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CHEMICAL WARFARE PROTECTIVE CLOTHING: IDENTIFICATION OF PERFORMANCE LIMITATIONS AND THEIR POSSIBLE SOLUTION

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The major factors which contribute to the increased thermal burden imposed by chemical warfare (CW) protective clothing are the insulation characteristics (clo) and the evaporative impedance (i_m) of the material; and, increased levels of energy expenditure for performing physical exercise while wearing these clothing systems. An approach to alleviating heat stress is through the use of auxiliary cooling. A number of prototype microclimate cooling systems which employ either air-cooled or liquid-cooled vests have been shown to be effective in reducing soldier heat strain during exercise while wearing CW protective clothing in hot environments. Our Institute has also developed the ability to predict the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in CW protective clothing in a wide variety of environmental conditions.

1. INTRODUCTION

Performance of muscular exercise in hot environments has been shown to be influenced by aerobic fitness [1], acclimation state [2] and hydration level [3]. An aerobically fit individual who is exercise-heat acclimated and fully hydrated should experience less body-heat storage and enhanced performance while exercising in the heat [3]. However, it is questionable whether these three factors would have major impact in reducing the added thermal burden imposed by wearing low permeable or impermeable protective clothing during exercise-heat stress of prolonged duration.

Chemical protective clothing characteristically has high thermal insulation and low moisture permeability. These clothing characteristics place severe limitations on the body's usual heat dissipating mechanisms, namely the evaporation of sweat. Auxiliary cooling has been suggested to be essential in industrial and military settings when exercising in hot environments while wearing low permeable or impermeable protective garments [4,5,6]. Effective auxiliary cooling is dependent on active sweating for evaporative cooling [6].

This paper will briefly review our biophysical test observations concerning the auxiliary cooling provided by five water-cooled undergarments in association with chemical protective clothing as directly evaluated on a life-size, sectional copper manikin. The report will then review recent findings from our Institute demonstrating that auxiliary cooling significantly reduces physiological strain and increases tolerance time of soldiers exercising in protective clothing in hot environments.

2. METHODS

2.1 Experiment 1

An electrically heated copper manikin capable of individual sectional evaluations of the head, torso, arms, hands, legs and feet was used for these experiments. The environmental conditions were either 29.4°C (85% relative humidity) or 51.7°C (25% relative humidity). The five water-cooled undergarments which were tested included: (a) a water-cooled cap for head cooling; (b) a water-cooled vest for torso cooling; (c) a water-cooled cap and vest for head and torso cooling; (d) a short water-cooled undergarment for upper arms, upper legs and torso cooling, and, (e) a long water-cooled undergarment for upper and lower arms, upper and lower legs, head and torso cooling. None of these water-cooled undergarments provided cooling to the hands or feet. Cooling water inlet temperature varied over the range of 7 to 28°C. The components of the combat vehicle crewman (CVC) ensemble and the chemical protective suit were worn over these water-cooled undergarments. A more detailed explanation of these methods can be found in a previously published report [7].

2.2 Experiment 2

In these experiments, water-cooled, air-cooled and ambient air-ventilated auxiliary cooling vests were evaluated in a hot-wet climate (35°C, 75% relative humidity) and a hot-dry climate with added infrared radiation (49°C, 20% relative humidity, 68°C black globe temperature). Twelve male volunteer soldiers, dressed in full chemical warfare uniforms, attempted 120 min of exposure to each combination of climate and cooling vest. Total exercise was 20 min and rest time 100 min which resulted in a mean time weighted metabolic rate of 180 W. The results concerning the ambient air-ventilated auxiliary cooling vest will not be presented in this report but can be found with a more detailed explanation of these methods in a previously published paper [6].

2.3 Experiment 3

After being heat acclimated for five consecutive days, four male volunteer soldiers dressed in CVC uniform and full chemical protective clothing attempted 300 min heat exposures (49°C, 20°C dp) at two different metabolic rates (175 and 315 W) each with five different auxiliary cooling combinations. The 175 W metabolic rate involved 45 min of rest and 15 min of walking (1.01 $m \cdot s^{-1}$) per hour while the 315 W metabolic rate involved 45 min of walking at this same speed and 15 min of rest per hour. At each of these two metabolic rates, five combinations of dry bulb and dew point temperatures that ranged from 20-27°C db and 7-18°C dp were supplied to an air-cooled vest at 15 scfm. During each of the two control tests, the subjects did not wear the air-cooled vest; however, the face piece to the mask was ventilated with 3 scfm of ambient air. A more detailed description of these methods can be found in a soon to be published report [5].

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2.4 Experiment 4

In these field observations, physiological responses of tank crew members inside the armored vehicle were evaluated while wearing an air-cooled vest under the standard CVC uniform and full chemical protective clothing in tropic (Tropic Test Center, Republic of Panama) and desert (Yuma Proving Grounds, AZ) environments. Six male volunteer tank crewmen participated in the tropic test while four different male volunteer crewmen were evaluated during the desert tests. During the tropic test, ambient temperature ranged from 27-36°C db and relative humidity between 40-81% while during the desert tests the ambient temperature ranged from 23-38°C db and relative humidity from 20-64%. These crewmen performed continuous operations for up to 12 hours. A more detailed description of these methods can be found in a recently published report [4].

3. RESULTS AND DISCUSSION

Figure 1 presents the range of cooling in watts provided by each of the five water-cooled undergarments as a function of the cooling water inlet temperature from Experiment 1. These findings illustrate that at a cooling water inlet temperature of about 10°C the water-cooled cap could not provide 100 W of cooling; however, both the short and long water-cooled undergarments provided approximately 400 W of cooling. A "comfortable" cooling water inlet temperature of 20°C was shown to provide 46 W of cooling for the water-cooled cap, 66 W for the water-cooled vest, 112 W for the water-cooled cap and vest, 264 W for the short water-cooled undergarment and 387 W for the long water-cooled undergarment [7]. As expected, these results support the conclusion that cooling in watts increases with greater body surface coverage from the water-cooled undergarment and illustrates the importance of biophysical assessments of the heat transfer characteristics concerning prototype auxiliary cooling systems using heat copper manikins.

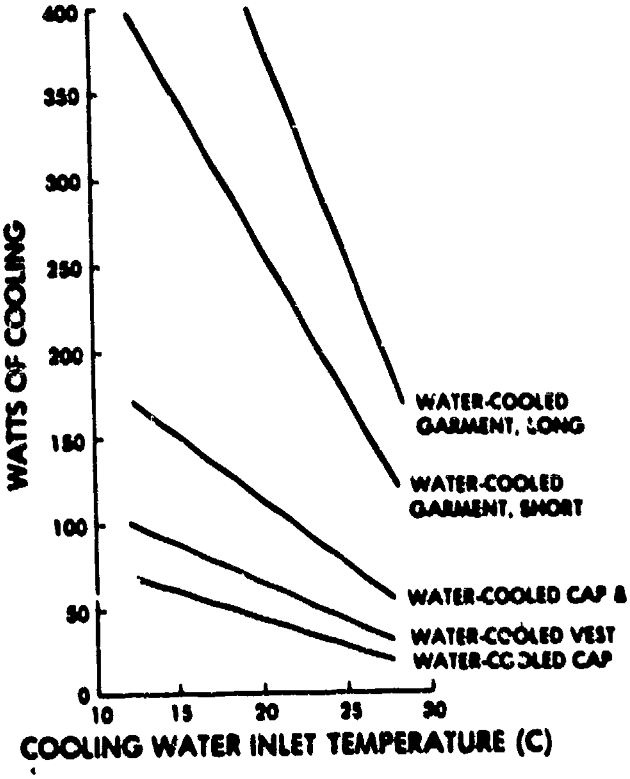

FIGURE 1. Watts of cooling provided by five water-cooled undergarments as a function of the cooling water inlet temperature for a completely wet (i.e., maximal sweating) skin condition [7].

Table 1 shows a summary of the thermoregulatory trends between auxiliary cooling (water-cooled and air-cooled vests) and no auxiliary cooling during both hot-wet and hot-dry exposures from Experiment 2. In the hot-wet condition, the water- and air-cooled vests displayed better thermoregulatory status than predicted for these subjects without auxiliary cooling: greater than 1°C lower rectal temperature (T_{re}), 2.5 to 3.5°C lower mean skin temperature ($\bar{T}_{sk}$), 10 to 20 $b \cdot min^{-1}$ lower heart rate (HR), about one tenth the heat storage (ΔS) and one third less sweating ($\dot{m}_{sw}$). When compared to no auxiliary cooling (predicted), the evaporative sweat rate (E_{sk}) was lower for the water-cooled vest but slightly higher for the air-cooled vest. Comparing the air- and water-cooled vests, no differences ($p>0.05$) were found for T_{re}, $\bar{T}_{sk}$, ΔS and $\dot{m}_{sw}$; however, HR was lower ($p<0.05$) and E_{sk} was higher ($p<0.05$) for the air-cooled vest. In the hot-dry condition, the water- and air-cooled vests again showed better thermoregulatory responses than no auxiliary cooling (predicted): 1°C lower T_{re}, 1 to 2°C lower $\bar{T}_{sk}$, 30 $b \cdot min^{-1}$ lower HR and one third the ΔS. Compared to no auxiliary cooling (predicted), $\dot{m}_{sw}$ was the same for both vests but E_{sk} appeared greater. The E_{sk} was greater ($p<0.05$) for the air-cooled vest when contrasted to the water-cooled vest. These authors concluded that an air-cooled vest can be used with the same efficiency as a water-cooled vest and both are clearly superior to no auxiliary cooling under hot-wet or hot-dry conditions [6].

TABLE 1. SUMMARY OF THERMOREGULATORY TRENDS BETWEEN AUXILIARY COOLING AND NO AUXILIARY COOLING DURING HOT-WET AND HOT-DRY EXPOSURES

	HOT-WET			HOT-DRY		
	WATER-COOLED VEST	AIR-COOLED VEST	DIFFERENCE	WATER-COOLED VEST	AIR-COOLED VEST	DIFFERENCE
T_{re} (°C)	↓	↓	NS	↓	↓	NS
$\bar{T}_{sk}$ (°C)	↓	↓	NS	↓	↓	NS
HR ($b \cdot min^{-1}$)	↓	↓	−	↓	↓	NS
ΔS (W)	↓	↓	NS	↓	↓	NS
$\dot{m}_{sw}$ ($g \cdot m^{-2} \cdot h^{-1}$)	↓	↓	NS	=	=	NS
$\dot{E}_{sk}$ ($g \cdot h^{-1}$)	↓	= OR ↑	+	↑	↑	+

↓, AUXILIARY COOLING (WATER- OR AIR-COOLED VEST) IS LOWER THAN NO AUXILIARY COOLING (PREDICTED); ↑, AUXILIARY COOLING (WATER- OR AIR-COOLED VEST) IS HIGHER THAN NO AUXILIARY COOLING (PREDICTED); =, NO DIFFERENCE BETWEEN AUXILIARY COOLING AND NO AUXILIARY COOLING; NS, NOT SIGNIFICANT; +, AIR-COOLED GREATER THAN WATER COOLED ($p<0.05$); −, AIR-COOLED LESS THAN WATER COOLED ($p<0.05$).

Figure 2 displays the T_{re} responses over time for the four subjects in Experiment 3 during the control test which involved no air-cooled vest but full chemical protective clothing at the low metabolic rate of 175 W. All subjects show a rapid rate of rise in T_{re} during this test and were unable to complete the proposed 300 min heat exposure. Average endurance time was 118 min. The rapid rate of rise in T_{re} which is associated with an increased rate of body heat storage has been implied to be a good prognosticator of exercise-heat tolerance [8].

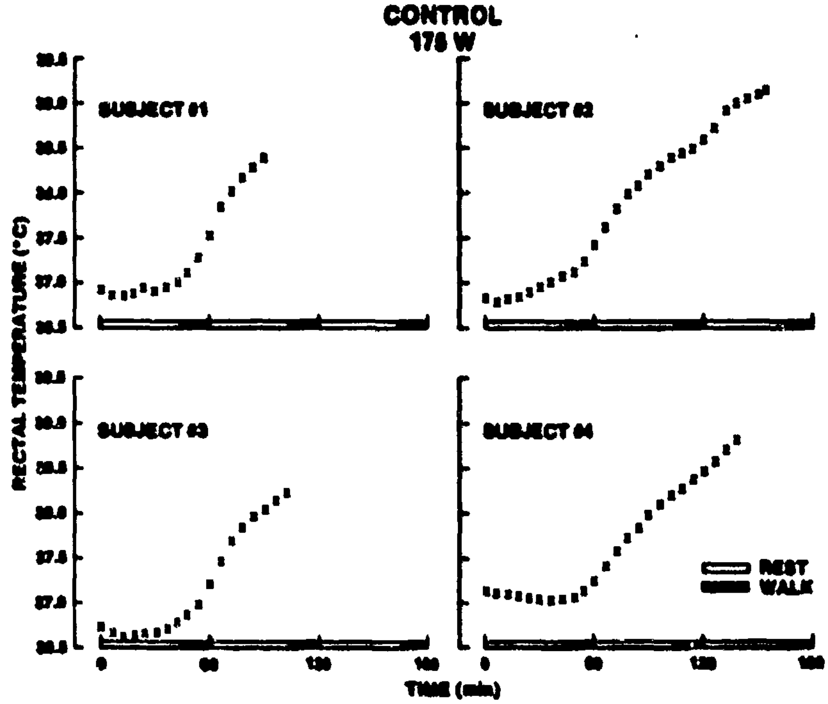

FIGURE 2. Rectal temperatures over time for four subjects during periods of rest and treadmill walking (1.01 $m \cdot s^{-1}$) while wearing full chemical protective clothing but no air-cooled vest [unpublished from 5].

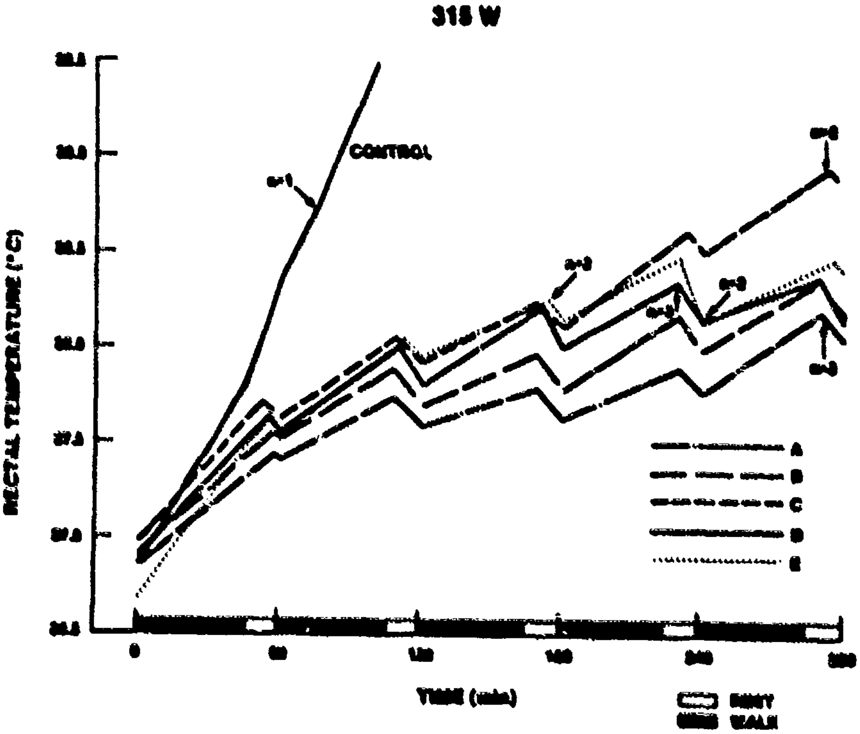

FIGURE 3. Rectal temperatures over time for the five cooling combinations (A,B,C,D and E provide 687, 631, 620, 564 and 498 total watts of cooling, respectively) and the control test at 315 W [5].

In contrast to the T_{re} values for the control test at 175 W in Experiment 3, all five cooling combinations allowed for the maintenance of a near constant body temperature while in full chemical protective clothing [5]. In addition, there were no significant differences in T_{re} responses among the five cooling combinations during the various rest or exercise periods ($p>0.05$). However, at the higher metabolic rate of 315 W also evaluated in Experiment 3, the air-cooled vest at all five cooling combinations was less effective in maintaining T_{re} as illustrated in Figure 3. With all five cooling combinations, T_{re} decreased during the various rest periods but also increased significantly over time ($p<0.05$). After the fourth exercise bout (about 235 min), peak T_{re} averaged 38.0 for A (n=4), 38.2 for B (n=4), 38.3 for D (n=3), 38.5 for E (n=3) and 38.6°C for C (n=4). Nevertheless, all five cooling combinations were more effective in lessening the rate of rise in T_{re} than no cooling (control).

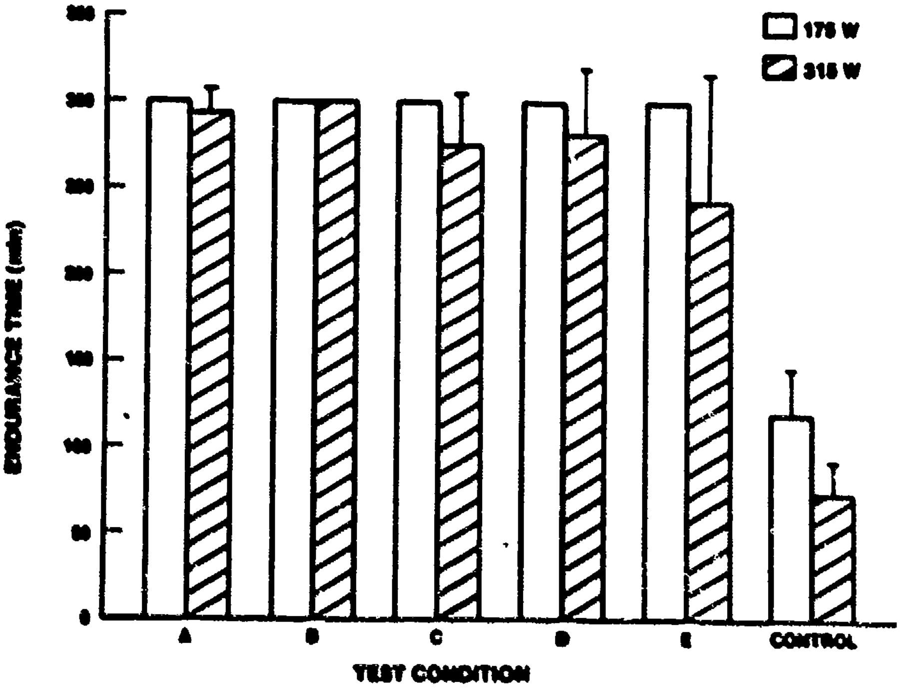

FIGURE 4. Endurance times for each of the five cooling combinations and control test at either 175 or 315 W [5].

Figure 4 presents the endurance times for each of the five cooling combinations and for the control tests at metabolic rates of 175 and 315 W. At 175 W, all subjects were able to complete the 300 min heat exposure for all five cooling combinations; however, without the cooling vest (control) endurance time was limited to an average of 118(±27,SD) min. At 315 W, endurance times did not differ significantly ($p>0.05$) between the five cooling combinations (range, 240-300 min); however, with no auxiliary cooling the endurance time averaged only 73(±19,SD) min.

Figure 5 shows the mean T_{re} responses for the four tank crewmen during the 12-hour tropic test of Experiment 4. These crewmen displayed a group decrease in T_{re} during the first hour in the tank followed by a mean increase in T_{re} of 0.5°C over the next 11 hours. While not approaching our physiological safety limit, T_{re} did show a statistically significant increase ($p<0.05$) over this 12-hour test [4]. Mean T_{re} at the start and end of this tropic test were 37.2±0.5 and 37.4±0.4°C, respectively. However, at this low metabolic rate, the air-cooled system appears to have helped increase the evaporative cooling capabilities of these subjects during extended operations in the tropics. Similar results were observed during extended operations in desert environments [4].

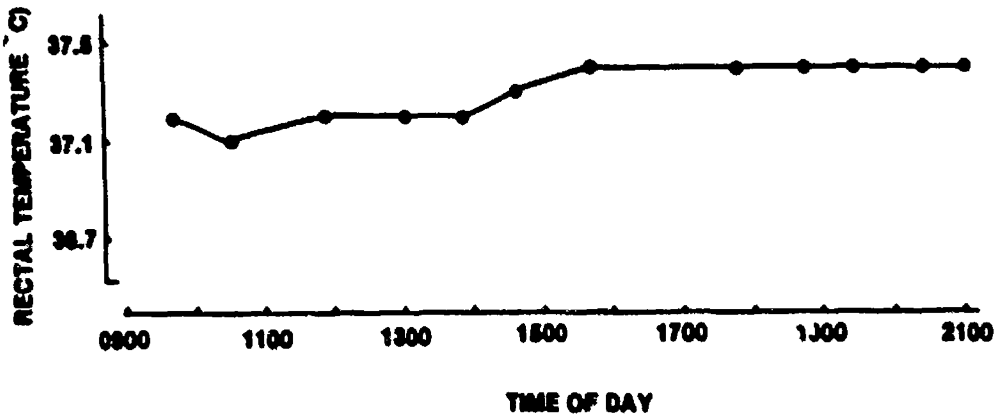

FIGURE 5. Mean rectal temperature of the four tank crewmen during a 12-hour extended operations field test in the tropics [4].

The Military Ergonomics Division of our Institute has developed the ability to predict the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in CW protective clothing in a wide variety of environmental conditions. This comprehensive heat stress prediction model encompasses a series of predictive equations for deep body temperature, heart rate and sweat loss responses for clothed soldiers performing physical exercise at various environmental extremes [9]. Our model includes a clothing menu which incorporates a variety of low permeable protective clothing ensembles. Currently, our prediction model is programmed on both a desk-top computer and hand-held calculator and with some possible minor adjustments should be quite applicable for industrial use.

4. CONCLUSIONS

Over the last decade, our Institute has maintained an active research program evaluating the thermal burden imposed by wearing chemical warfare (CW) protective clothing during exercise-heat stress. Through the use of a sectional copper manikin which is life-size, measurements can be made of the insulation characteristics (clo) and evaporative impedance (i_m/clo) of low permeable or impermable clothing ensembles. In addition, the cooling power in watts at a given cooling water inlet temperature has been shown to increase with greater body surface area coverage by a water-cooled undergarment. Except for the separate use of a water-cooled cap, a collection of five water-cooled systems, singularly or in combination, have the potential to remove the metabolic heat produced in the sedentary state (about 80 W; water-cooled vest, water-cooled cap and vest) or in a highly active state (about 400 W; short or long water-cooled undergarment). A number of prototype microclimate cooling systems involving both air-cooled and liquid-cooled vests have been shown to be effective in alleviating heat stress in soldiers during light exercise while wearing CW protective clothing in hot-wet or hot-dry environments. Microclimate cooling while wearing CW protective clothing in armored vehicles has also been shown to be effective in alleviating heat stress during sustained 12-hour operations involving light exercise in tropic or desert environments. For soldiers performing exercise in CW protective clothing, the most important factor affecting thermal strain appears to be the level of metabolic energy expenditure. We have demonstrated that when moderate to heavy exercise is performed in hot environments, some soldiers cannot tolerate these conditions for prolonged periods of time even with the inclusion of an air-cooled vest. Possibly, a greater body surface area coverage by microclimate cooling would help solve this problem. Finally, our Institute has developed the ability to predict the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in CW protective clothing or other low permeable clothing ensembles in a variety of hot environments.

REFERENCES

[1] Pandolf, K.B., Effects of physical training and cardiorespiratory fitness on exercise-heat tolerance: recent observations, Med.Sci.Sports 11:60-65, 1979.

[2] Nadel, E.R., Pandolf, K.B., Roberts, M.F. and Stolwijk, J.A.J., Mechanisms of thermal acclimation to exercise and heat, J.Appl.Physiol. 37:515-520, 1974.

[3] Sawka, M.N., Francesconi, R.F., Young, A.J. and Pandolf, K.B., Influence of hydration level and body fluids on exercise performance in the heat, JAMA 252:1165-1169, 1984.

[4] Cadarette, B.S., Pimental, N.A., Levell, C.A., Bogart, J.E. and Sawka, M.N., Thermal responses of tank crewmen operating with microclimate cooling under simulated NBC conditions in the desert and tropics, Tech.Rpt. T7/86, U.S. Army Research Institute of Environmental Medicine, Natick, MA, 1986.

[5] Pimental, N.A., Cosimini, H.M., Sawka, M.N. and Wenger, C.B., Effectiveness of an air-cooled vest using selected air temperature and humidity combinations, Aviat.Space Environ.Med. 58:in press,1987.

[6] Shapiro, Y., Pandolf, K.B., Sawka, M.N., Toner, M.M., Winsmann, F.R. and Goldman, R.F., Auxiliary cooling: comparison of air-cooled vs. water-cooled vests in hot-dry and hot-wet environments, Aviat.Space Environ.Med. 53:785-789, 1982.

[7] Fonseca, G.F., Effectiveness of five water-cooled undergarments in reducing heat stress of vehicle crewmen operating in a hot-wet or hot-dry environment, Tech.Rpt. T2/81, U.S. Army Research Institute of Environmental Medicine, Natick, MA, 1981.

[8] Pandolf, K.B. and Goldman, R.F., Convergence of skin and rectal temperatures as a criterion for heat tolerance, Aviat.Space Environ. Med. 49:1095-1101, 1978.

[9] Pandolf, K.B., Stroschein, L.A., Drolet, L.L., Gonzalez, R. and Sawka, M.N., Prediction modeling of physiological responses and human performance in the heat, Comput.Biol.Med. 16:319-329, 1986.