE September 2023

**EVALUATION OF THREE COLD WEATHER ENSEMBLES WITH
A HEATED BASE LAYER AT -20°C USING A THERMAL
MANIKIN WITH DYNAMIC HEAT FLUX SENSORS**

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USARIEM TECHNICAL REPORT T23-009

**EVALUATION OF THREE COLD WEATHER ENSEMBLES WITH A HEATED BASE
LAYER AT -20°C USING A THERMAL MANIKIN WITH DYNAMIC HEAT FLUX
SENSORS**

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September 2023

U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

REPORT DOCUMENTATION PAGE

1. REPORT DATE 20230919		2. REPORT TYPE Technical Report		3. DATES COVERED	
				START DATE 20220101	END DATE 20230731
4. TITLE AND SUBTITLE EVALUATION OF THREE COLD WEATHER ENSEMBLES WITH A HEATED BASE LAYER AT -20°C USING A THERMAL MANIKIN WITH DYNAMIC HEAT FLUX SENSORS					
5a. CONTRACT NUMBER		5b. GRANT NUMBER		5c. PROGRAM ELEMENT NUMBER	
5d. PROJECT NUMBER		5e. TASK NUMBER		5f. WORK UNIT NUMBER	
6. AUTHOR(S) Xiaojiang Xu, Ph.D., Meredith McQuerry, Ph.D., Maddy Bogan, MSc, Juliette I. Jacques, B.Sc., Timothy Rioux, B.Sc., Julio A Gonzalez, B.Sc., Reed W. Hoyt, Ph.D.					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Thermal & Mountain Medicine Division, Military Nutrition Division US Army Research Institute of Environmental Medicine ThermaNOLE Comfort Lab®, Florida State University				8. PERFORMING ORGANIZATION REPORT NUMBER T23-009	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The goal of this project was to determine the efficacy and performance of a heated clothing system when it is used with three Air Warrior ensembles at different environmental conditions. The baseline thermal properties of the heated base-layer (heat off), and three Air Warrior ensembles (each worn over the unpowered base layer) were measured (see Xu et. al, USARIEM tech report T23-004). In the present series of tests, three Air Warrior ensembles with a heated base-layer (Human Systems Integration (HSI), East Walpole, MA) were measured to determine the heating power provided by the HSI system. The three Air Warrior ensembles were light, intermediate, and cold weather ensembles. They were tested on an ANDI thermal manikin (Thermetrics, Seattle, WA) in a -20°C environment while the active heating system was turned on at power levels of low, medium, and high. The heat gains, i.e., the heat from the HSI heated layer to the manikin, ranged from approximately 25 W to 48 W. This heat was distributed to four body regions: torso, thighs, hands, and feet.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	unclassified		21

19a. NAME OF RESPONSIBLE PERSON

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INSTRUCTIONS FOR COMPLETING SF 298**1. REPORT DATE.**

Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

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Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER.

Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

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5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER.

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).

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11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

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ACKNOWLEDGMENTS

The authors would like to thank Richard Luechtefeld, Lead Systems Engineer and Product Manager, Air Warrior, for his support of this project. The authors would like to thank Drs. Nisha Charkoudian and John Castellani and the Military Operational Medicine Environmental Health Protection program for their support of this project.

EXECUTIVE SUMMARY

The goal of this project was to determine the efficacy and performance of a heated clothing system when it was used with three Air Warrior ensembles at different environmental conditions. The baseline thermal properties of the heated base-layer (heat off), and three Air Warrior ensembles (each worn over the unpowered base layer) were measured (see Xu et. al, USARIEM tech report T23-004). In the present series of tests, three Air Warrior ensembles with a heated base-layer (Human Systems Integration (HSI), East Walpole, MA) were measured to determine the heating power provided by the HSI system. The three Air Warrior ensembles were light, intermediate, and cold weather ensembles. They were tested on an ANDI thermal manikin (Thermetrics, Seattle, WA) in a -20°C environment while the active heating system was turned on at power levels of low, medium, and high. The heat gains, i.e., the heat from the HSI heated layer to the manikin, ranged from approximately 25 W to 48 W. This heat was distributed to four body regions: torso, thighs, hands, and feet.

INTRODUCTION

The overarching goal of this project was to determine the efficacy of heated clothing when various ensembles are worn at different environmental conditions. The ThermaNOLE Comfort Lab® in the Jim Moran College of Entrepreneurship at Florida State University evaluated the thermal performance of four ensembles in collaboration with USARIEM and Human Systems Integration (HSI) (East Walpole, MA) (www.humansystemsintegration.com). The ensembles include a heated base layer (HSI base layer), and three Air Warrior ensembles (light, intermediate, and cold weather ensembles). The baseline information of these four ensembles (heat off), i.e., regional and whole body thermal and evaporative resistances, was measured and reported (1). The HSI base layer system was expected to deliver heating power at three power levels: low power, medium power, and high power. The efficacy of heated clothing depends on the outer garments and the environmental conditions (2-5). Thus, heating efficacy of the HSI base layer (heat on) worn underneath each of the three Air Warrior ensembles was tested on the advanced dynamic sweating thermal manikin (ANDI) at a chamber temperature of -20°C . This report describes the samples tested, procedures used, and the results collected from the laboratory tests.

METHODS

SAMPLE DESCRIPTION

Three individual ensembles worn over a HSI heated base layer were tested on an ANDI thermal manikin (Thermetrics, Seattle, WA; <https://thermetrics.com/products/manikin/andi/>), as detailed in Table 1 below. Each ensemble was tested for thermal resistance per ASTM F1291 (6), with modified environmental conditions. The garments and accessories worn for each ensemble are summarized in Table 1. More specific ensemble element details can be found in the “Cold Weather Clothing Ensemble Matrix” shown in Appendix A. Three replicate tests

were performed on each ensemble for dry (thermal resistance) in a static state (manikin standing; 0.4 m/s air speed).

Table 1. Test Ensembles

Ensembles	Ensemble Elements*
HSI Heated Base Layer System	Heated long sleeve thermal shirt, heated long thermal drawers, vest, heated glove liner, heated boot liner, socks, Army combat boots
Light Ensemble	Short sleeve undershirt, briefs, long sleeve thermal undershirt, long thermal drawers, Army Aircrew Combat jacket, Army Aircrew Combat trouser, Riggers belt, socks, Army combat boots, HGU-56/P helmet, Flyers' glove GS/FRP-2, HANZ glove liner
Intermediate Ensemble	Short sleeve undershirt, briefs, long sleeve thermal undershirt, long thermal drawers, Army Aircrew Combat jacket, Army Aircrew Combat trouser, Riggers belt, Intermediate Weather Outer Layer Jacket, socks, Army combat boots, LPH hood, HGU-56/P helmet, Flyers' glove GS/FRP-2, HANZ glove liner
Cold Weather Ensemble	Short sleeve undershirt, briefs, long sleeve thermal undershirt, long thermal drawers, Army Aircrew Combat jacket, Army Aircrew Combat trouser, Riggers Belt, midweight insulated shirt, midweight insulated drawers, Intermediate Weather Outer Layer Jacket, Intermediate Weather Outer Layer pants, socks, cold weather combat boots, LPH hood, HGU-56/P helmet, HAU 15/P Intermediate Flyer's Glove, HANZ glove Liner

*HSI Heated Base Layer System: Human Systems Integration, Inc., Waltham, MA. TacHEAT heated base layer system. The Light, Intermediate and Cold Weather Ensembles correspond to current Air Warrior clothing and individual equipment configurations.

ANDI SWEATING THERMAL MANIKIN SYSTEM

An “ANDI” instrument is an articulated, 35-zone, carbon epoxy, dynamic heat flux, sweating thermal manikin system designed to evaluate heat and moisture management properties of clothing systems. This instrument simulates heat and sweat production making it possible to assess the influence of clothing on the thermal comfort process for a given environment. Simultaneous heat and moisture transport through the

clothing system, and variations in these properties over different parts of the body can be quantified. The manikin consists of several features designed to work together to evaluate clothing comfort and/or heat stress. It should be noted, the sweating system was not utilized for this phase of thermal insulation testing.

ANDI is uniquely different from other sweating thermal manikin models as ANDI incorporates dynamic heat flux sensors and an internal active cooling system to allow for positive and negative heat flux measurements (heat gained and lost) in high ambient temperature environments or with the addition of heated power or radiant loads. Housed in a climate-controlled chamber (Figure 1), the manikin surface is divided into 35 separate sections, each of which has its own sweating, heating, and temperature measuring system.

For this testing, the manikin was operated in temperature control mode in which the skin temperature of the manikin surface in all 35 zones was set to 35°C and the heat flux required to maintain the skin temperature at the fixed setpoint was measured. With the addition of external heating in localized zones applied by the HSI base layer, body regions were not isothermal and therefore the dynamic heat flux (HF) sensors unique to ANDI were utilized in the first round of this testing (HF_{measured}). These sensors measure both positive (losing heat to the environment) and negative (gaining heat from the environment) heat fluxes. When applying external heating, the surface of traditional manikins (e.g., Newton, Thermetrics, Seattle, WA) will overheat, the heaters will turn off, and the manikin “coasts” until the regulation system regains control following the heat exposure. The active cooling system provides continuous energy removal from the manikin via embedded fluid channels and an external chiller system (Figure 1), which allows the manikin to remain in-control at a fixed skin temperature setpoint during sustained negative heat fluxes. ANDI is therefore capable of measuring negative heat flux (manikin gaining heat from environment).

In the second round of this testing, all measurements were repeated without the active cooling technology, or backside cooling. This repeat round of testing was conducted using the heat flux generated (HFG) device map such that HFG was

calculated, per traditional standard methods, as opposed to being determined directly from the dynamic heat flux sensors.

Continuous temperature control for the 35 body segments is accomplished by a process control unit that uses analog signal inputs from separate Resistance Temperature Detectors (RTDs). These evenly distributed RTDs are used instead of point sensors because they provide temperature measurements in a manner such that all areas are equally weighted. Distributed over an entire section, each RTD is embedded just below the surface and provides an average temperature for each section. Software establishes any discrepancy between temperature set point and the input signal and adjusts power to section heaters as needed. Temperature controls are adjustable, by the operator, for each heater control. Figure 2 illustrates the 35 zones of the ANDI model.

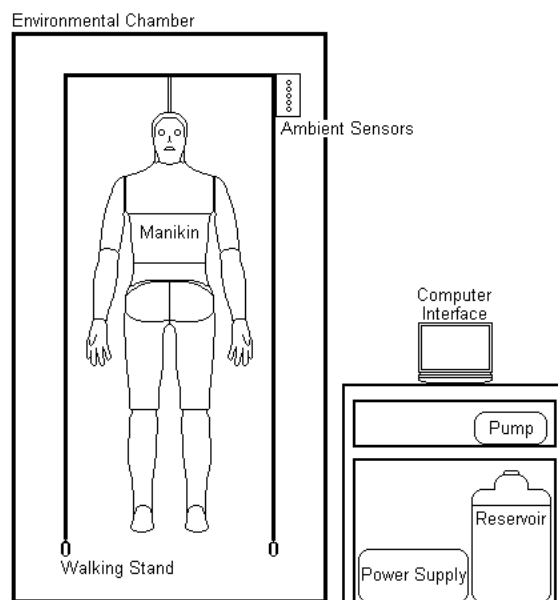


Figure 1. Test Apparatus Setup

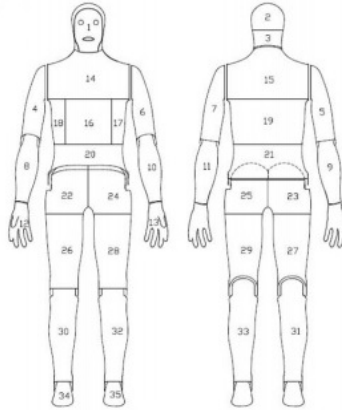


Figure 2. A schematic of the 35 Zone ANDI Manikin

TESTING PROCEDURES

The test consisted of two parts: 1) determination of the thermal resistances; and 2) determination of the heating powers of the HSI heated layer with three ensembles (this test was conducted without the backside cooling running). The first phase of testing determined the thermal resistance (R_t) of three cold weather warfighter ensembles worn with a heated base layer underneath, powered at various heat levels (no power, low, medium, high) at ambient conditions of -20°C and 50-65% RH. The thermal resistance of each ensemble was measured utilizing the temperature control mode with the manikin surface temperature set to 35°C . The dynamic heat flux sensors and active cooling system were utilized in the first round of testing to measure both positive (heat loss) and negative (heat gain) heat flux. Due to the large differences in thermal insulation provided by the clothing ensembles and the heated power levels (W), the manikin voltage and chiller temperature had to be adjusted as the ensembles increased in insulation and power level (medium and high), to avoid overheating the sensors in the HSI heated zones. Furthermore, intrinsic thermal resistance (R_{ci}) and thermal resistance in clo unit (I_t) were also calculated.

Tests for thermal resistance occurred under non-isothermal environmental conditions of $-20^{\circ}\text{C}/50\text{-}65\%$ relative humidity and 0.4 m/s air velocity. Three repetitions

were completed for each ensemble configuration, at each power level (unpowered, low, medium, and high power) for a total of 12 tests. For the unpowered test, the manikin was allowed to reach steady state and remained for 30 minutes of data to be collected. To capture the heat benefits of each power level, the change in surface temperature, dynamic heat flux, and calculated R_{ct} were measured for the first 30 minutes after powering up to each level (low, medium, and high). The average of the three repetitions at each power level was calculated for each parameter, with the manikin redressed in between each repetition.

Tests for the heating power (without backside cooling) occurred under non-isothermal conditions of $-20^{\circ}\text{C}/50\text{-}80\%$ relative humidity, and 0.4 m/s air velocity environment. Three repetitions were completed for each garment configuration, at each power level (unpowered, low, medium, and high power) for a total of 12 tests. For the unpowered test, 30 minutes of steady state data was collected. To capture the heat benefits of each power level, the change in surface/skin temperature, dynamic heat flux, and calculated R_{ct} were measured for the first 30 minutes after powering up to each level (low, medium, and high). The average of the three repetitions at each power level was calculated for each parameter, with the manikin redressed in between each repetition.

DATA ANALYSIS

In addition to thermal resistances, the data was used to determine the heat gain, i.e., the heat that the manikin takes from the heated clothing. A MATLAB tool was developed and used to analyze the data and determine the heating power. As shown in **Figure 3**, the raw data file can be selected and imported. Then, the regions in relevant areas are selected to calculate the regional heating power. In addition, a period with stable data is selected to calculate the average regional heating power during this stable period. The regional heating power for torso, leg, hand, and foot were calculated as follows:

Torso: R Shoulder, L Shoulder, Chest, Stomach, Upper Back, Lower Back

Leg: R Up Thigh Fr, R Up Thigh Bk, L Up Thigh Fr, L Up Thigh Bk, R Lwr Thigh Fr,
R Lwr Thigh Bk, L Lwr Thigh Fr, L Lwr Thigh Bk
Hand: R Hand, L Hand
Foot: R Foot, L Foot

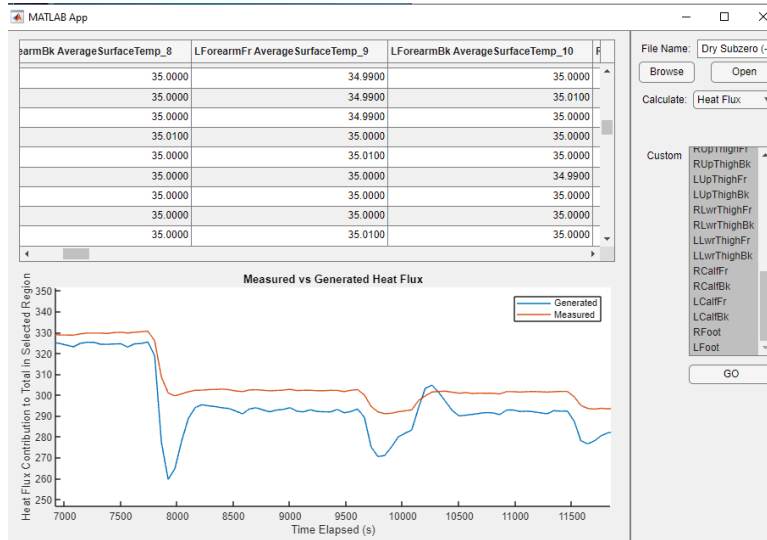


FIGURE 3. MATLAB tool to calculate heating power.

RESULTS

The average values for three replicate tests for R_t , R_{cl} , and I_t (clo) for each warfighter ensemble at -20°C are reported in **Table 2**. Values were calculated first using HF_{measured} from the tests with backside cooling and second using $HF_{\text{generated}}$ from the tests that did not run with backside cooling.

Table 2 Average R_t , R_{cl} , and I_t (clo) in -20C, 65%RH; Standing; Calculated using HFM and HFG.

Ensemble	Power Level	Heat Flux Measured			Heat Flux Generated		
		R_t	R_{cl}	I_t	R_t	R_{cl}	I_t
		m ² K/W	m ² K/W	Clo	m ² K/W	m ² K/W	clo
Light Ensemble	None	0.2614	0.0213	1.69	0.2565	0.0144	1.65
	Low	0.2793	0.0374	1.80	0.2761	0.0327	1.78
	Med	0.2873	0.0445	1.85	0.2848	0.0407	1.84
	High	0.2935	0.0499	1.89	0.2897	0.0451	1.87
Intermediate Ensemble	None	0.3058	0.0659	1.97	0.3063	0.0638	1.98
	Low	0.3312	0.0895	2.14	0.3305	0.0862	2.13
	Med	0.3411	0.0983	2.20	0.3373	0.0924	2.18
	High	0.3501	0.1065	2.26	0.3435	0.0982	2.22
Cold Weather Ensemble	None	0.4548	0.2141	2.93	0.4443	0.2015	2.87
	Low	0.5028	0.2596	3.24	0.5032	0.2588	3.25
	Med	0.5138	0.2697	3.31	0.5145	0.2691	3.32
	High	0.5204	0.2759	3.36	---	---	---

Figure 4 is an example of typical results from this study and shows how the heating power of the HSI heated layers are determined. After the manikin reached steady state at ~120 min, the HSI heated layer was turned on at the “low” level. As a result, the manikin power needed to maintain a constant manikin surface temperature was reduced and the manikin reached steady state once again. The difference in manikin power is the heating power of the HSI heated layer at the low power level. Similarly, the heating powers at medium and high levels were determined.

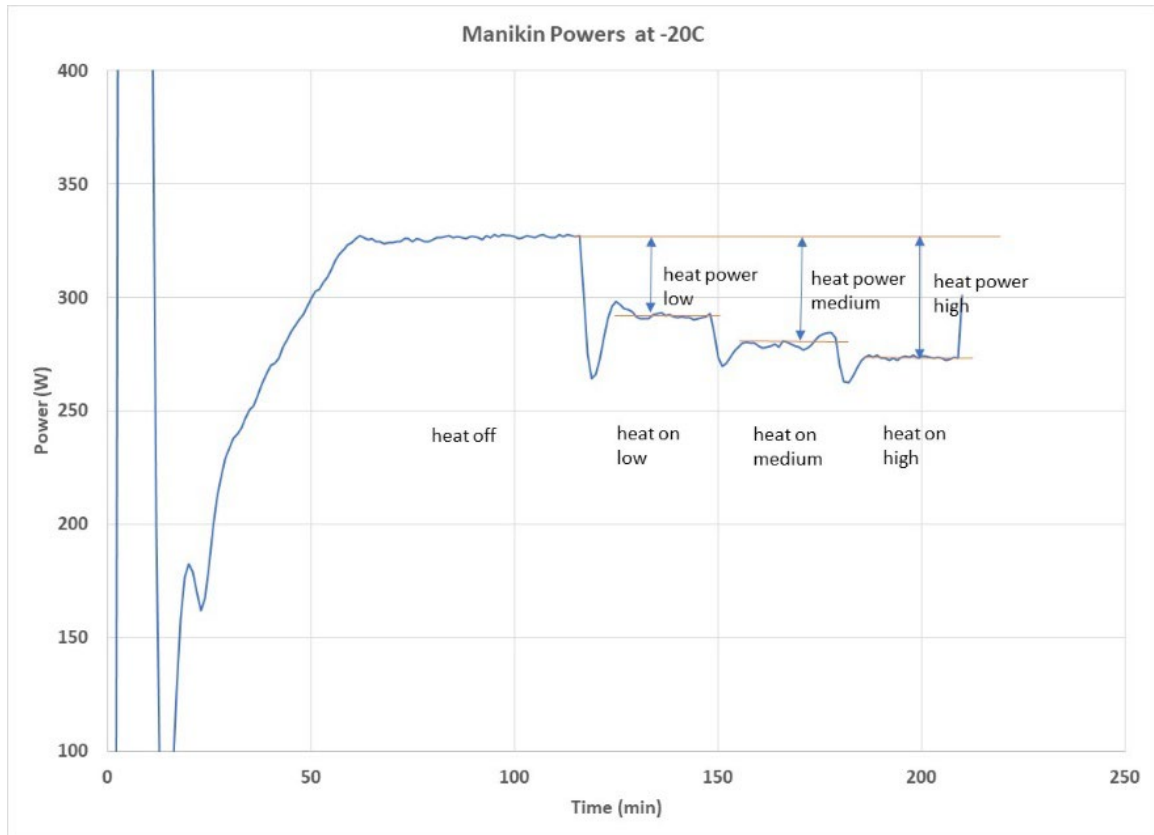


Figure 4. Manikin power (heat flux) changes and determination of the heating power of the HSI heated base layer.

Table 3 contains the values of regional and whole-body heating powers (W) of the HSI heated base layer, calculated from the manikin’s “heat flux generated” value when no backside cooling was running. The whole-body values are the sum of the four regional values. The light and intermediate ensembles were tested three times. The values in Table 3 are the average of three measurements. The cold weather ensemble was tested only one time due to overheating limitations when backside cooling was not running. For the heating powers of the foot, empty indicates that no measurements were taken.

The HSI heated base layer was connected to a power supply system, the current and voltage were around 2.9 amp and 28 V at the high power level. Thus, the whole-body heating power was about 81 W at the high power level.

Table 3. Regional and Total Heating Power (W)

Light Ensemble	Torso	Legs	Hand	Foot	Whole Body (total)
Low	9.7	13.6	4.3	0.5*	28.1
Medium	14.1	18.5	5.8	0.9*	39.2
High	18.0	22.8	7.0	-0.1*	47.8
Intermediate Ensemble					
Low	10.1	10.5	4.5		25.1
Medium	14.0	11.4	6.0		31.4
High	18.1	14.2	7.5		39.8
Cold Weather Ensemble*					
Low	10.1	12.6	4.5	1.2	28.4
Medium	13.9	17	6.2	0.6	37.7
High	17.1	21.9	7.6		46.6

* only one measurement; empty: no measurement

DISCUSSION

Heated clothing and individual equipment (CIE) with active heating are needed to provide the level of thermal protection necessary for training and deployment in extreme cold conditions. Providing adequate thermal protection for vulnerable hands and feet is of particular concern. An added benefit to heated CIE is that pilots and other personnel needing high levels of dexterity to perform their jobs can also benefit from the use of heated CIE which may reduce the need for cumbersome passive insulation layers.

The insulation values in **Table 2** are effective insulation, not clothing insulation. Effective insulation increases when the power was turned on and the power level increases from low to high. The reason is that the heated power from the base layer reduces the manikin power, and results in insulation increase. At the high power level, effective insulation increases by 6, 12 and 15% for the light, intermediate and cold weather ensembles, respectively. The increase in effective insulation indicates that the HSI heated layer may potentially allow for the reduction of clothing layers in the ensemble while maintaining the same insulation.

The manikin heating powers in Table 3 show that the HSI base layer provides between 25 to 48 W of heat to the body. The remaining heat from the HSI base layer

dissipates to the environment at rates that vary with air temperature (4, 7). The power supplied to the HSI base layer was ~81 W at high power level. The regional heating powers in Table 3 show that the heating power distributions were not even. Heating requirements of body regions and its effectiveness varied with body regions. For example, analyzing the results with a simulation of human thermoregulation showed that the hand, foot, and torso required 20 W, 40 W and > 55 W respectively to provide protection in -40°C environments (7). Previous studies showed clearly that hand or foot heating are beneficial and energy efficient (3, 7, 8), but demonstrated seemingly inconsistent results about whether or not heating the torso in addition to heating the extremities is beneficial (3, 8). A recent study demonstrated that heating the forearm is beneficial to hand performance (9). Given the fact that power supplies are always limited in practical scenarios, the HSI heating controller should have options for different scenarios to ensure that the limited heating power can be utilized effectively and efficiently.

As to the foot heating power, HSI have had to reduce the power to foot due to user feedback during HSI user evaluations (Allan Neville, private communication). However, the foot heating power is minimal as shown in Table 3. Many potential factors may likely contribute to this. The foot region was the only area of the HSI garment system that was not worn directly next to the skin. It attached to the pants in such a way that it had to be worn outside the sock, placing it between the sock and the boot. All other layers, including the glove liners, were worn directly against the manikin surface. The HSI heating controller might not be functioning properly during this test at -20°C without backside cooling and delivered only a small amount or no heating to the foot region. It is necessary to analyze the results at 0 and -10°C with backside cooling on to see if the HSI controller functioned properly.

The basis for calculating clothing insulation using a thermal manikin is the heat balance principle (10, 11). Most thermal manikins measure only two primary parameters: power input and manikin surface temperature. At a state of thermal equilibrium, the power supplied to a thermal manikin is equal to heat loss, making it possible to derive the remaining measurement parameters (i.e., thermal and

evaporative resistances, heating or cooling powers). New features of the ANDI thermal sweating manikin are the inclusion of heat flux sensors and a backside cooling system. The heat flux sensors measure the heat flow on the manikin surface. The relationship between the backside cooling, the heat fluxes measured on the manikin skin surface, and the heated garment are not fully understood yet. Thus, in the tests of HSI heating powers, the backside cooling was turned off. When the backside cooling is off, the $HF_{\text{generated}}$ are expected to be the same as the HF_{measured} . However, total powers determined from $HF_{\text{generated}}$ and from HF_{measured} are slightly different during some tests, as shown in **Figure 3**. Further research is required to understand the new features of the ANDI manikin and to use the new features in a sensible manner for testing heated clothing. To ensure that the result is consistent with the manikin without backside cooling, the heat generated were used to determine the heat gain shown in Table 2.

The heating efficiency was not determined from this study as the regional powers were not measured during the manikin tests. The heating efficiency is defined as the ratio of the heat gain to the power. The efficiency is expected to decrease as the ambient temperature reduces and temperature gradient increases. A heated glove was effective at 0°C environment and was essentially ineffective at -18°C environment (5). In other words, heated clothing will be only effective at certain environmental conditions.

REFERENCES

1. Xu X, McQuerry M, Bogan M, Jacques JI, Rioux T, Gonzalez J, et al. Thermal Properties of Three Cold Weather Ensembles and An Unpowered Heated Base Layer Ensemble. Natick, MA: US Army Research Institute of Environmental Medicine; 2023 March. Report No.: USARIEM T23-005.
2. Xu X, Endrusick T, Laprise B, Santee W, Kolka M. Efficiency of liquid cooling garments: prediction and manikin measurement. *Aviat Space Environ Med.* 2006;77(6):644-8.
3. Hickey Jr CA, Woodward Jr AA, Hanlon WE. A pilot study to determine the thermal protective capability of electrically heated clothing and boot inserts. ARMY RESEARCH LAB ABERDEEN PROVING GROUND MD; 1993.
4. Wang F, Lee H. Evaluation of an electrically heated vest (EHV) using a thermal manikin in cold environments. *Ann Occup Hyg.* 2010;54(1):117-24.

5. Santee WR, Mullen SP, Laprise BS, Blanchard LA. An Evaluation of Prototype Electrically Heated Handwear. Natick, MA: U.S. Army Research Institute of Environmental Medicine; 1999. Report No.: ADA363276.
6. ASTM International. Standard test method for measuring the thermal insulation of clothing using a heated manikin (ASTM F1291). West Conshohocken, PA: 2022.
7. Rioux T, D'Angelo P, Hirst E, Castellani MP, Xu X. Determining Energy Requirements For Heated Clothing and Individual Equipment Using Manikin and Modeling Methods. Natick, MA; 2022. Report No.: USARIEM Technical Report T 22-14. AD1179652.
8. Brajkovic D, Ducharme MB, Frim J. Influence of localized auxiliary heating on hand comfort during cold exposure. *J Appl Physiol* (1985). 1998;85(6):2054-65.
9. Castellani JW, Yurkevicius BR, Jones ML, Driscoll TJ, Cowell CM, Smith L, et al. Effect of localized microclimate heating on peripheral skin temperatures and manual dexterity during cold exposure. *J Appl Physiol* (1985). 2018;125(5):1498-510.
10. Xu X, Endrusick TL, Gonzalez J, Santee WR, Hoyt RW. Comparison of parallel and serial methods for determining clothing insulation. *Journal of ASTM International*. 2008;5(9).
11. Xu X, Gonzalez J, Karis A, Rioux T, Potter A. Use of Thermal Mannequins for Evaluation of Heat Stress Imposed by Personal Protective Equipment. *Performance of Protective Clothing and Equipment: 10th Volume, Risk Reduction Through Research and Testing*. West Conshohocken, PA: ASTM International; 2016.

APPENDIX A: Test Ensemble Photos (as dressed and tested on ANDI)



Light Ensemble with HSI system



Intermediate Ensemble with HSI system.



Cold Weather Ensemble with HSI system