Personal Cooling Systems

Different personal cooling systems (PCS) were selected for testing based on the work completed in Phase I of the project and based on directives from Project Manager Soldier and Equipment. These systems are described by type in Table 1, detailed descriptions are given in Appendix A-L, and photographs of them on the manikin are shown in Figures 3-18. Each PCS was evaluated as part of the basic military ensemble which consisted of the Army lightweight desert combat uniform (DCU) with belt, underwear briefs, T-shirt, Kevlar® helmet with internal pads, socks, and athletic shoes. A vinyl vest was made that covered the same parts of the body as the interceptor body armor (IBA) – outer tactical vest (OTV) with enhanced small arm protective insert plates (ESAPI), deltoid auxiliary protection system (DAPS), and enhanced side ballistic inserts (ESBI). The body armor was not used on the manikin because of its weight. The vinyl vest stopped evaporative heat transfer from occurring where the body armor would.

Methodology

The cooling effectiveness of the personal cooling systems was measured according to ASTM F 2371, Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin (ASTM, 2005).

Apparatus

The insulation values and evaporative resistance values for the clothing systems were measured using an electrically-heated manikin in thermal equilibrium with its surroundings. The manikin at Kansas State University – STAN – consists of a shell formed to simulate the physical shape and size of a typical man (i.e., 1.80 m^2 surface area, 177.2 cm height). The manikin consists of 20 independently heated thermal zones (see Figure 1), with an additional fluid heater inside the manikin. All thermal zones are fit with heaters to simulate metabolic heat output rates and distributed wire sensors for measuring temperature. A chart describing the body segments (zones) and their surface areas is shown in Table 2.

The power cables, measurement cables, fluid supply tubes, and fluid return tubes connect to his face. A photograph of the manikin in his sweating suit is shown in Figure 2. The entire system is computer operated. The ThermDAC control software is a 32-bit Windows based program that provides control capabilities, data recording, and real-time numerical and graphical displays of section temperatures.

Manikin Procedures for Sweating Tests

The environmental conditions for the isothermal sweating manikin tests were controlled as follows:

- ambient air temperature, 35ºC (95ºF)
- air velocity, 0.3 m/s
- relative humidity, 40% or 26%
- manikin surface temperature, 35ºC (35ºF)

The manikin was covered with a knitted "skin" and sprayed with distilled water to simulate skin saturated with sweat (i.e., 100% skin wettedness). Then the flow rates to the manikin were adjusted so that enough water was distributed through his pores to keep the skin saturated. Two air temperature sensors and one relative humidity sensor were hung in back of the manikin at waist level about 2 ft. from the manikin. The air velocity was measured periodically using an anemometer.

Baseline test. First a baseline test was conducted on the ensemble with the PCS turned off. In the case of phase change materials, a "used" component of the PCS was tested (e.g., cartridge of water at 35°C instead of ice, etc.). To conduct a baseline test, the manikin was dressed in the PCS ensemble, and all closures were secured. The manikin was hanging from his metal stand by a hook in his head. His feet did not touch the floor because excess water runs out of small holes in his shoes during a test and pools in a tray beneath him. As soon as steady-state conditions had been reached, a 30 minute test was run. Steady-state was indicated by an evaporative resistance reading that had not changed more than 1%.

The equation for calculating the total resistance to evaporative heat transfer provided by the PCS ensemble is

$$R_{et} = \frac{(P_s - P_a)A_s}{H} \qquad (1)$$

where

R_{et} = resistance to evaporative heat transfer provided by the clothing and the boundary air layer, $m^2 \cdot Pa/W$
A_s = manikin surface area, m^2
P_s = water vapor pressure at the skin surface, Pa
P_a = the water vapor pressure in the air, Pa
H = power input, W

PCS test. Next the "heat difference" program was opened on the manikin's computer. This program quantifies the cooling rate of the PCS by subtracting the average power level during the baseline test from the power used to keep the manikin's skin temperature at 35°C when the PCS is turned on. When the program was ready, the PCS was turned on (or in the case of phase change materials, a new component was added to the PCS), and the experiment was started immediately. Data were collected for 2 hours.

Three replications of the baseline tests with the PCS turned off, followed by the heat difference test with the PCS turned on, were conducted for each type of PCS. All PCS systems were tested at 40% relative humidity – the condition specified in the standard. However, ambient air circulation systems were also tested under drier, desert conditions of 26% relative humidity.

Results

The standard defines the cooling rate as the time average of the power input to the manikin from the time the PCS was activated and data collection was started until the effective power (power to the manikin minus the baseline power level) decreased to 50 W – for a maximum test of 2 hours. However, some of the PCS we tested never reached 50 W to begin with, so we ran each test for 2

hours. We calculated the cooling rate two ways: 1) the time the system was drawing 50 W or more of power, as the standard specified, and 2) the average cooling rate over 2 hours – even though this is somewhat meaningless if a system did not cool for very long. Table 3 provides a summary of the key data measured in the manikin tests on the systems that were also evaluated on human subjects (PCS #1 – 10). Table 4 provides a summary of the data for additional PCS that were tested on the manikin. Figures 19-38 show the average graphs of cooling effectiveness for the systems.

Table 3
Cooling Effectiveness of Personal Cooling Systems Evaluated on Human Subjects

		120 Minute Test		50 Watt Cut-off Test	
PCS Name	**RH (%)**	**Cooling Effectiveness[a] (W)**	**Power Level at 120 min. (W)**	**Cooling Effectiveness[b] (W)**	**Time to 50 W cut-off (min)**
PCS #1: ClimaTech Safety ForcedAIR Vest 1 (worn over DCU shirt)	40	69.5	69.6		
PCS #1: ClimaTech Safety ForcedAIR Vest 1 (worn over DCU shirt)	26	88.3	87.7		
PCS #9: ClimaTech Safety ForcedAIR Vest 2 (worn over T-shirt and under DCU shirt)	40	225.4	225.0		
PCS #9: ClimaTech Safety ForcedAIR Vest 2 (worn over T-shirt and under DCU shirt)	26	226.8	223.3		
PCS #10: ClimaTech Safety ForcedAIR Vest 3 (worn over T-shirt and under DCU shirt)	40	109.5	109.9		
PCS #10: ClimaTech Safety ForcedAIR Vest 3 (worn over T-shirt and under DCU shirt)	26	195.3	195.9		

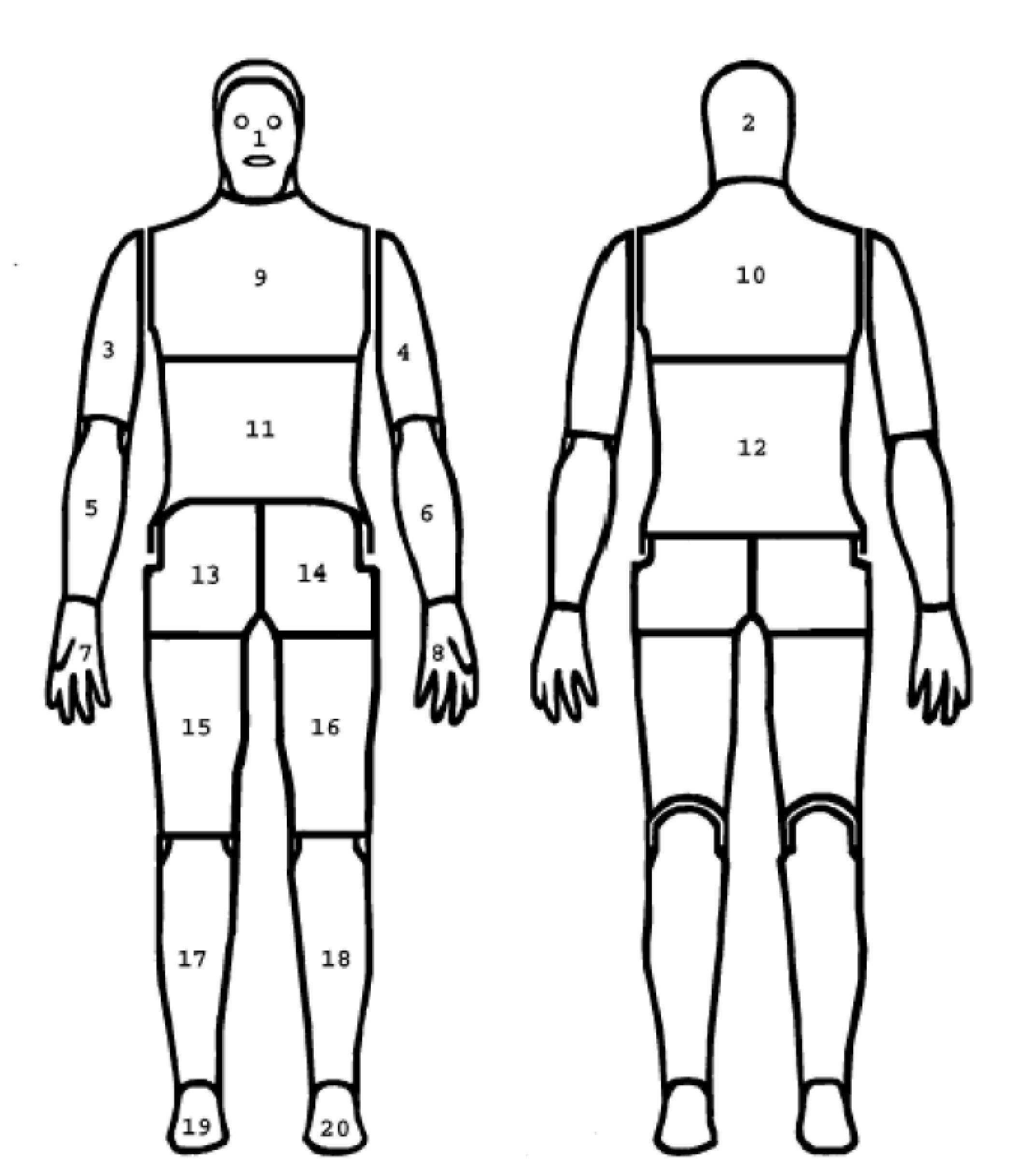

Figure 1. Manikin body segments (20).

Figure 2. Stan the manikin in his sweating skin; he is beginning to sweat in the right view.

Figure 3. PCS #1: ClimaTech Safety ForcedAIR Vest 1 worn over the DCU shirt; vinyl vest is opened in left view and not shown in right view.

Figure 10. PCS #9: ClimaTech Safety ForcedAIR Vest 2 (worn under DCU shirt).

Figure 11. PCS #10: ClimaTech Safety ForcedAIR Vest 3 (worn under DCU shirt).

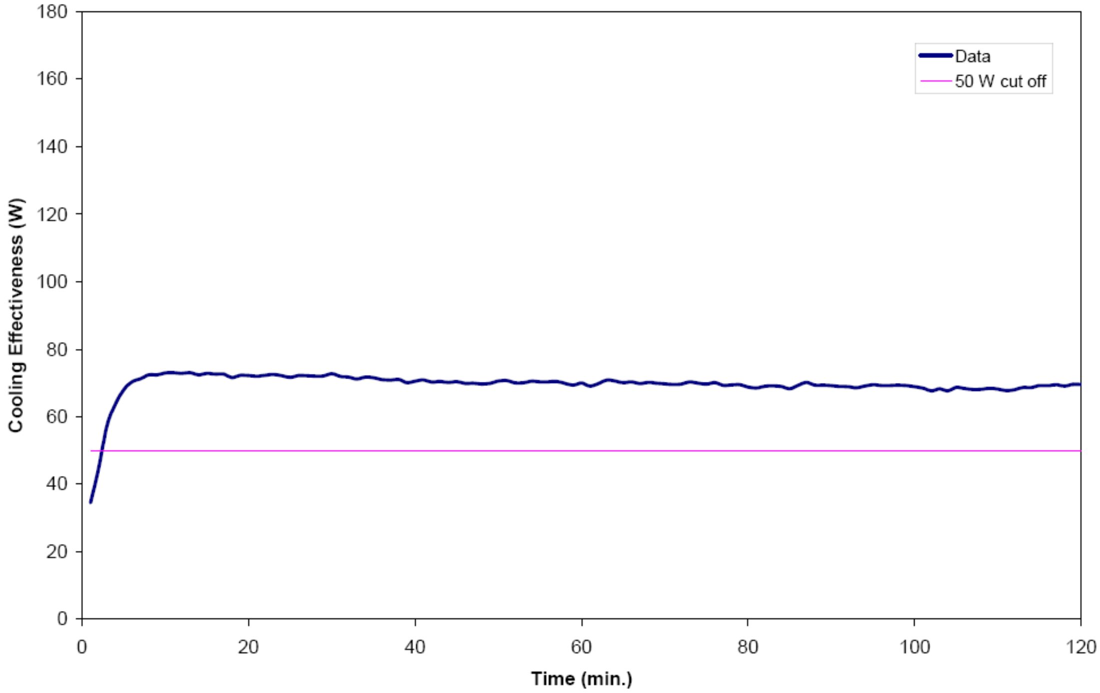

Figure 19. Cooling effectiveness of PCS #1: ClimaTech Safety ForcedAIR Vest 1 worn over DCU shirt (tested at 40% RH).

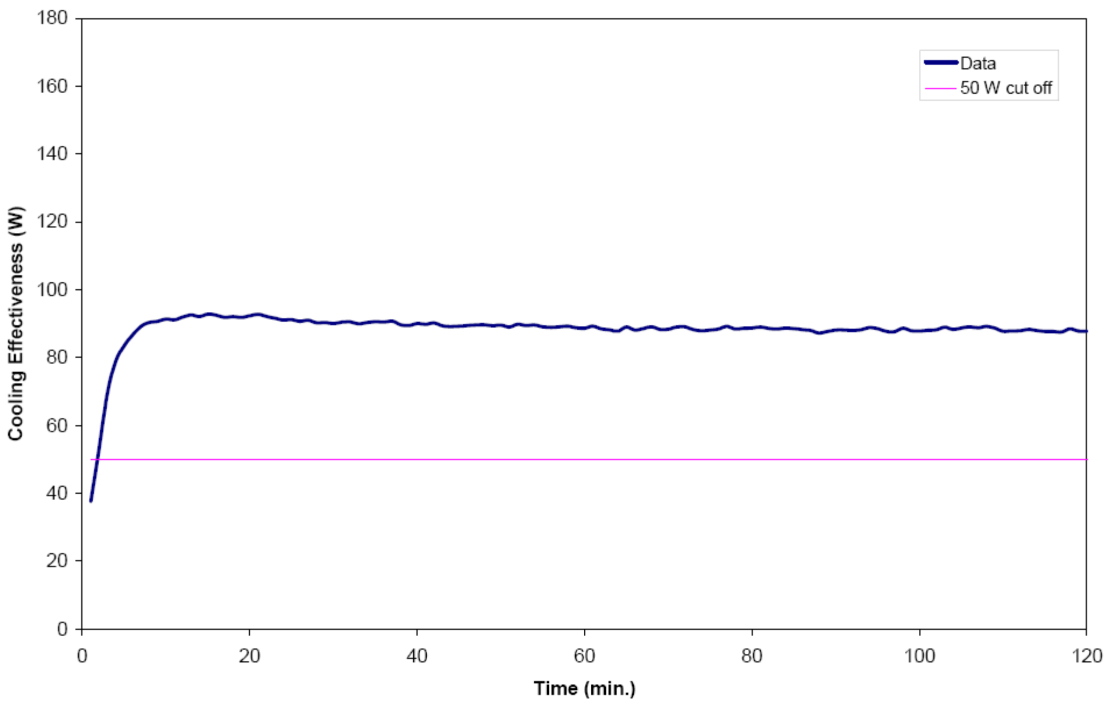

Figure 20. Cooling effectiveness of PCS #1: ClimaTech Safety ForcedAIR Vest 1 worn over DCU shirt (tested at 26% RH).

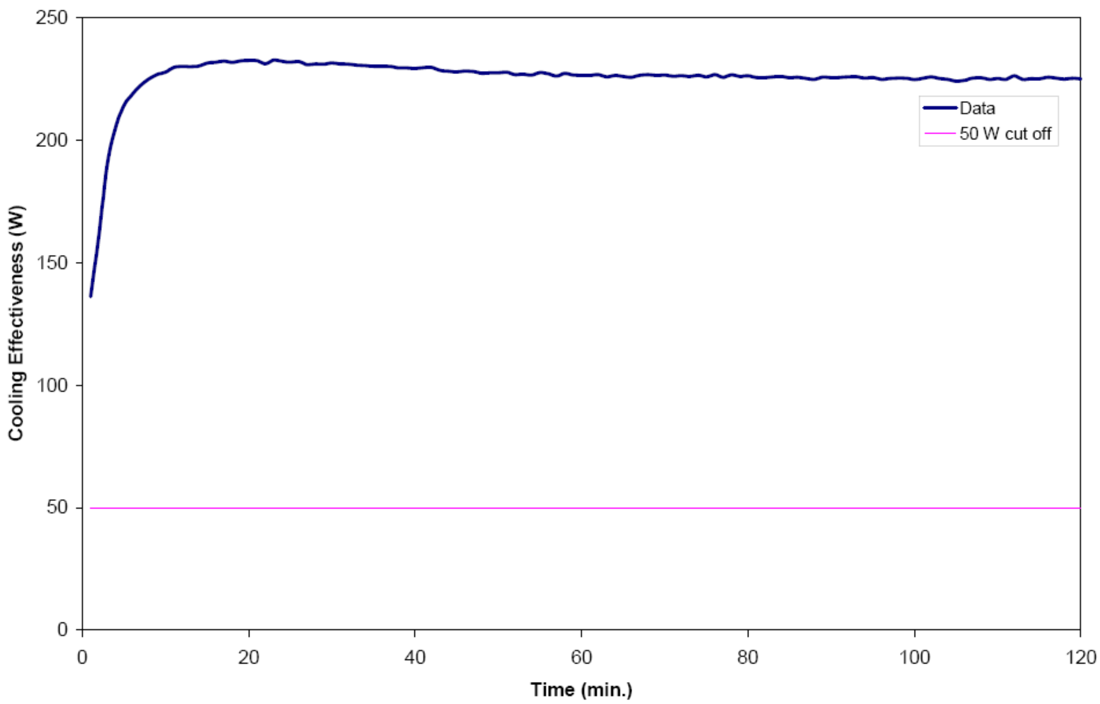

Figure 31. Cooling effectiveness of PCS #9: ClimaTech Safety ForcedAIR Vest 2 worn under DCU shirt (tested at 40% RH).

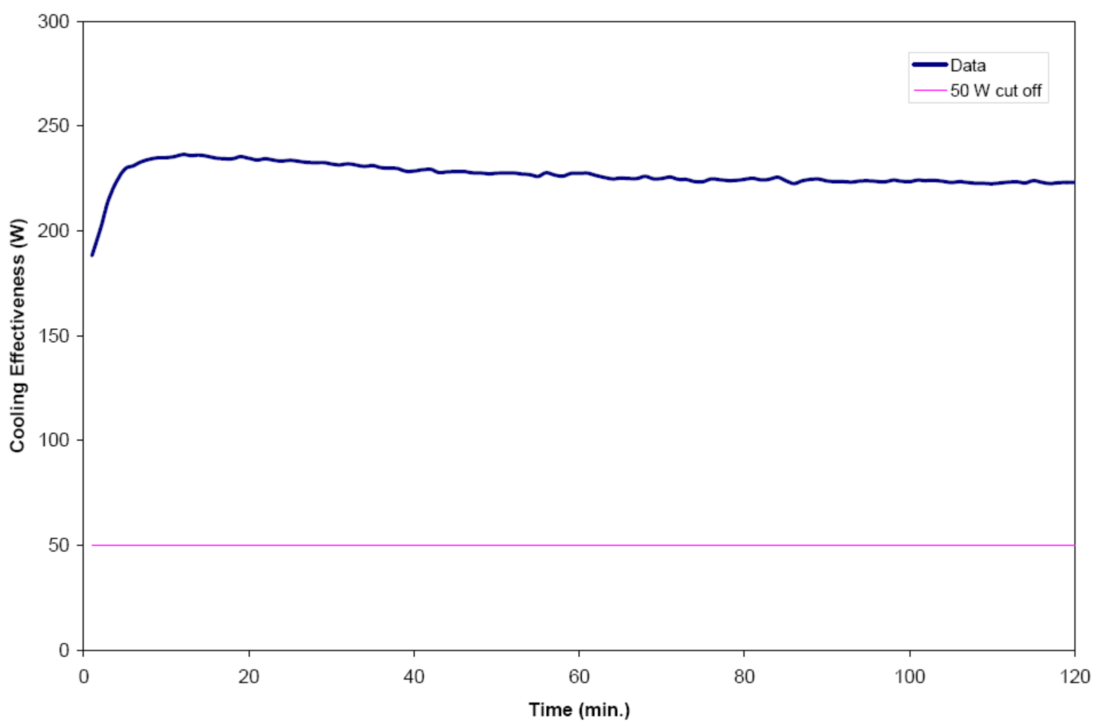

Figure 32. Cooling effectiveness of PCS #9: ClimaTech Safety ForcedAIR Vest 2 worn under DCU shirt (tested at 26% RH).

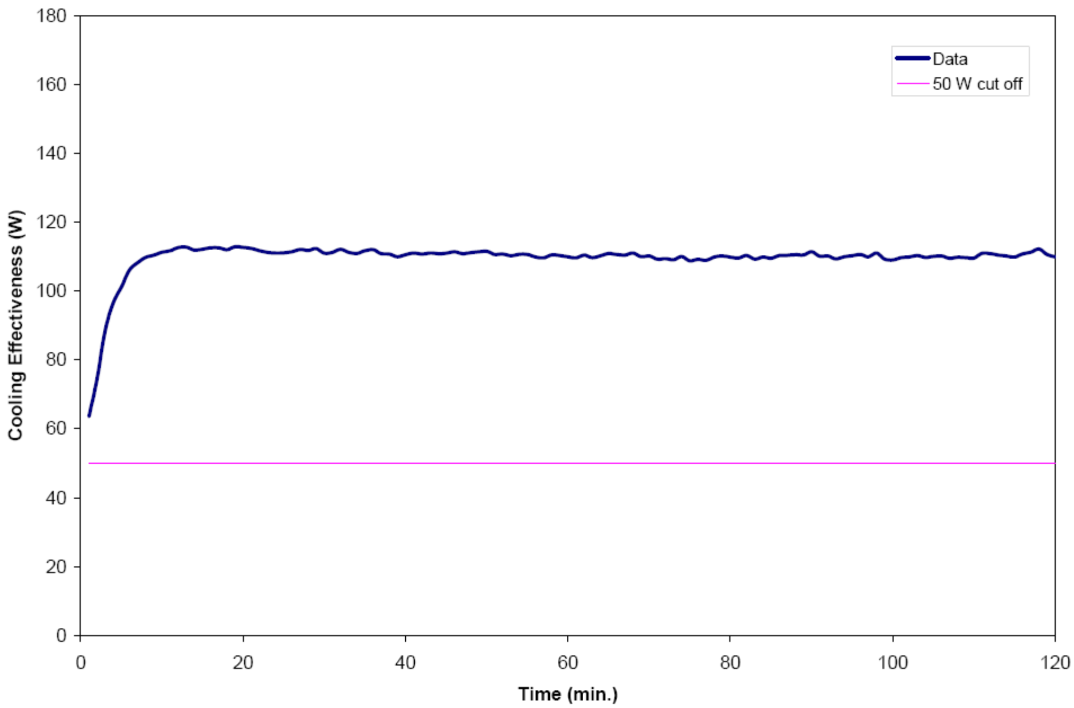

Figure 33. Cooling effectiveness of PCS #10: ClimaTech Safety ForcedAIR Vest 3 worn under DCU shirt (tested at 40% RH).

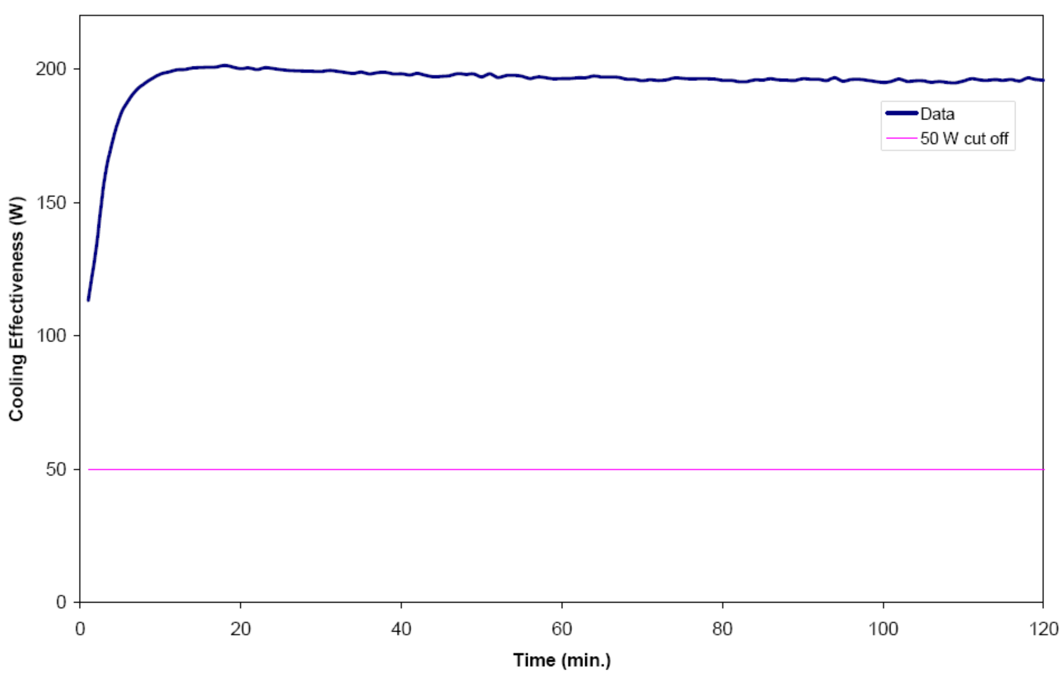

Figure 34. Cooling effectiveness of PCS #10: ClimaTech Safety ForcedAIR Vest 3 worn under DCU shirt (tested at 26% RH).

Phase III: Human Subject Trials

Section I: Personal Cooling Systems and Experimental Protocol

The cooling effectiveness of selected personal cooling systems was evaluated using Soldiers walking on treadmills in an environmental chamber under hot desert conditions. The basic procedures in ASTM F 2300, Standard Test Method for Measuring the Performance of Personal Cooling Systems Using Physiological Testing (ASTM, 2005) were followed except that the environmental conditions were hotter (i.e., to simulate a desert climate in the summer).

Project Design

Groups of four subjects – two in the morning and two in the afternoon – evaluated three personal cooling systems and the baseline condition without a PCS over a seven-day period (including three days for heat familiarization). The design of the experiment was a 4 x 4 Latin square design where subjects and test days serve as blocks. Each subject wore all four PCS treatments in a different order. The Latin square design was repeated two more times for a total of 12 test subjects. (See Table 1-1.) Although the standard requires a minimum of five subjects, 12 subjects were used because 1) human variability is high, 2) a subject might quit the experiment prior to completing all trials and none of his data would be used, and 3) data from different groups of subjects may ultimately be combined when additional PCS are compared in subsequent sessions.

This design for a three-week session was conducted four times so that 12 PCS could be evaluated with 48 subjects. Unfortunately, the Aspen mini-system prototype broke twice during the last session, so only 11 PCS were actually tested. An example of a test schedule is shown in Table 1-2.

Personal Cooling Systems and Clothing

Project Manager Soldier Equipment (PM SEQ) selected the personal cooling systems to evaluate based on information generated in Phase I of the project and product availability. We purchased the experimental cooling garments/systems from the manufacturers/developers, or they were loaned to us. The Army provided us with the garments used in the basic desert combat uniform (DCU) ensemble with body armor in a variety of sizes so that each subject was able to select garments for optimum fit. The ensembles that were evaluated are listed below. The mass (weight) of the garments and the fully charged PCS were recorded before the experiment began (Table 1-3). This information was needed each day for use with the met cart and for calculating the proper speed on the treadmill for each subject. Photographs of the Soldiers dressed in the PCS ensembles are shown in Figures 1-1 to 1-12.

PCS #0 Basic ensemble. This ensemble consisted of the Army lightweight desert combat uniform (DCU) with belt, underwear briefs, T-shirt, Kevlar® helmet with internal pads, interceptor body armor (IBA) – outer tactical vest (OTV) with enhanced small arm protective insert plates (ESAPI), deltoid auxiliary protection system (DAPS), enhanced side ballistic inserts

Volunteer Subjects

The target population for this study was male Soldiers on patrol in a hot desert environment. ASTM F 2300 requires that PCS be evaluated with either all males or all females. According to the Demographics Chief of the Office of the Deputy Chief of Staff, G1, there are more males (85%) than females (15%) in the Army, and an even higher percentage of males serve in combat situations in Iraq. Therefore, only males were recruited for this study. The Institutional Review Board at Kansas State University and the DOD Human Subjects Research Review Board approved the protocol and consent form prior to the recruitment of subjects. The Soldiers were recruited from Ft. Riley, Kansas.

Criteria for Inclusion/Exclusion of Volunteers. The Soldiers had to meet the following criteria in order to participate:

1. Be a male between 19-40 years of age (ASTM F 2300).
2. Weigh between 65-100 kg (143-220 lb.) (ASTM F 2300).
3. Have a height between 1.70-1.95 m (67-77 in.) (ASTM F 2300).
4. Be free of chronic disease and generally in good health (ASTM F 2300).
5. Meet the Army height and weight standards and have passed their most recent Army Physical Fitness Test.
6. Have no history of heat-related illness/injury (heat exhaustion, heat stroke, etc.)
7. Have no recent history of respiratory illness.
8. Have no history of orthopedic problems that could be made worse by walking in the DCU with body armor and helmet.
9. Have no recent history of skin disorder or disease.
10. Have no known allergy to adhesive tape.
11. Be willing to refrain from the use of any medications (prescription or over-the-counter) or dietary supplements throughout the length of the study, unless approved by both the Principal Investigator and staff providing medical care. Volunteers already taking medications or dietary supplements will not be admitted as test volunteers unless approved by both the Principal Investigator and staff providing medical coverage.
12. Refrain from the use of any caffeine or nicotine-containing product for at least 12 hours prior to the start of any test (ASTM F 2300).
13. Refrain from the use of alcohol for at least 24 hours before the start of any test (ASTM F 2300).
14. Avoid moderate-to-high exercise 22 hours prior to the test session (i.e., participate in no other exercise other than the test sessions during the test week) (ASTM F 2300).
15. Have not had a vaccine in the preceding month.

Two Army chaplains from Ft. Riley served as the ombudsman to assist Dr. McCullough with the recruiting effort and ensure that the Soldiers understood that participation was voluntary. Dr. McCullough explained the protocol, distributed the protocol/consent forms to Soldiers to read, and answered questions. After the volunteers signed the consent form, they were cleared for participation by an Army physician. The physician reviewed the Soldiers' medical records (if they were less than 1 year old) or gave the Soldiers a new physical exam which included an assessment of their cardio-respiratory status. The physician provided the principal investigator with written documentation regarding the fitness of each volunteer to participate in the project. Then TDY orders were issued for one week of testing. The subjects did not receive any benefits for participating in the study.

The experimental setup was housed in two environmental chambers at the Institute for Environmental Research. The primary chamber (18 x 23 x 12.5 ft) was set up with two treadmills, two fans (Figure 1-13), and solar lights (Figure 1-14). The second chamber (11.2 x 11.2 x 9 ft) was used as a preconditioning chamber and contained the dressing rooms and instrumentation stations (Figure 1-15). The environmental conditions in both chambers were maintained by external air handling units that kept the dry bulb and dew point at specified levels.

According to NASA Surface Meteorology and Solar Energy Tables, the highest average environmental values for June and July for central Iraq are: air temperature, 42.2°C (108°F); relative humidity, 31%; wind speed, 4.7 m/s; and a high solar radiant load. The ASTM standard requires using an air temperature of 35°C (95°F), a relative humidity of 50%, and still air conditions (0.15 m/s). We decided to use conditions that would more closely simulate those found in the Middle East. We used these conditions in a previous study on passive cooling, and the subjects were able to complete the 2-hour trial when no cooling was provided. However, they had a 10 minute rest in the middle of the session (McCullough, Eckels, & Harms, 2005).

The conditions were:

- Air (dry bulb) temperature = 40°C (104°F)
- Dew point temperature = 12.8°C (55°F)
- Relative humidity = 20%
- Air velocity = 2 m/s (4.5 mph) average in chamber
- Mean radiant temperature = 54.4°C (130°F)

The small chamber (adjacent to the large one) was held at approximately 30°C and 25% RH in order to expose subjects to warm conditions for 45 minutes prior to the test session while they were getting instrumented and dressed.

Data Acquisition System

An HP VXI bus data acquisition system was used to measure eight skin temperatures on each Soldier, core body temperature, two chamber dry bulb temperatures, and two dew point temperatures. A Labview® interface was developed to read and store each of the instrument readings during testing. Dry bulb temperatures were measured with type K thermocouples; skin and core temperatures were measured with type T thermocouples. Dew point temperatures were measured with General Eastern hygrometers. Heart rates were measured with Polar™ S810i heart rate monitors that consist of a chest strap – with electrodes and a transmitter – and a watch. Oxygen consumption and metabolic rate were measured with a ParvoMedics True One 2400 Metabolic Measuring System.

Prior to the beginning of the project, the entire system was calibrated. Each thermocouple was calibrated in a constant temperature bath. The average air speed was set with a vane anemometer positioned at chest level for a person standing on the treadmill. Specifically, the speed of the fan located in front of each treadmill was varied until an average velocity of 2 m/s was obtained. The environmental conditions in the chamber were set by three primary variables: the dry bulb temperature, the wet bulb temperature, and the mean radiant temperature. The dry bulb and relative humidity were actively controlled by the chamber during the experiments. The wattage and number of lights in the solar simulator controlled the mean radiant temperature. The method outlined in the ASHRAE Handbook (ASHRAE, 1995) was used to measure this temperature. A small black ball with four thermocouples mounted on the surface was placed under the solar lights. The average temperature of the bulb, the dry bulb temperature of the air, and the air speed was then used to calculate the mean radiant temperature. The spectral distribution of the light emitted by the solar simulator was also measured by a photo spectrometer. The solar simulator consisted of approximately 40 150 W GE heat lamp bulbs laid out in a square matrix above the treadmills (Figure 1-14). The dry bulb, wet bulb, and mean radiant temperature were also used to calculate the WBGT Index (ISO, 1982).

Test Procedures

Determining work load. According to the ASTM standard, an energy expenditure between 250-400 W could be selected for the evaluation of PCS (ASTM, 2005). We selected an initial energy expenditure of 350 W for this study. To determine the speed of the treadmill at 1% incline that would generate 350 W of metabolic heat production, the following equation was used (ACSM, 2006). Note: oxygen consumption is directly related to energy expenditure.

$VO_2 = R + H + V$

where

VO_2 = rate of oxygen consumption (ml/kg/min)

R = resting component of energy expenditure (3.5 ml/kg/min)

H = horizontal component of energy expenditure (0.1 × walking speed in m/min × 26.8 to convert to mph = 2.68 mph)

V = vertical component of energy expenditure (1.8 × walking speed in m/min × 26.8 to convert to mph × grade expressed as a decimal) In this study, grade was 1% (0.01), so V = 0.48.

To determine the speed of the treadmill (at a specific grade) that will result in a particular metabolic expenditure, the watts must first be converted to VO_2 in ml/kg/min to solve the equation above. To equate oxygen consumption (VO_2) with energy expenditure (W):

1 W = 0.0143 kcal/min
1 liter O_2/min = 4.825 kcal/min
Therefore: 1 W = 0.00296 liter O_2/min

To determine 350 W: (350 x 0.00296) = 1.036 liter O_2/min.

To convert to correct units for VO2 (ml/kg/min):

$$\frac{1.036 \text{ liter O2/min} \times 1000}{\text{body + clothing weight (kg)}} = \text{VO2 ml/kg/min}$$

For a 150 lb. subject wearing 50 lb. of protective clothing (total 200 lb. or 90.9 kg):

$$\frac{1.036 \text{ liter O2/min} \times 1000}{90.9 \text{ kg}} = \text{VO2 ml/kg/min} = 11.4$$

Example: The original equation can be turned around to determine the treadmill speed in mph (s) at a 1% incline that would generate 350 W of metabolic heat production for a 200 lb. subject:

$$s = \frac{(\text{desired metabolic rate in W} \times 0.00296 \times 1000 / \text{weight of clothed subject in kg}) - 3.5}{3.16}$$

$$s = (11.4 - 3.15) / 3.16 = 2.5 \text{ mph}$$

Each day of the experiment, the weight of each subject and his clothing and PCS (if worn) were entered into a computer program that calculated the treadmill speed that would produce 350 W of energy expenditure at the beginning of the test period (using the equation above). The energy expenditure was expected to increase over the 2-hour test period, however.

Heat familiarization sessions. When a person gets acclimated in the heat, his/her heart rate and core temperature under a certain set of conditions will become lower and his/her sweat rate will become higher. Consequently, the physiological strain of exercising in a hot environment lessens as the person conditions his/her body. Unfortunately, we were not able to schedule a week or more of acclimatization sessions for the subjects. However, we planned several days of heat familiarization sessions for each subject prior to the test sessions. There was still a chance that a subject might feel more comfortable on the last day of the experiment – regardless of what he was wearing – simply because he had become fully acclimatized by that time. Therefore, a statistical analysis using "day" as a factor was used to indicate whether any differences in between the subjects confounded the results in any way.

During the first three days of each week of testing, the subjects participated in a 2-hour exercise/rest test session under the same environmental conditions used in the study. They followed the exercise/rest protocol given below.

- 0-10 minutes: sitting for 10 minutes
- 10-55 minutes: walking for 45 minutes
- 55-65 minutes: sitting for 10 minutes
- 65-110 minutes: walking for 45 minutes
- 110-120 minutes: sitting for 10 minutes

The purpose of these sessions was to familiarize the subjects with the hot environment, instrumentation, and procedures. The procedures used and measurements taken during the heat familiarization sessions were the same as those described for the experiment (see test protocol below) except that skin temperature and oxygen consumption were not measured during the first two days of heat familiarization. Although considerable data were collected, they were not used in the analysis.

Day 1: On the first day of the experiment, the subjects provided their demographic information (age, race). Their height and weight were measured, and their Body Mass Index was determined. The appropriate size garments were assigned to each subject. Then the physiological instrumentation and test protocol were explained to them in detail. They wore the DCU ensemble and helmet – without the interceptor body armor – in the first 2-hour heat familiarization session.

Day 2: On the second day, the subjects wore the DCU ensemble and helmet – without the interceptor body armor – in the second 2-hour heat familiarization session.

Day 3: On the third day, the subjects wore the DCU ensemble, helmet, and body armor. The treadmill speed for each subject was adjusted to account for the increase in weight due to wearing the body armor.

Test Protocol. When the subjects arrived for an experiment, they entered a small, warm environmental chamber adjacent to the large one. All of the garments and the PCS that each subject was assigned to wear in the test session were placed at numbered stations. (See Figure 1-15). Each subject undressed in a private area, put on a pair of briefs, and got weighed. Then he went back into the dressing area and inserted a sterilized, flexible Physitemp rectal thermocouple (for monitoring body core temperature) 10 cm into his rectum. Each subject had his own rectal sensor during the project. The nurse and an experimenter put thermocouples on the subjects' skin with transpore hospital tape. This tape minimized the heat transfer barrier effect and discomfort to the subjects. If the subject was excessively hairy in a location where a sensor was to be taped, some of the hair was shaved so that the sensor was securely attached. Skin temperature was measured in eight locations on the body: forehead, right scapula, right upper chest, right upper arm, right lower arm, left hand, right anterior thigh, and right calf. The nurse and experimenter put the Polar™ S810i heart rate strap and watch on the subjects. The subjects also wore a wrist strap to provide an electrical ground so that they did not build up a static charge and cause electrical interference. An example of an instrumented subject is shown in Figure 1-16.

The nurse and experimenter helped the subjects dress in the appropriate baseline ensemble and PCS. Then the nurse gave the subjects 250 ml of water to drink.

During the heat familiarization sessions, both subjects entered the chamber and got hooked up to the data acquisition system at the same time. During the experimental test sessions, one subject entered the chamber 15 minutes before the other and got hooked up to the data acquisition system and the oxygen analyzer. To start the experiment, his PCS was activated according to the manufacturer's instructions, and he started walking on the treadmill at his predetermined speed. The nurse monitored him for 15 minutes, adjusting the speed if necessary based on his metabolic rate. (See Figure 1-17). This gave the subject enough time to equilibrate at the required work rate while preventing a potential increase in metabolic cost due to the weight of the clothing and PCS and exercise-induced stress. This was repeated with the second subject starting 15 minutes after the first. Each subject walked for 2 hours with no rest periods. (See Figure 1-18). The nurse measured each subject's metabolic rate during the last 15 minutes of the test period also. She asked the subjects to drink 250 ml of water every 30 minutes to prevent dehydration (i.e., 30, 60, 90 minutes from the time their treadmill run started). Subjects were permitted to listen to the music of their choice. If a subject needed to urinate, he did so in a hand-held urinal in the chamber. The nurse recorded all fluid intake and excretion.

The test session ran for 2 hours for each subject unless one of the following removal criteria was met (ASTM F 2300):

- The subject's rectal temperature reaches 39°C or increases 0.6°C in a 5 minute period (whichever occurs first).
- The subject's heart rate reaches 90% of his age predicted maximum.
- The subject's skin temperature at any site reaches 38°C (see note below)
- The subject experiences heat exhaustion symptoms, including headache, extreme weakness, dizziness, vertigo, "heat sensations" on the head or neck, heat cramps, chills, "goose bumps", vomiting, nausea, and irritability (Hubbard & Armstrong, 1998).
- The subject wants to quit the experiment.

Note: The 38°C limit was not used for the hand sensor because it was not shielded from the radiant heat of the lights.

After a 2-hour test session, the subjects returned to the small chamber and the nurse or experimenter assisted in removing the thermocouples and heart rate monitors. Then the subjects removed all of their garments as well as their rectal sensors and were weighed in their briefs. The subjects then put on their own clothes. If the subject's weight after the experiment was not within 1% of his initial weight, he was asked to drink cool water or Gatorade® and stay for observation for about 15 minutes or until his target body mass was achieved.

The experimenter laundered the garments and PCS garment (if necessary) and returned them to the small chamber prior to the next day's test. The skin sensors and wires were cleaned with makeup remover towelettes and alcohol wipes to remove perspiration oils and tape residue. The 12 subjects in each test session each had their own rectal sensor which was sterilized prior to use. Each subject cleaned his sensor with an alcohol wipe when he finished using it for the day. Each sensor was stored in a plastic bag labeled with the subject's identification number between uses. After testing was completed for the week, the experimenter soaked the rectal sensors for 10 hours in Cidex Plus™ (an FDA cleared sterilant and high level disinfectant) to disinfect them for the next subject.

Personnel. Several people participated in running the test sessions. A registered nurse with heat stress training was in the chamber with the subjects at all times. She monitored the subjects' oxygen consumption, heart rate, and overall well being. An engineer continuously monitored the other physiological responses of the subjects and the environmental conditions on a computer outside the chamber. A research assistant cleaned the sensors and garments between sessions, weighed the clothing and PCS, and assisted the nurse and investigators with the instrumentation of the subjects and other tasks. The investigators supervised all project activities and checked the data files daily. At least one investigator was present during all test sessions.

Figure 1-2. Subject dressed in PCS #1: Summitstone ForcedAir Vest (FAV1) worn over DCU shirt

Figure 1-10. Subject dressed in PCS #9: Summitstone ForcedAir Vest – Redesigned (FAV2) and worn over T-shirt and under DCU shirt.

Figure 1-11. Subject dressed in PCS #10: Summitstone ForcedAir Vest (FAV3) worn over T-shirt and under DCU shirt.

Figure 1-18. Subjects walking on the treadmills during a test session.

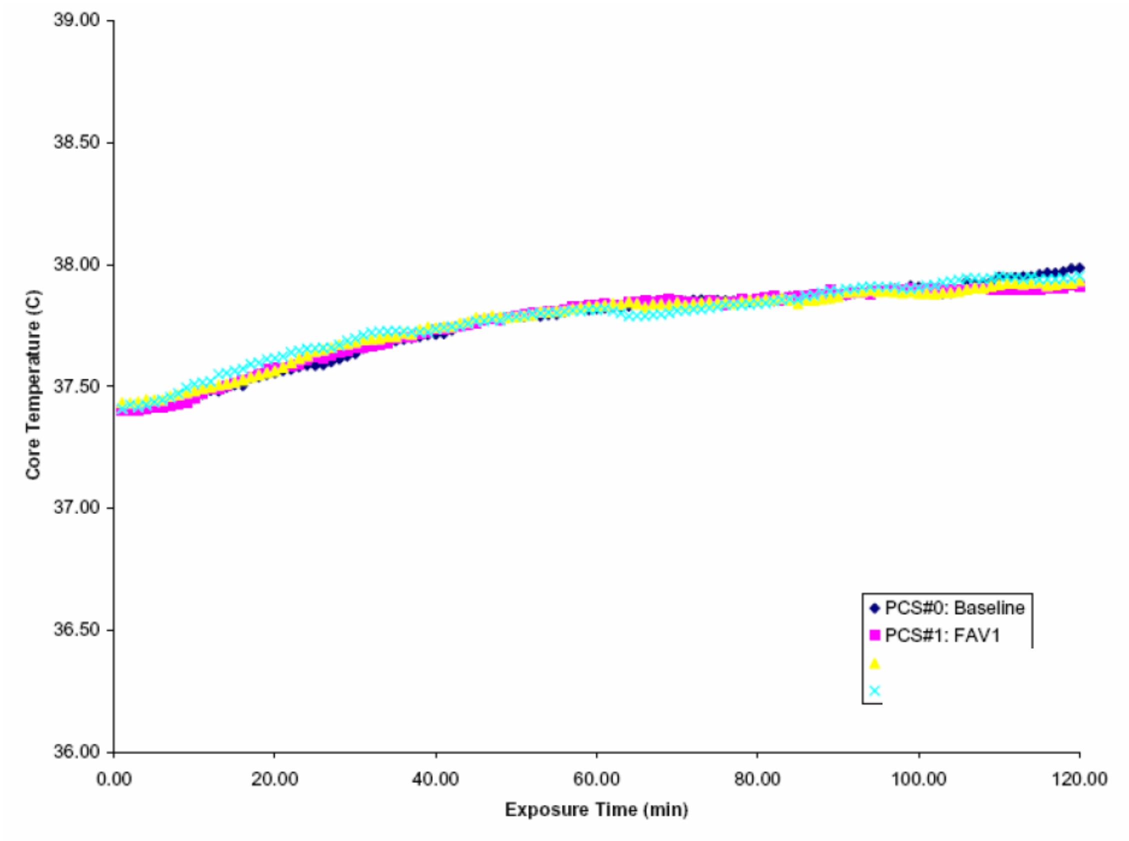

Figure 2-3. Average core temperatures of Soldiers while wearing different PCS.

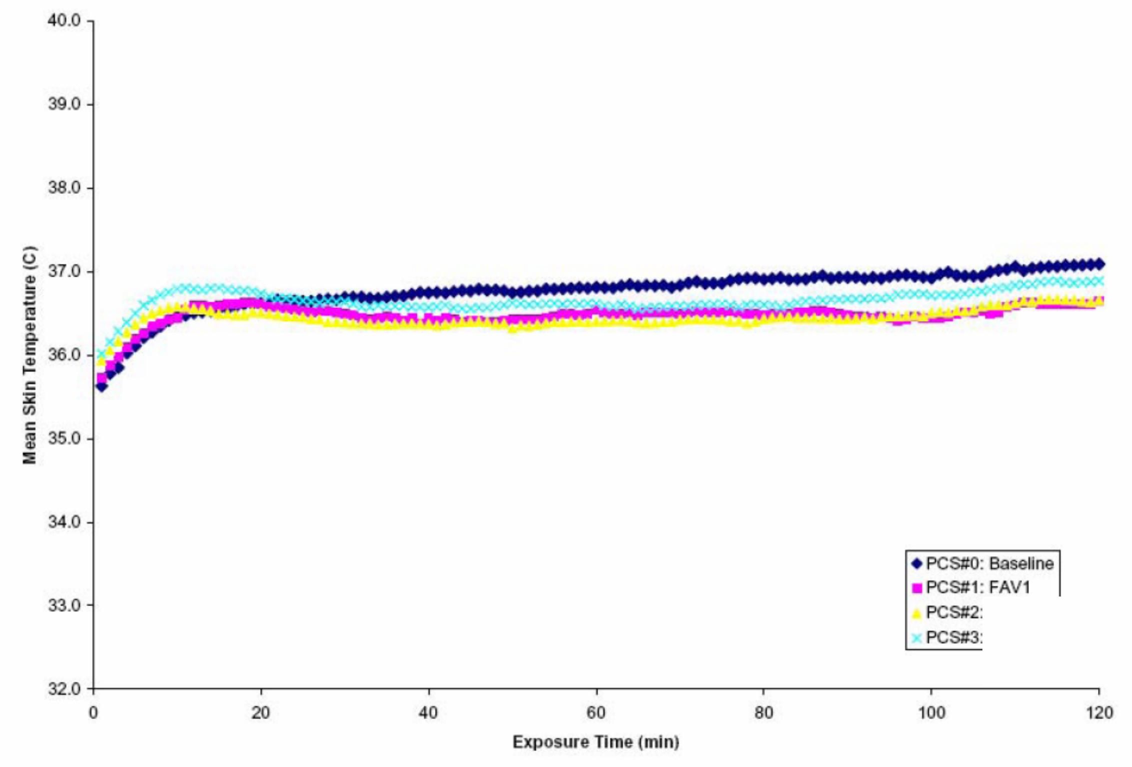

Figure 2-4. Mean skin temperatures of Soldiers while wearing different clothing systems.

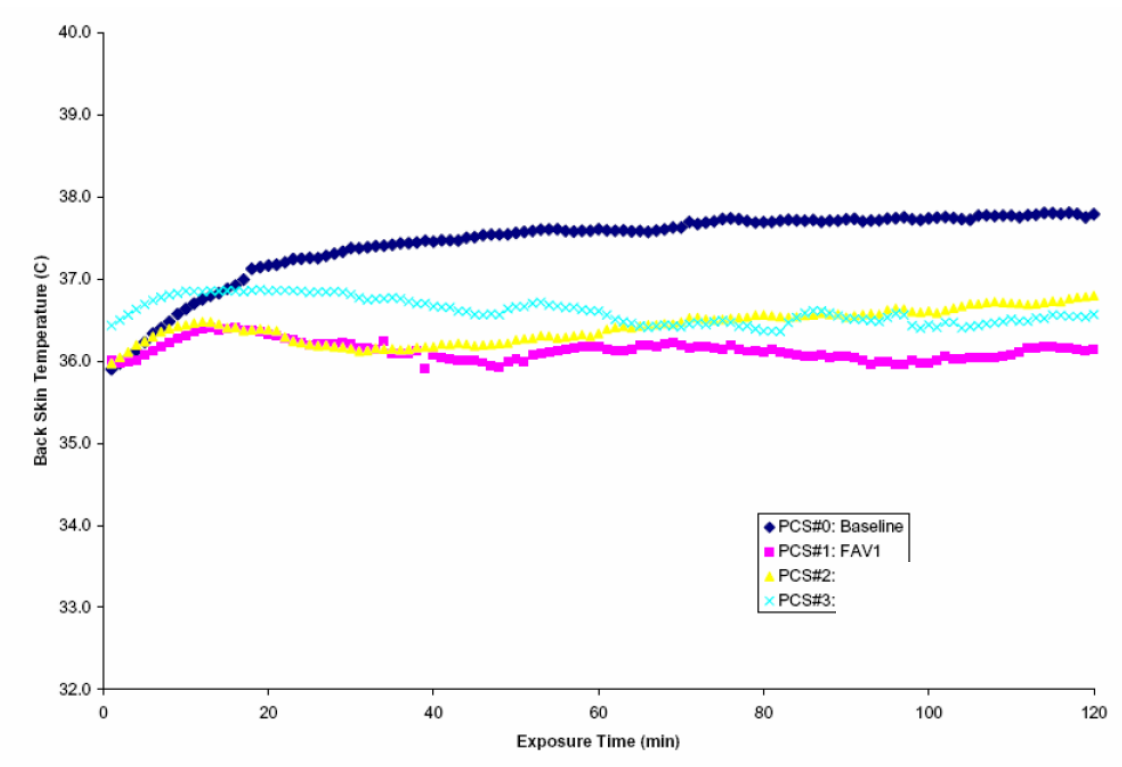

Figure 2-5. Average back skin temperatures of Soldiers while wearing different PCS.

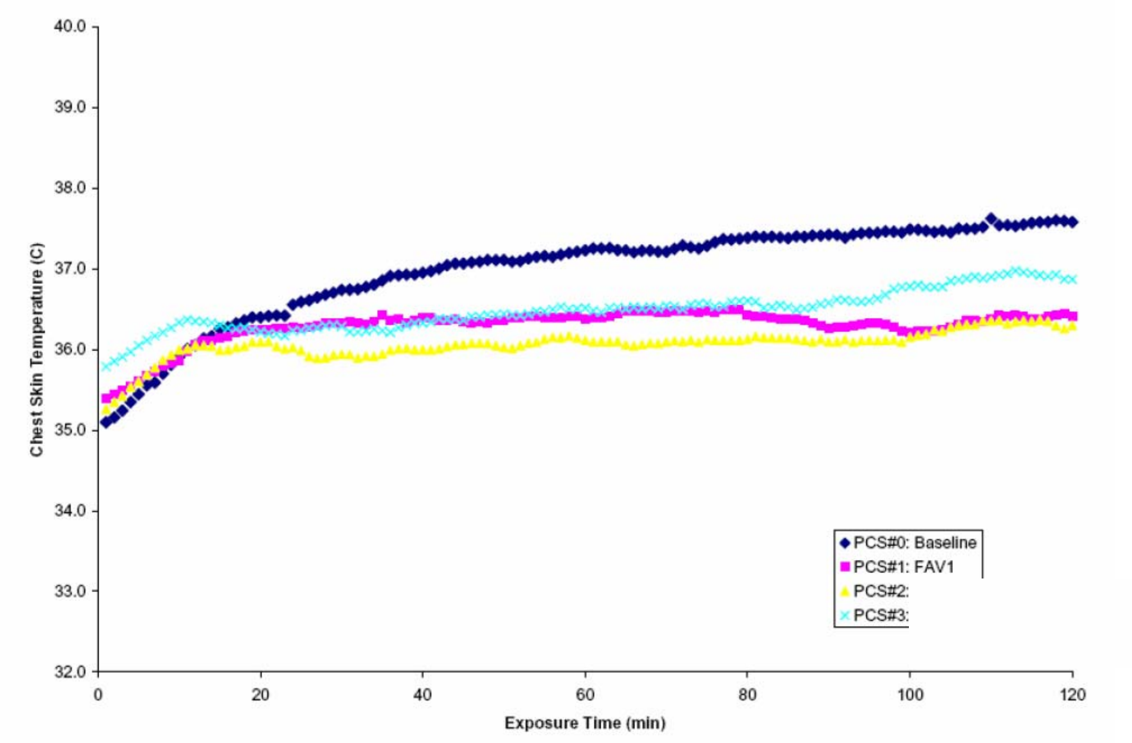

Figure 2-6. Average chest skin temperatures of Soldiers while wearing different PCS.

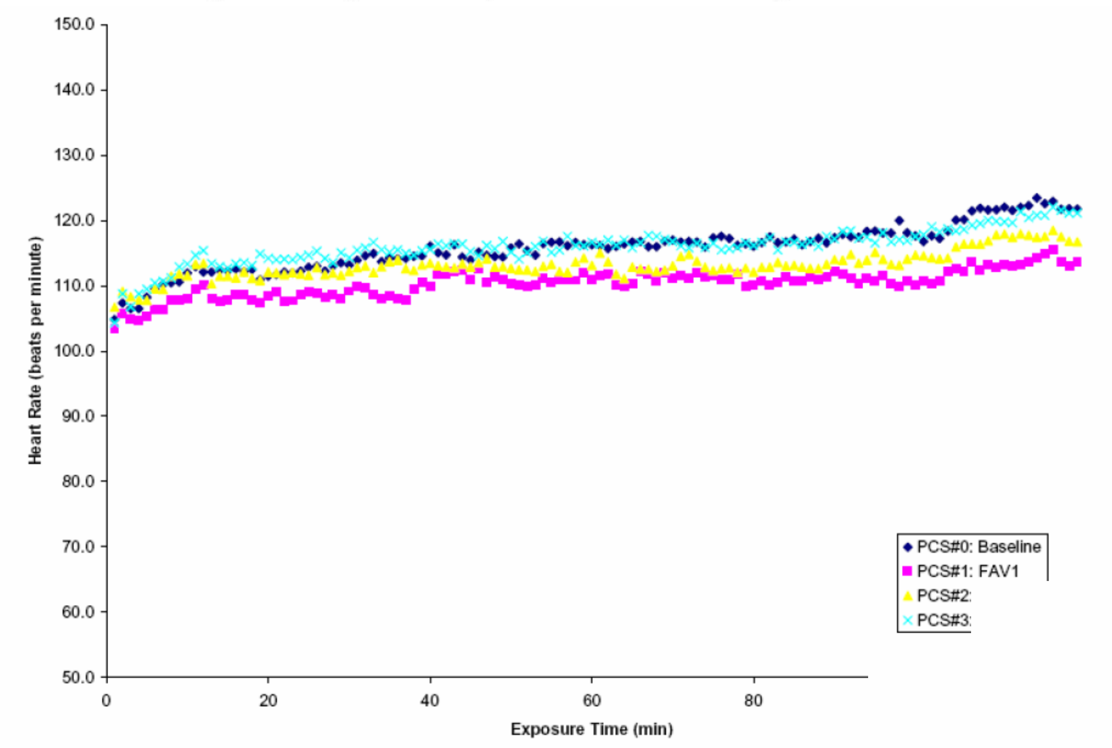

Figure 2-7. Average heart rates of Soldiers while wearing different PCS.

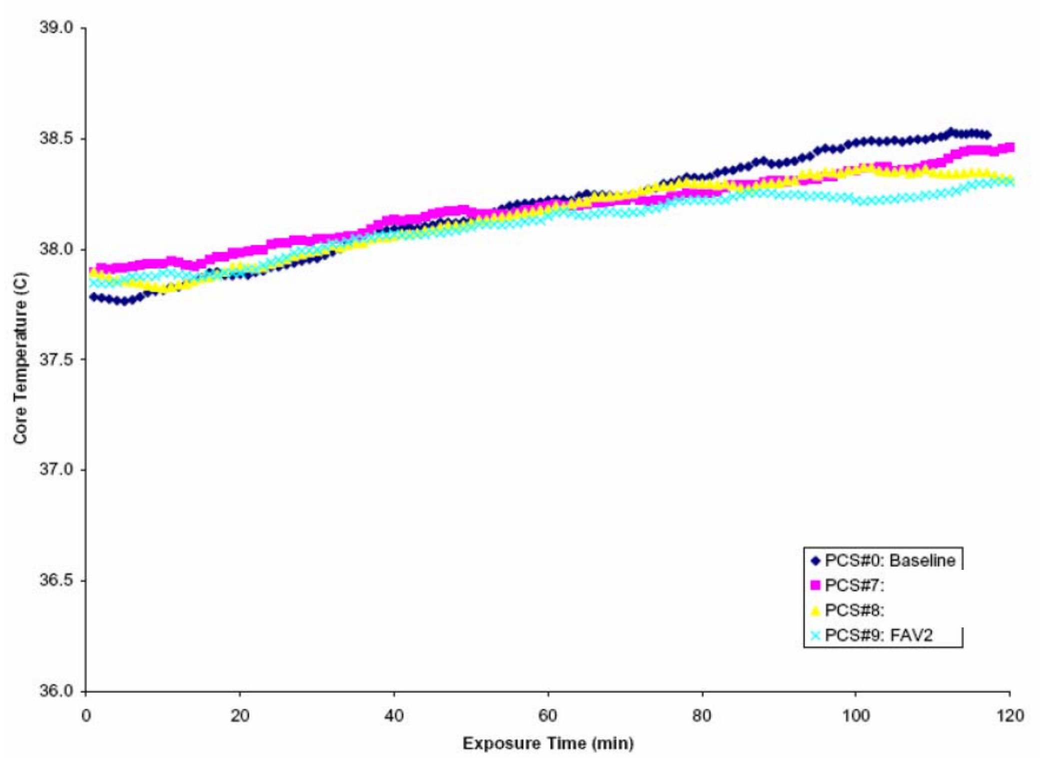

Figure 2-17. Average core temperatures of Soldiers while wearing different PCS.

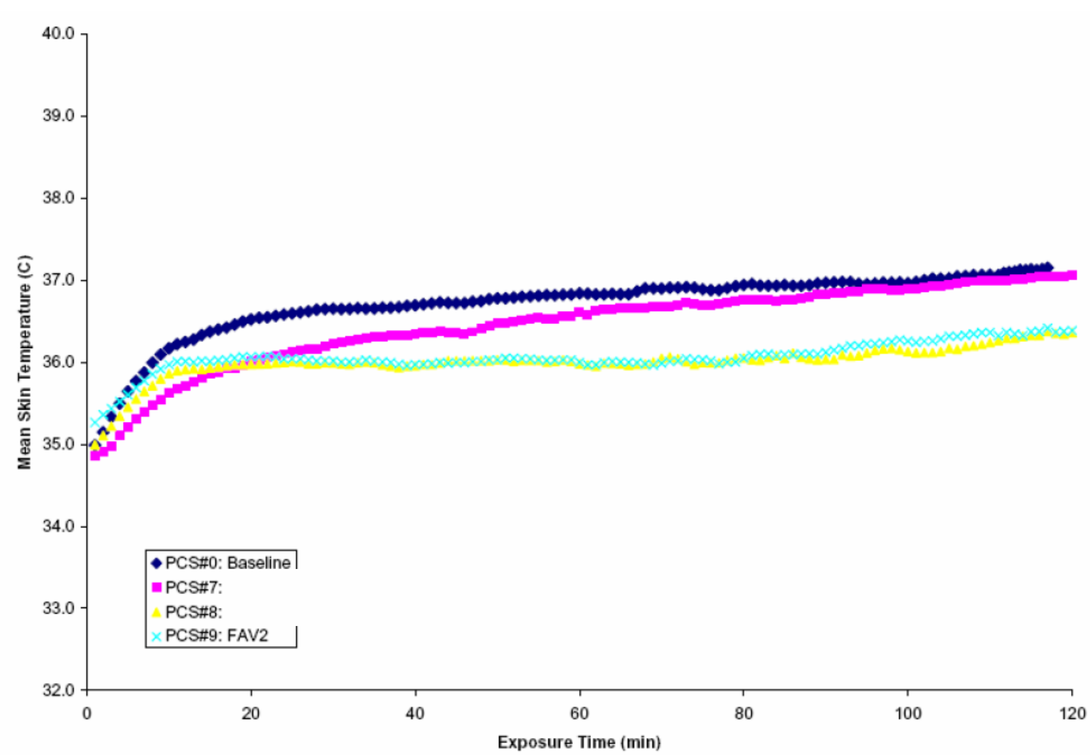

Figure 2-18. Mean skin temperatures of Soldiers while wearing different clothing systems.

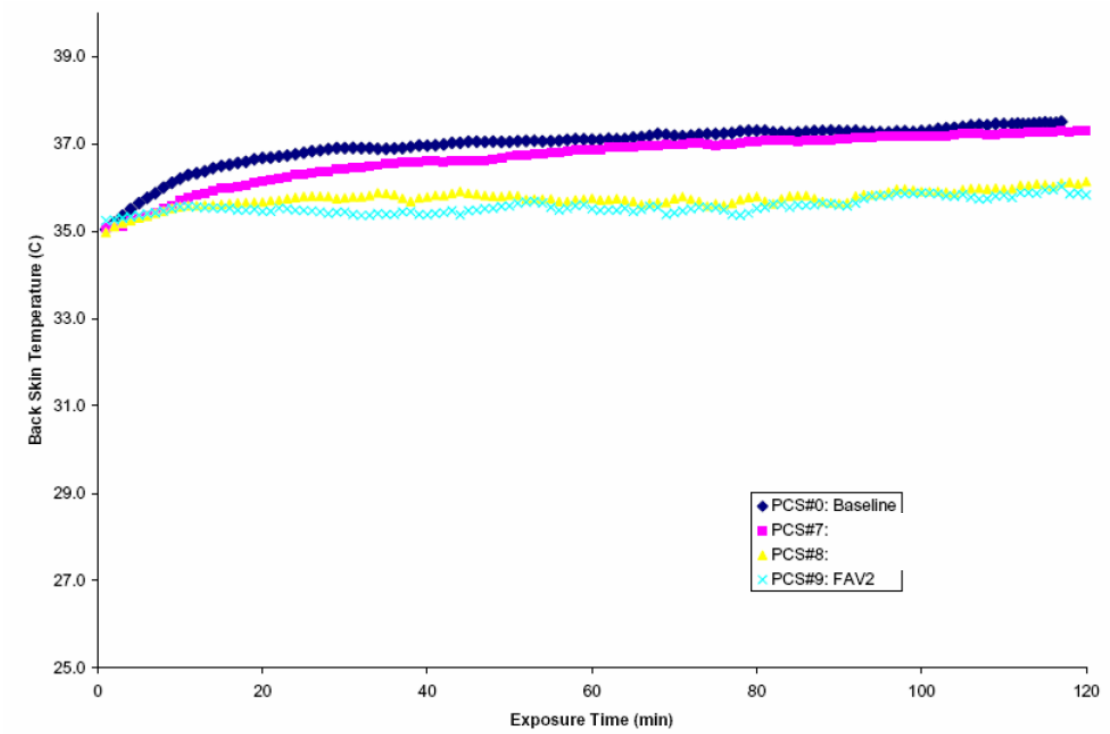

Figure 2-19. Average back skin temperatures of Soldiers while wearing different PCS.

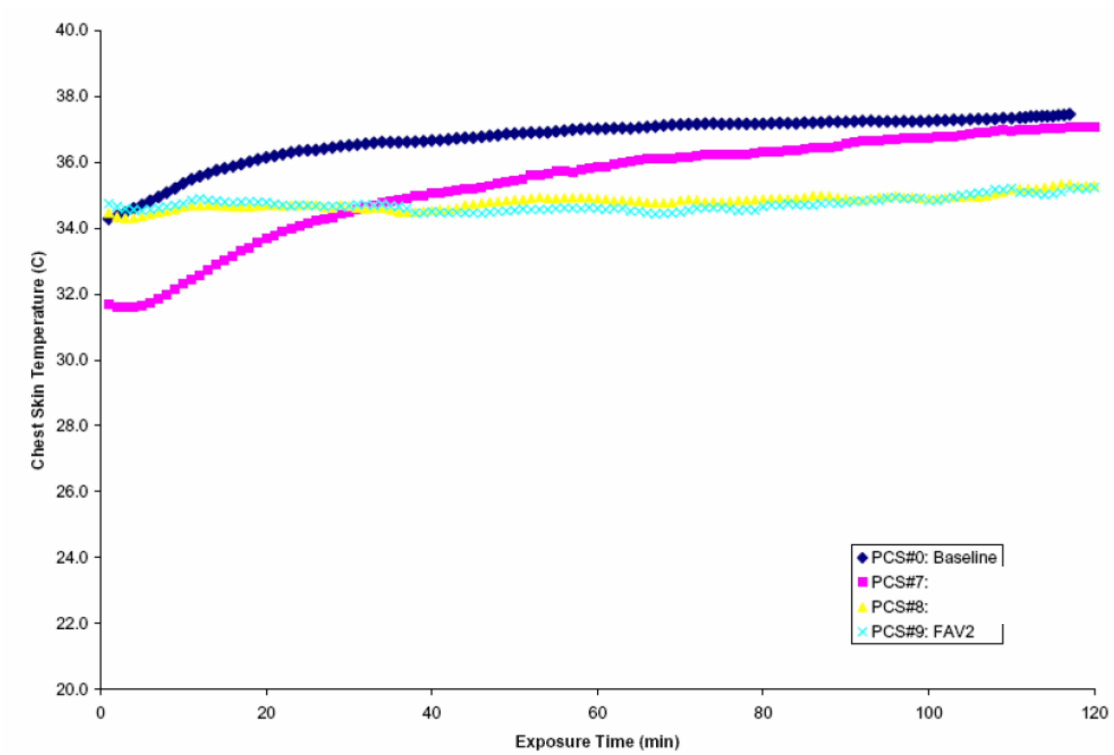

Figure 2-20. Average chest skin temperatures of Soldiers while wearing different PCS.

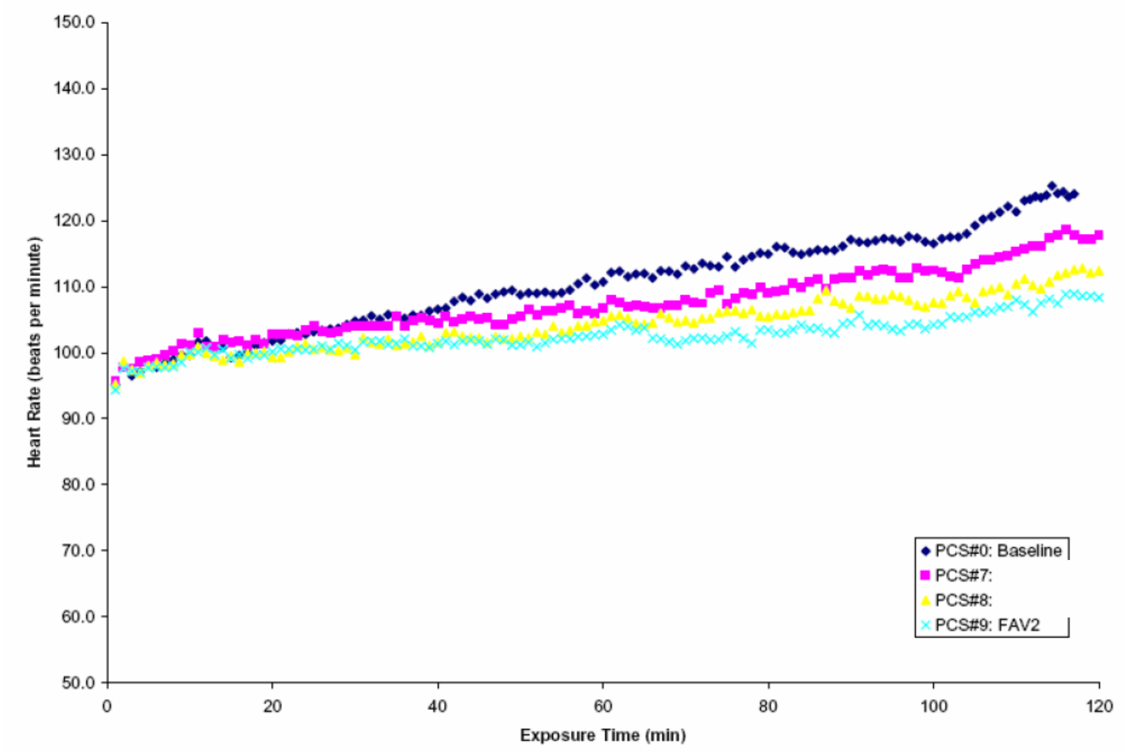

Figure 2-21. Average heart rates of Soldiers while wearing different PCS.

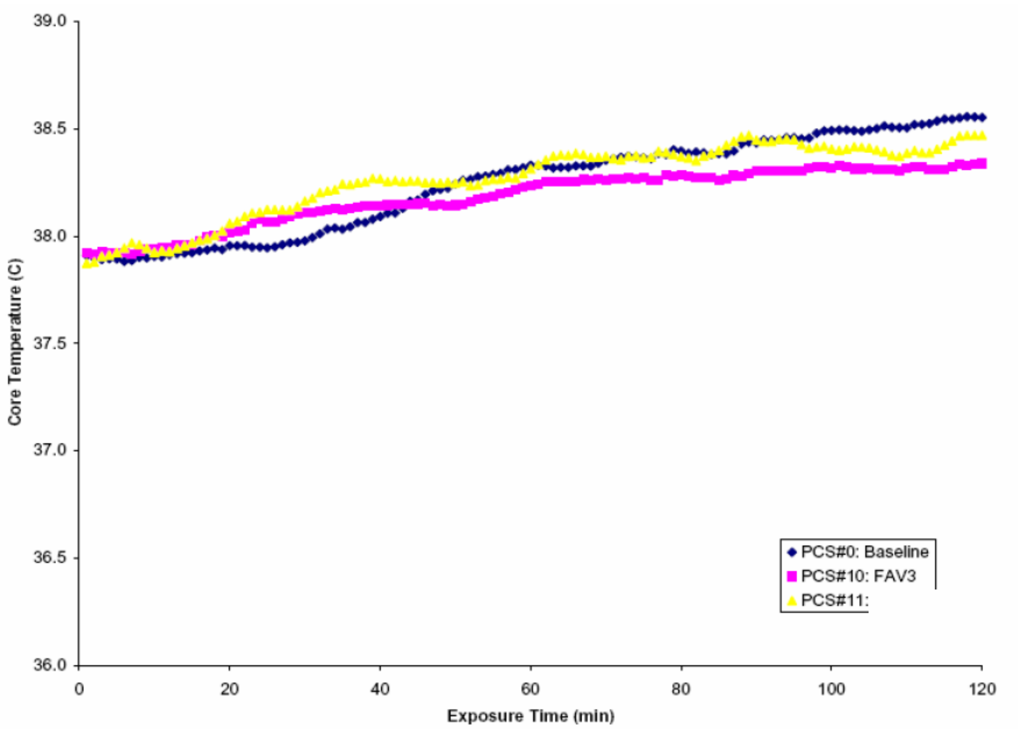

Figure 2-24. Average core temperatures of Soldiers while wearing different PCS.

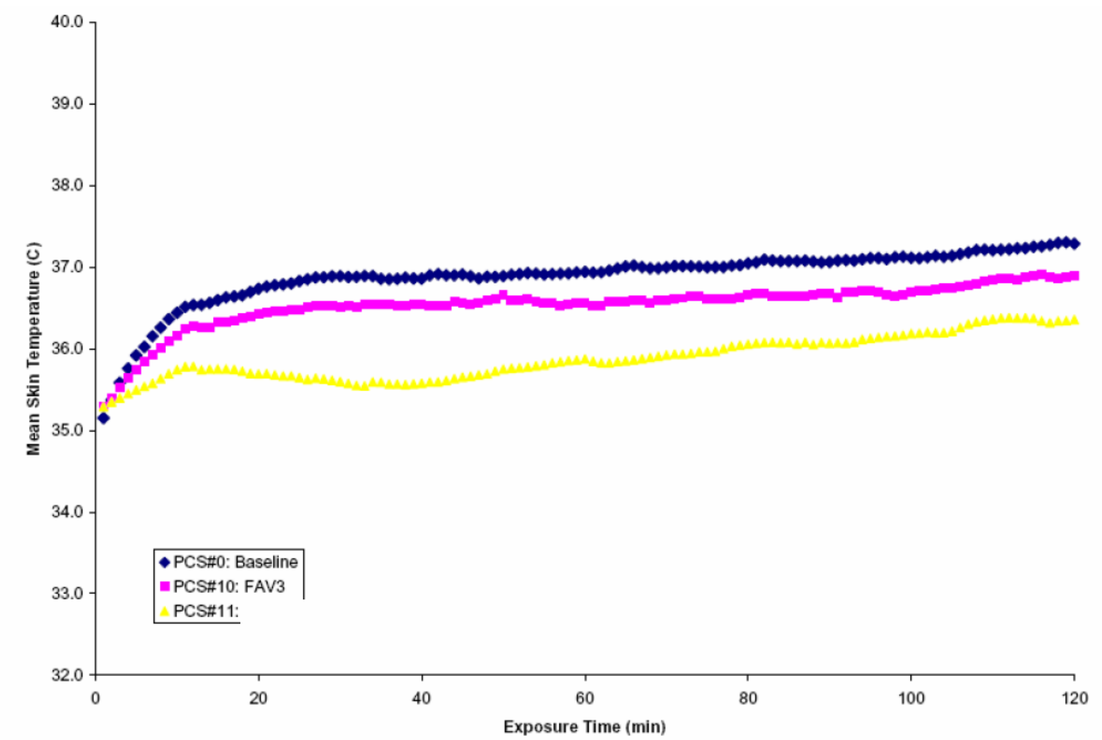

Figure 2-25. Mean skin temperatures of Soldiers while wearing different clothing systems.

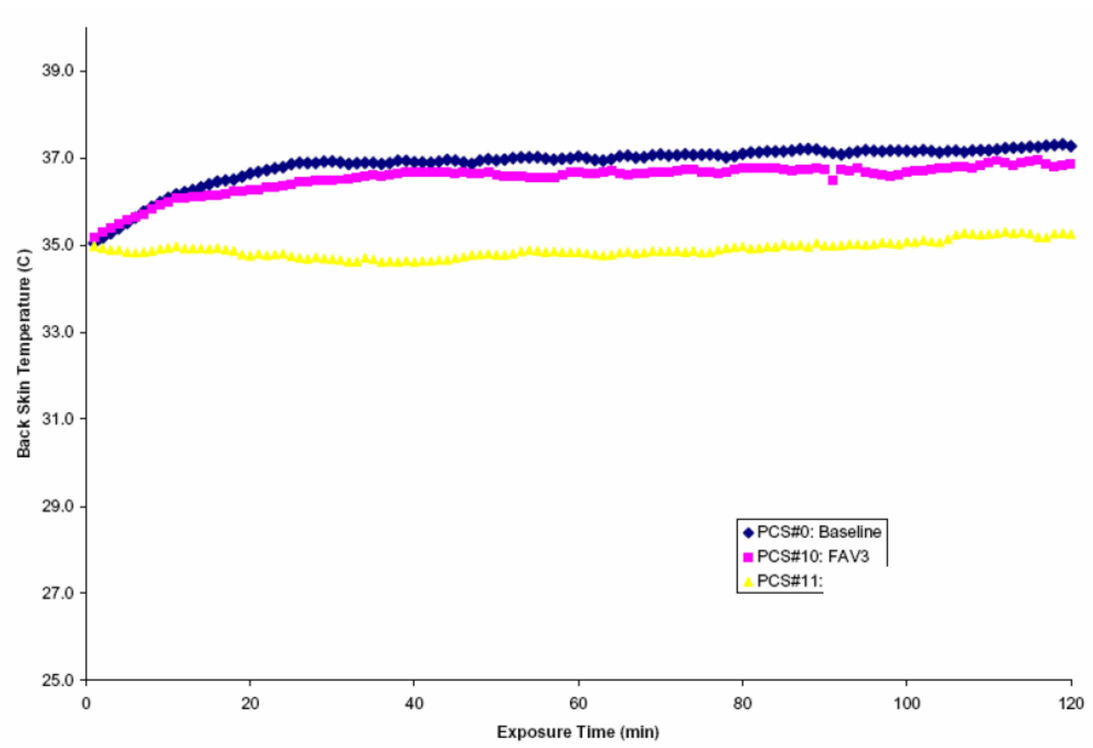

Figure 2-26. Average back skin temperatures of Soldiers while wearing different PCS.

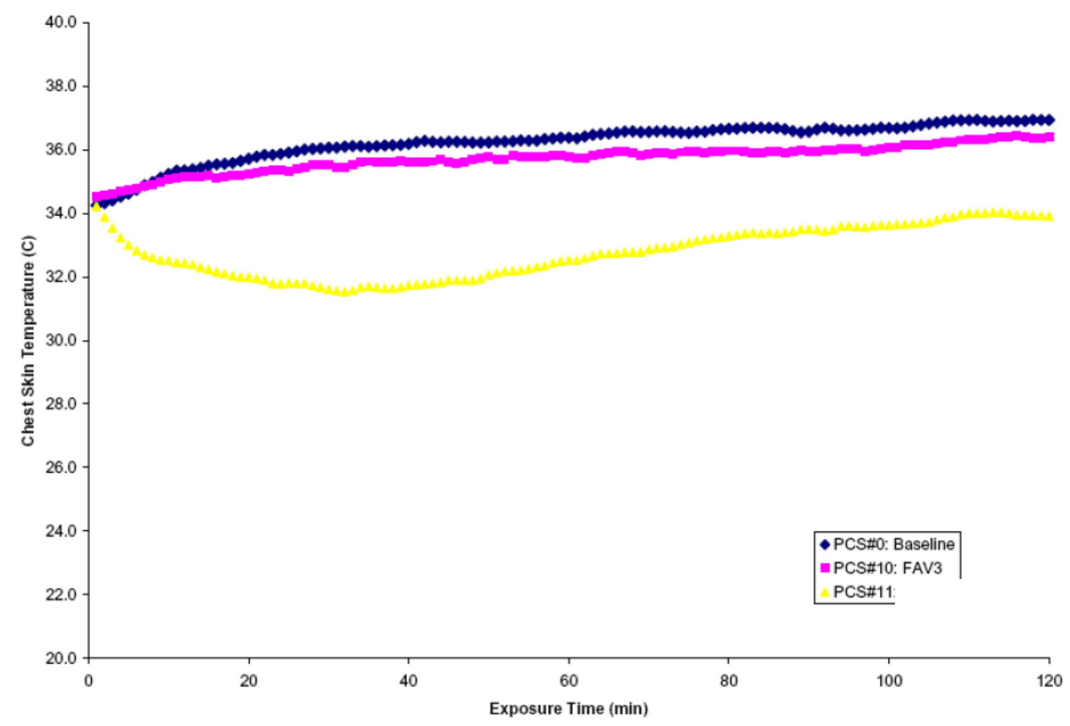

Figure 2-27. Average chest skin temperatures of Soldiers while wearing different PCS.

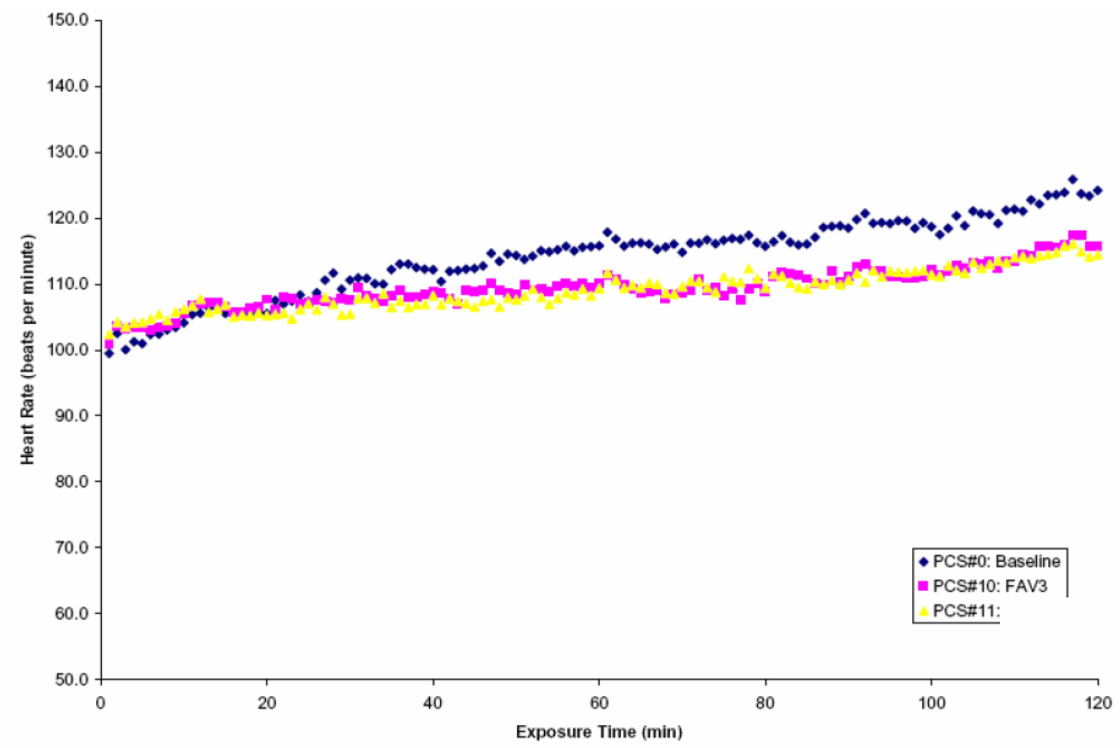

Figure 2-28. Average heart rates of Soldiers while wearing different PCS.

Results

The standard defines the cooling rate as the time average of the power input to the manikin from the time the PCS was activated and data collection was started until the effective power (power to the manikin minus the baseline power level) decreased to 50 W – for a maximum test of 2 hours. However, some of the PCS we tested never reached 50 W to begin with, so we ran each test for 2 hours. We calculated the cooling rate two ways: 1) the time the system was drawing 50 W or more of power, as the standard specified, and 2) the average cooling rate over 2 hours – even though this is somewhat meaningless if a system did not cool for very long.

The ambient air circulation systems that work by blowing air between the body armor and the clothing layers increase convective and evaporative heat losses. These systems were evaluated at a lower humidity level of 26% and their performance improved in a drier environment. PCS #9 ForcedAir Vest 2 worn over the T-shirt and under the DCU shirt (FAV2) provided the most cooling of all of the systems at 226.8 W. However, the manikin's skin and T-shirt were totally saturated with water (i.e., 100% skin wettedness) during the test, and his flow rates were adjusted to high levels to keep the surface saturated. In real life, it would take some time for the Soldier to accumulate that much sweat, and it is unlikely that he/she could sweat continuously at that rate.

Most of the Soldiers were able to complete the two-hour test session. Six Soldiers reached the 39°C cut off for rectal temperature prior to 120 minutes – usually when wearing the baseline ensemble. The metabolic rates of the Soldiers increased as they walked, so they were between 350-400 W at the end of the experiment.

The ambient air circulation systems were usually more effective at lowering heart rate and skin temperature when they were worn over the T-shirt and under the DCU shirt and body armor (as opposed to over the DCU shirt). However, these PCS only decreased body core temperature 0.1-0.2°C; this was not a significant decrease as compared to wearing no PCS at all. The Soldiers were able to perceive differences in their comfort while wearing them though.

Overall Conclusions

Although some of the ambient air systems removed higher amounts of heat from the body during the manikin tests conducted at low levels of humidity, these results were not seen in the human subject evaluations because the Soldiers could not sweat at the same rate as the manikin did in order to maintain 100% skin wettedness and maximize evaporative cooling. In fact, some of the systems actually dried out the Soldiers' T-shirts under the body armor in some places, thus stopping the evaporative cooling from taking place in those areas. Some phase change material vests can provide adequate cooling for less than an hour – thus limiting their use in military applications.

Recommendations

Providing a personal cooling system for the dismounted Infantry Soldier is an engineering challenge from many perspectives. Soldiers are actively working in difficult environments with limited access to power. It is also clear that many companies are actively working on products that could be used by Soldiers. It is recommended that the Army stay abreast of developments in this area as new products are constantly entering the market place.

The primary benefit of a Soldier using a PCS is to guard against heat stress and extend mission time. The experimental evaluation of the PCS systems on Soldiers was done at 40°C under high solar load. Although this represents a challenging condition, environmental conditions in the desert can get much worse. The majority of Soldiers completing this study were able to complete baseline 2-hour tests wearing body armor without a PCS. This limited our ability to delineate the systems based on mission time and made core temperature the primary variable to compare. Increasing the environmental temperature during testing would provide a more challenging evaluation of the PCS systems. Subject safety is always a concern, however, so the proper protocols and safety measures would need to be in place for such a study.

The research team feels strongly that many of the systems tested can be optimized for the dismounted Soldier. This includes optimum ergonomics and optimum thermal operation of the systems. Continued work with suppliers supporting advanced testing will provide designers with the type of feedback necessary to increase performance of these systems. Support from the DOD to allow advanced component testing and optimization has high potential to increase performance of these systems. Our team recommends a two part approach. First, limited field testing should be done on systems under consideration to provide valuable ergonomic feedback to the designers. Second, performance optimization work should be done focusing on specific components in the PCS. For example, air distribution and air flow rates are a critical consideration in the design of air motion systems.