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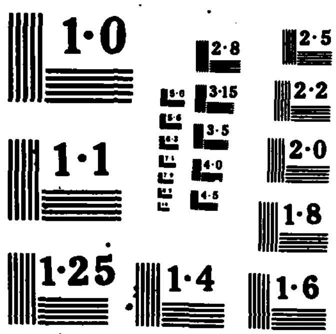

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REPORT NO. T5/86

AD-A168 370

EFFECTIVENESS OF AN AIR-COOLED VEST IN REDUCING HEAT STRESS OF SOLDIERS IN CHEMICAL PROTECTIVE CLOTHING

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

DECEMBER 1985

UNITED STATES ARMY
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This study evaluated the effectiveness of an air-cooled vest in reducing physiological strain of soldiers in chemical protective clothing during exercise-heat stress. Four male soldiers attempted a 12-hour and a 3-hour heat exposure while wearing chemical protective clothing and an air-cooled vest (air supplied to vest - 16°C db, 3°C dp; 15 scfm to torso, 3 scfm to face). During these exposures, subjects performed repeated bouts of rest and treadmill walking; metabolic rate averaged 240 and 340 W for the 12- and 3-hour tests, respectively. Environmental conditions were 49°C db, 20°C dp; a radiant heat load of

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70 W was added during the 3-hour test. All subjects were able to complete the 12- and 3-hour tests. Mathematical equations by Givoni and Goldman (2, 3) predicted tolerance times for the 12- and 3-hour tests with no auxiliary cooling to be about 110 and 80 min, respectively. During the 12-hour test, final rectal temperature (exercise) averaged 38.0 ± 0.3°C and peak rectal temperature did not exceed 38.5°C for any subject. Final heart rate (exercise) averaged 140 ± 19 $b \cdot min^{-1}$. Sweating rate averaged 275 ± 19 $g \cdot m^{-2} \cdot hr^{-1}$. During the 3-hour test, final rectal temperature averaged 38.5 ± 0.6°C and peak rectal temperature did not exceed 39.2°C for any subject. Final heart rate (exercise) was 150 ± 15 $b \cdot min^{-1}$. Sweating rate averaged 566 ± 50 $g \cdot m^{-2} \cdot h^{-1}$. The air-cooled vest was effective in reducing physiological strain, and increasing tolerance time, of soldiers during exercise-heat stress. In addition, soldiers rated the heat exposures with the vest as thermally comfortable.

TECHNICAL REPORT

No. T5/86

EFFECTIVENESS OF AN AIR-COOLED VEST IN REDUCING HEAT STRESS OF SOLDIERS IN CHEMICAL PROTECTIVE CLOTHING

by

Nancy A. Pimental, Michael N. Sawka, Ph.D., and Thomas H. Tassinari*

December 1985

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The views, opinions and/or findings in this report are those of the authors, and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation.

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

ABSTRACT

This study evaluated the effectiveness of an air-cooled vest in reducing physiological strain of soldiers in chemical protective clothing during exercise-heat stress. Four male soldiers attempted a 12-hour and a 3-hour heat exposure while wearing chemical protective clothing and an air-cooled vest (air supplied to vest = 16°C db, 3°C dp; 15 scfm to torso, 3 scfm to face). During these exposures, subjects performed repeated bouts of rest and treadmill walking: metabolic rate averaged 240 and 340 W for the 12- and 3-hour tests, respectively. Environmental conditions were 49°C db, 20°C dp; a radiant heat load of 70 W was added during the 3-hour test. All subjects were able to complete the 12- and 3-hour tests. Mathematical equations by Givoni and Goldman (2,3) predicted tolerance times for the 12- and 3-hour tests with no auxiliary cooling to be about 110 and 80 min, respectively. During the 12-hour test, final rectal temperature (exercise) averaged 38.0 $\pm$ 0.3°C and peak rectal temperature did not exceed 38.5°C for any subject. Final heart rate (exercise) averaged 140 $\pm$ 19 $b \cdot min^{-1}$. Sweating rate averaged 275 $\pm$ 19 $g \cdot m^{-2} \cdot hr^{-1}$. During the 3-hour test, final rectal temperature averaged 38.5 $\pm$ 0.6°C and peak rectal temperature did not exceed 39.2°C for any subject. Final heart rate (exercise) was 150 $\pm$ 15 $b \cdot min^{-1}$. Sweating rate averaged 566 $\pm$ 50 $g \cdot m^{-2} \cdot h^{-1}$. The air-cooled vest was effective in reducing physiological strain, and increasing tolerance time, of soldiers during exercise-heat stress. In addition, soldiers rated the heat exposures with the vest as thermally comfortable.

INTRODUCTION

The insulation and low moisture permeability of chemical protective clothing severely limit the body's normal heat dissipating mechanisms, most markedly the evaporation of sweat. The magnitude of this heat stress problem has been documented for many years (4-6, 10-13). The average tolerance time when soldiers perform moderate work in hot environments while wearing protective clothing is limited to about 30-90 minutes (2-6, 11-13). This heat stress problem has led to the development and evaluation of various auxiliary cooling devices.

The Individual Protection Laboratory, US Army Natick Research, Development and Engineering Center (USANRDEC), has developed an air-cooled vest for soldiers wearing protective clothing (see Appendix A). The vest is designed to provide 15 scfm of conditioned air to the chest, neck and back and 3 scfm to the face. This cooling system was previously tested on soldiers under moderate heat stress conditions. The system was tested on crewmen operating for 165 min in an M1E1 tank parked in a climatic chamber (12). Temperature in the turret was 28°C; metabolic rates of the crewmen were 150-360 W. The vest was supplied with 15 scfm of air at about 17°C dry bulb temperature. Vest cooling was found to be a significant improvement over air shower alone cooling. The USANRDEC air-cooled vest was also tested on soldiers working at a metabolic rate of 180 W in a hot-humid (35°C dry bulb, 30°C dew point) and a hot-dry (49°C dry bulb, 20°C dew point, 70W solar load) environment (9). The vest was supplied with 11 scfm of air at 20°C dry bulb. The vest significantly reduced thermal strain, and enabled the subjects to complete the 120-min heat exposures.

The purpose of the present study was to evaluate the effectiveness of the USANRDEC air-cooled vest under more severe heat stress conditions. The vest was tested on soldiers working for three hours at a moderate metabolic rate of 340 W, under desert conditions (49°C, 19°C dew point, radiant load 70 W). It was also tested on soldiers working at a light metabolic rate of 240 W for an extended duration (12 hours).

METHODS

Subjects. Four male tank crewmen from the 2nd Battalion, 6th Cavalry, Fort Knox, Kentucky, participated in this study. They received a physical examination and were informed of the purpose and procedures of the study, any known risks, and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent. The physical characteristics of the subjects were: age, 22 years (range 20-25); height, 183 cm (range 167-203); weight, 78.2 kg (range 58.5-95.2); body surface area, 2.00 m^2 (range 1.65-2.20); and body fat, 12% (range 6-22) as estimated from skinfold thickness at four sites (1).

Experimental design. Testing was conducted in a climatic chamber at USANRDEC (Natick, MA) in July-August. All four subjects had previously worn chemical protective clothing a number of times, for at least four hours continuously. On one day before testing, the subjects were familiarized with walking on the treadmill while wearing the combat vehicle crewman uniform, body armor and MOPP level 4 protective clothing (overgarment, overboots, mask/hood, gloves). Subjects were then heat acclimated on four consecutive days by walking on a level treadmill at 1.4 $m \cdot s^{-1}$ for 180 min in a 49°C dry bulb, 20°C dew point environment. During heat acclimation, subjects wore shorts, T-shirts, socks and tennis shoes. Following acclimation, subjects attempted a 3-hour and a 12-hour heat exposure while wearing the combat vehicle crewman uniform, body armor, helmet, MOPP level 4 protective clothing and the USANRDEC air-cooled vest. The air supplied to the cooling vests was 16°C db, 2°C dp; it was provided by an air conditioning unit located outside the climatic chamber. Environmental conditions during the 12-hour test were 49°C dry bulb, 20°C dew point and 49°C black globe temperature. A radiant heat load of approximately 70 W was added during the 3-hour test; dry bulb temperature was 49°C, dew point temperature was 19°C and black globe temperature was 70°C. Wind speed was 1.1 $m \cdot s^{-1}$ during both tests. These conditions correspond to WBGT temperatures of approximately 34°C and 38°C for the 12-hour and 3-hour tests, respectively. During the 3-hour test, subjects repeated three bouts of 10 min seated rest, 50 min walking on a level treadmill at 1.0 $m \cdot s^{-1}$ (time-weighted metabolic rate 340 W). During the 12-hour test, subjects alternated sitting and walking in 50-min intervals (time-weighted metabolic rate 240 W). Both tests began at approximately 0800. Subjects were encouraged to drink water during the heat exposures. Since the M17 mask had no drinking tube, subjects drank through a flexible plastic straw threaded under the hood and mask. During the 12-hour test, subjects were given one Meal, Ready-to-Eat (they were allowed to take off the mask and hood for approximately 30 minutes to eat).

Measurements. The electrocardiogram was obtained from chest electrodes (CM5 placement) and displayed on an oscilloscope and cardiotachometer unit. Rectal temperatures were measured using rectal thermistor probes inserted approximately 10 cm beyond the anal sphincter. Total body sweating rates were calculated from pre- and post-test nude body weights, adjusted for food and water intake and urine output. During the heat exposures, subjects were asked to rate their thermal sensation for various body parts - arms, back, chest, face, feet, hands, head, legs, overall. The Thermal Sensation Scale is included as Figure 5A.

Subjects were removed from the heat exposures: if rectal temperature reached 39.5°C, if heart rate exceeded 180 $b \cdot min^{-1}$ for five minutes continuously, if they voluntarily withdrew, or at the discretion of the medical monitor or principal investigator.

Statistical treatment. Repeated measures analyses of variance and t-tests were used to analyze rectal temperature and heart rate data. Statistical significance was accepted at the 0.05 level.

RESULTS

Heat acclimation was demonstrated by the absence of a decrease in either the final rectal temperature or heart rate between days three and four of heat acclimation ($p > 0.05$). Final rectal temperature averaged 37.9°C on day three, and 37.8°C on day four. Final heart rate averaged 119 $b \cdot min^{-1}$ on day three, and 117 $b \cdot min^{-1}$ on day four.

All subjects were able to complete both the 3- and 12-hour heat exposures. Rectal temperature responses ($\bar{X}$, SD) during the 12-hour test are presented in Figure 1. Peak rectal temperature following each exercise bout increased slightly over time ($p < 0.05$). Rectal temperature dropped significantly ($p < 0.05$) during the 50-min rest breaks, to an average of 37.3°C. Peak rectal temperature (after the final exercise bout) averaged 38.0 $\pm$ 0.3°C (range 37.7-38.5); this represented an average increase of 1.1°C over the initial resting value. The highest rectal temperature (following exercise) for any individual subject was 38.5°C. Heart rate responses during the 12-hour test are shown in Figure 2. Heart rate during the final exercise bout averaged 140 $\pm$ 19 $b \cdot min^{-1}$ (range 112-153). During the final rest period, heart rate was 102 $\pm$ 16 $b \cdot min^{-1}$ (range 80-114).

The rectal temperature and heart rate data for the 3-hour heat exposure are presented in Figures 3 and 4, respectively. Peak rectal temperature following exercise bouts increased significantly over time ($p < 0.05$). During the 10-min rest breaks, rectal temperature decreased by an average of 0.1°C. Rectal temperature at the end of the exposure averaged 38.5 $\pm$ 0.6°C (range 37.8-39.2). This represented a 1.7°C increase in rectal temperature over the initial resting value. The highest rectal temperature for any subject was 39.2°C. Heart rate increased over time during the 3-hour test ($p < 0.05$) (Figure 4). Final heart rate (during exercise) was 150 $\pm$ 15 $b \cdot min^{-1}$; the range was 128-163 $b \cdot min^{-1}$.

Sweating rate during the 12-hour test averaged 275 $\pm$ 19 $g \cdot m^{-2} \cdot h^{-1}$ (range 250-294). During the 3-hour test, sweating rate averaged 566 $\pm$ 50 $g \cdot m^{-2} \cdot h^{-1}$ (range 501-616). For the 3-hour test, the average body weight loss was less than 1%. For the 12-hour test, there was a slight gain in body weight (0.4%).

The Thermal Sensation Scale and the thermal sensation ratings are presented in Figures 5A and 5B. Ratings for the various body parts are shown in increasing order. For both the 12-hour and 3-hour tests, the torso was rated the lowest ("cool"), the face and overall ratings were "comfortable", the arms, feet, head and legs were "warm", and the hands were "hot-very hot".

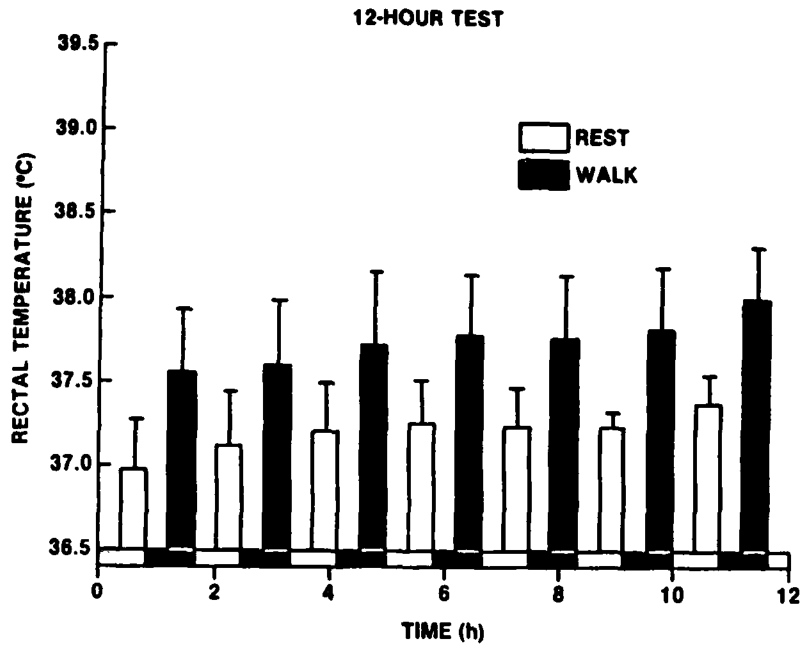

Figure 1. Rectal temperature responses ($\bar{X}$, SD) during the 12-hour test.

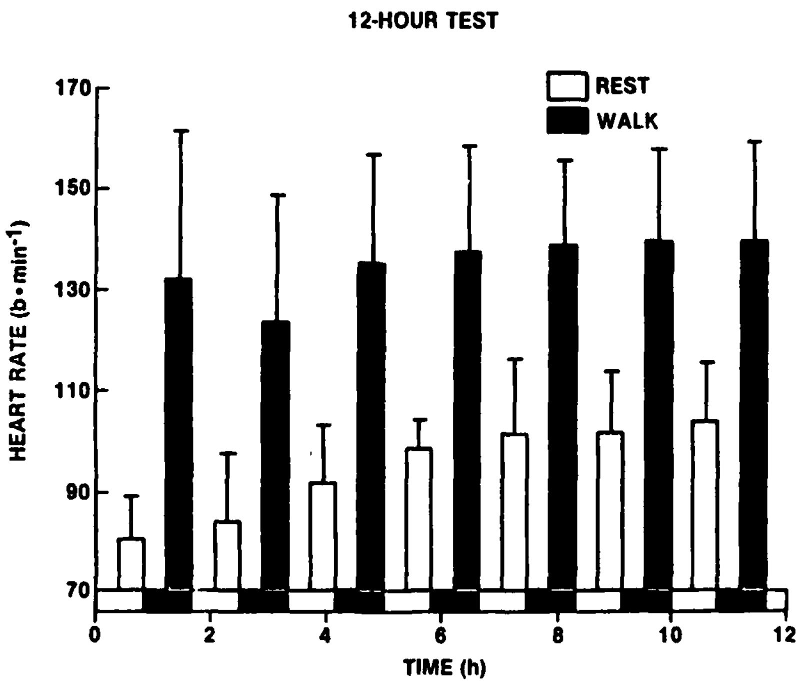

Figure 2. Heart rate responses ($\bar{X}$, SD) during the 12-hour test.

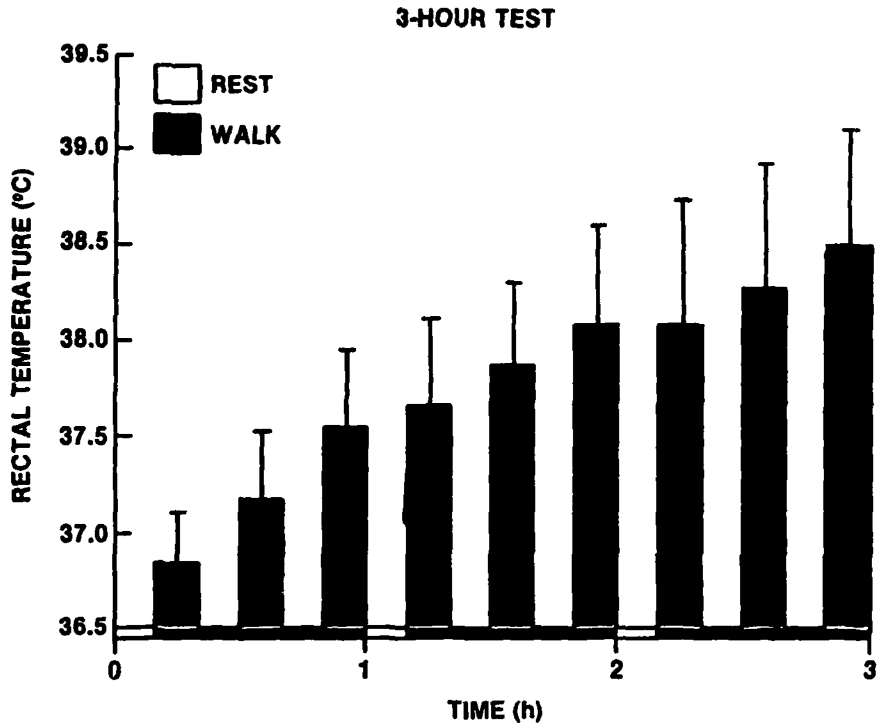

Figure 3. Rectal temperature responses ($\bar{X}$, SD) during the 3-hour test.

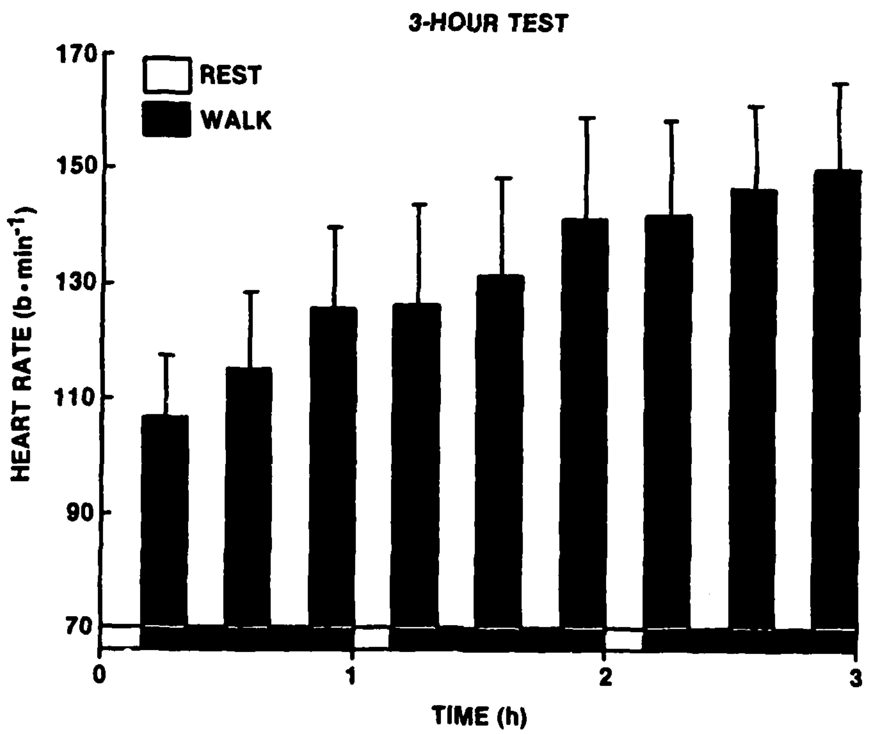

Figure 4. Heart rate responses ($\bar{X}$, SD) during the 3-hour test.

THERMAL SENSATION SCALE

0.0	UNBEARABLY COLD
0.5	
1.0	VERY COLD
1.5	
2.0	COLD
2.5	
3.0	COOL
3.5	
4.0	COMFORTABLE
4.5	
5.0	WARM
5.5	
6.0	HOT
6.5	
7.0	VERY HOT
7.5	
8.0	UNBEARABLY HOT

Figure 5A. Thermal Sensation Scale.

THERMAL SENSATION

	12-HOUR TEST		3-HOUR TEST
TORSO	3.1	CHEST	3.3
		BACK	3.4
FACE	4.2	FACE	4.0
OVERALL	4.3	OVERALL	4.2
ARMS	4.8	HEAD	4.7
HEAD	4.9	FEET	5.0
LEGS	5.1	ARMS	5.1
FEET	5.5	LEGS	5.2
HANDS	5.8	HANDS	6.7

Figure 5B. Thermal sensation ratings for the 3- and 12-hour tests.

DISCUSSION

In the present study, the 3-hour test was conducted at an average metabolic rate of 340 W. This simulates the metabolic rate of an armored vehicle's loader loading 40 rounds per hour or commander during battle (12). Tolerance time under these conditions without the cooling vest was predicted to be about 80 minutes using mathematical equations of Givoni and Goldman (2,3). In our study, the air-cooled vest enabled all four subjects to complete the three hours. Final average rectal temperature was 38.5°C. The air-cooled vest was effective in extending endurance time, however, under these conditions, endurance time is limited to a maximum of about 4-5 hours. If we extrapolate our data, rectal temperature would reach 39.5°C after about 4-1/2 hours; this temperature represents the level at which heavy heat casualties can be expected. During the 10-min rest breaks, rectal temperature dropped only about 0.1°C. Therefore, if endurance time must be extended at this metabolic rate beyond 4-5 hours, longer "rest" breaks (through crew rotation) must be incorporated.

The 12-hour test was conducted at an average metabolic rate of 240 W (50-min work, 50-min rest intervals). This approximates the metabolic rate of an armored vehicle's gunner, driver, or loader during intermittent battle (12). Predicted tolerance time without cooling under these conditions was only about 110 minutes. With the air-cooled vest, subjects were able to complete the 12 hours, with final rectal temperature averaging 38.0°C. The 50-min rest breaks were effective in enabling subjects to perform for an extended duration; during these breaks, rectal temperature dropped to near-initial levels.

Subjects were encouraged to drink water in order to maintain hydration in the present study. Pre- and post-test nude body weights indicated that the subjects did not become dehydrated during either the 3- or 12-hour test. Average body weight loss was less than 1% for the 3-hour test. A 1% reduction in body weight is considered euhydration; increased thermal strain due to hypohydration is usually considered to occur with body weight losses of 2% or more (7). For the 12-hour test, post-test nude body weights were slightly higher than pre-test weights in three of the four subjects. Water consumption averaged 0.9 and 0.6 quarts per hour for the 3- and 12-hour tests, respectively. Water requirements without the cooling vest were predicted using a modified version (USARIEM field model V2.A272) of the equation of Shapiro et al. (8). The predicted requirements were 2.1 and 1.7 quarts per hour for the 3- and 12-hour tests, respectively. Thus, the air-cooled vest reduced drinking water requirements by 2-3 times. This is advantageous for military operations conducted in hot environments, where drinking water supplies may be limited.

Subjects rated their thermal sensation for the various body parts similarly in magnitude and in order for the 3- and 12-hour tests (see Figure 5B). The one exception was the higher rating for the hands in the 3-hour test (6.7; approaching "very hot") as compared to the 12-hour test (5.8; approaching "hot"). This difference may be attributed to the effect of the added radiant heat load on the black butyl gloves. Subjects rated the torso the coolest of the body parts ("cool"). The more peripheral body areas (arms, legs, feet) were rated as "warm". Therefore, the body areas in direct contact with air from the vest felt cool. The average overall thermal effect was "comfortable". Although the face was also rated as comfortable, three of the four subjects commented after the tests that their faces felt hot and they would like more air to the face. Subjects also complained of headaches due to pressure from the mask, its straps and/or the helmet in both tests.

In summary, the USANRDEC air-cooled vest significantly reduced physiological strain, and increased tolerance time of soldiers working in protective clothing in hot environments. In this extreme environment (49°C), the vest enabled soldiers to work at a metabolic rate of 340 W for 3 hours. Using a 1:1 work to rest ratio, tolerance time is extended to over 12 hours. Soldiers perceived these conditions as overall thermally comfortable with the use of the air-cooled vest.

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APPENDIX A

Air-Cooled Vest/Connector for the M1E1 Abrams Tank

The M1E1 microclimate vest is designed to provide chest, neck, and back cooling via a hose and manifold system mounted on an open weave fabric (Figure A1). The hoses are lightweight and crush-resistant and will maintain a constant inside diameter upon bending. Cooled air from the cooling unit is distributed by the connector so that 15 scfm is delivered to the vest and distributed at a ratio of approximately 40% to the chest, 20% to the neck and 40% to the back. The vest is lightweight (approximately 0.45 kg) and offers low resistance to airflow. It is worn over the undershirt and beneath the fragmentation protective vest (Figure A2).

Vest design allows the wearer to connect to the vehicle umbilical from the left or right side using the single air supply hose located in the center of the garment. This feature provides for maximum interface compatibility with the vehicle NBC system. Another design advantage is the bib configuration. The vest can be easily integrated with the fragmentation protective vest.

The prototype air connector (Figure A3) is a multi-functional cooling component that interfaces with the primary and backup NBC protective systems. It splits 18 scfm of cooled air into 3 scfm for the ventilated facepiece and 15 scfm for the vest. Temperature control of vest cooling air is provided by a seven-position by-pass valve in the connector that restricts airflow to the vest while releasing the excess into the crew compartment. Other design features include low pressure drop through the connector, quick-release when disconnecting for rapid vehicle egress, and provisions for using the ventilated facepiece without the vest when the M13A1 backup NBC protective system is being utilized. The vest side of the connector is self-sealing when disconnected to prevent the entry of chemical agents. The connector is fabricated of a lightweight, high-strength engineered thermoplastic that can be injection-molded for maximum production cost effectiveness. Figure A4 illustrates the interface of the air connector with the vest and facepiece.

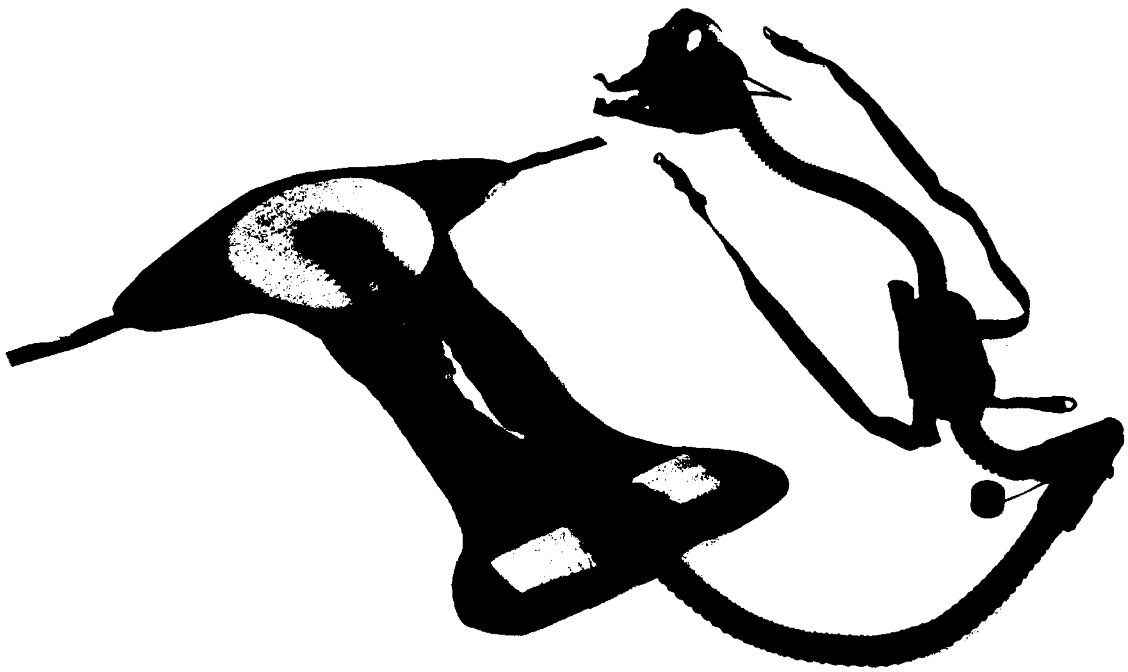

Figure A1. USANRDEC prototype air-cooled vest and connector.

Figure A2. Crewman wearing microclimate system beneath the fragmentation protective vest.

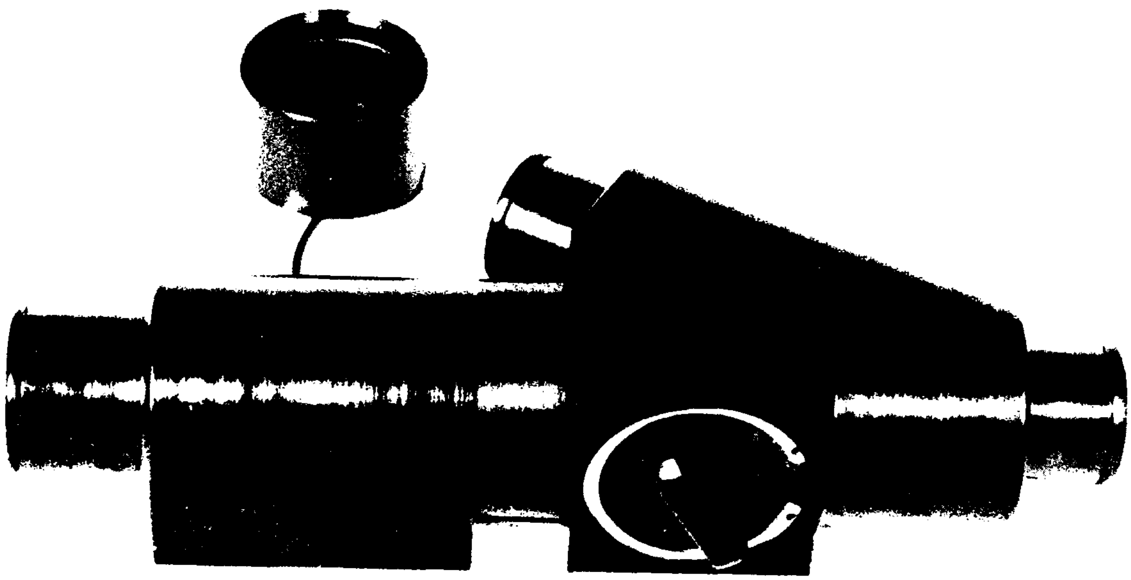

Figure A3. USANRDEC prototype air connector.

Figure A4. Interface of air connector with air-cooled vest and ventilated facepiece.

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