A Review, U.S. Navy (NCTRF) Evaluations of Microclimate Cooling Systems

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13. ABSTRACT *(Maximum 200 words)*

The U. S. Navy Clothing & Textile Research Facility has been involved in the development and testing of microclimate cooling systems (MCS) for several decades. MCS have significantly reduced heat strain in hot environments when worn with either general utility or encapsulating garments. Passive cooling systems, available to the Fleet under a commercial item description, have proven most effective for use with general utility clothing for U. S. Navy applications. Because of problems associated with replenishment, the commercial passive systems are of limited use with encapsulating garments. Prototype passive and active systems for use with encapsulating clothing have been developed and have significantly reduced heat strain in laboratory tests; further development is required to enhance the reliability of these systems.

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INTRODUCTION

Heat stress on land and at sea has always been a concern for the Navy. Shipboard heat stress results from the climatic environment, from heat generated within the spaces, especially in engineering spaces, from the work being performed, and from protective clothing. Common methods of dealing with shipboard heat stress include: improvements to shipboard lagging, repair of steam leaks, increased use of air showers, and rotation of personnel based upon the allowable stay times dictated by the Navy's Physiological Heat Exposure Limit (PHEL) curves.

Another method of providing the relief from heat stress is the use of Microclimate Cooling Systems (MCS) which extract heat from the individual through a garment worn close to the skin. There are basically three categories of MCS: passive systems, liquid systems and gas systems. The passive MCS extract heat by conduction through the use of a frozen gel material that is held in the pockets of a torso vest. The liquid MCS operate by circulating a cooling liquid through a torso vest and extracting heat from the body through conduction. The heat is transferred to a cold substance, i.e., a heat sink, by the circulation of the cooling liquid. The commercially available gas-operated systems consist mainly of either air drawn directly from a compressed air source and fed into an air vest or air that has been conditioned (cooled) before being fed into the air vest. Through convection and evaporation, heat is transferred from the body to the air.

HUMAN FIELD STUDIES

Study #1 The Liquid-Air and the Dry-Ice Cooling Systems (Liquid Systems)

Introduction

In August 1980, the Navy Clothing and Textile Research Facility (NCTRF) conducted a field evaluation test of the cooling capabilities of two life-support-suit assembles at the Naval Explosive Ordnance Disposal Technology Center (NAVEODTECHCEN), Indian Head, Maryland (1). The two assembles were:

a. The Liquid Air System (LAS). A self-contained backpack and suit/helmet ensemble which utilized liquid air to provide breathing air and convective cooling to the body and head.

b. The Dry-Ice Cooling System (DICS). A modified suit and helmet similar to (a) above, which was altered to accommodate liquid-cooled long underwear. A dry-ice cooling backpack supplied the chilled coolant to the underwear, which provided conductive cooling to the body and head. This backpack was developed by NCTRF (2).

Test Method

Six volunteers participated in a total of 29 trials, 15 with the DICS and 14 with the LAS, over an 8 day period. The suited volunteer performed typical tasks required of explosive ordnance disposal personnel in emergency conditions, such as walking distances of 2.3 km and 2.9 km. Both walks involved climbing an incline. Both walks occurred on blacktop roads and generally in direct sunlight. The ambient temperatures were generally in the mid-20°C range in the morning tests and the low-30°C range in the afternoon tests. Oral temperature was measured immediately prior to and after the exercise. Questionnaires were completed daily.

Results

The results indicated that the majority of volunteers preferred the DICS overall and that it provided more effective cooling for a longer period than did the LAS. The average change in oral temperature during exercise was +0.6°C with the LAS, and +0.2°C with the DICS.

Discussion/Conclusions

From the subjective comments of the volunteers, the DICS appeared superior to the LAS suit under moderate to heavy workloads. The change in oral temperature, although relatively small, was significantly greater for the LAS than the DICS and confirmed the subjective findings.

Study #2 Microclimate Cooling Systems: Shipboard Evaluation of Commercial Models

Introduction

NCTRF, under contract to the Navy Science Assistance Program, evaluated the feasibility of using commercial microclimate cooling systems on board ships by conducting an evaluation on the USS LEXINGTON (AVT 16) in the Gulf of Mexico (3).

Test Method

Five commercially available cooling systems from three manufacturers were evaluated. The systems evaluated included: three liquid-cooled MCS - The Life Support Systems, Inc. (LSSI) Cool Head, the LSSI Portapack (LSSIP), and the ILC Dover Cool Vest (ILC); and two air-cooled MCS - the Encon Air System, with (ENCON) and without (AIR) a vortex tube. To provide protection from the possibility of fire, all exterior surfaces of the systems were covered with a fire-retardant fabric.

Both air systems were tethered to a low pressure air line. The LSSIP included a tethered suitcase-like pack which could be picked up and easily moved. The remaining two MCS's were portable, battery-operated, backpack systems. The lightest system was the ambient air system (1.6 kg) while the heaviest system was the LSSI backpack system (7.6 kg).

Twenty nine volunteers were tested in various work spaces which had been identified by ship personnel as having heat stress problems. Sailors were tested during their entire duty shift, normally 4 hours, but in some cases as short as 2 hours. Due to a variety of factors including time constraints, the feasibility of using tethered systems in certain work spaces, and poor performance of the AIR system in early tests, not all subjects tested every cooling system. Each of the systems was tested by at least 13 subjects (except for AIR).

The measurements taken included: dry bulb temperature, wet bulb globe temperature, rectal temperature, skin temperature (3 sites) and heart rate. Cognitive performance was measured with an interactive, computerized, performance assessment battery. Subjects were periodically asked to rate their thermal sensation on a nine point scale ranging from "very cold" to "very hot."

To determine if the commercial systems could be used onboard ship, we monitored several key logistical items including: air line tether set up, battery usage, ice/canister usage, and operational difficulties.

Results

Due to the unseasonably cold weather, environmental conditions during the course of the evaluation were relatively mild. Overall WBGT averaged 24°C; the range was 16-34°C. Overall DB averaged 31°C; the range was 22-42°C.

Even during the control tests with no cooling, rectal temperatures did not increase by more than 0.2°C over the 4-hour duty shifts. Rectal temperature did not significantly differ between the control test and any of the cooling tests, nor among any of the cooling tests. However, there was a significant difference in chest temperature, which was lowest with the ILC (22.2°C).

For the four tasks included in the performance assessment battery, there were no differences in either speed or accuracy between the control test and cooling tests. On the thermal sensation scale, all cooling systems were rated "slightly cool". Control tests were rated significantly higher ("slightly warm").

Of the 10 subjects who used the LSSI, ILC, Vortex, and LSSIP systems, nine rated the ILC system as their first choice. Overall, the Vortex was the second choice, the LSSI Portapack was third and the LSSI backpack was fourth. Of the 10 subjects who used only the ILC and the LSSI backpack systems, all of them preferred the ILC. Subjective reasons for the overwhelming preference of ILC Cool Vest included its simple construction, low profile, ease of operation and reliability.

Discussion/Conclusions

Because of the mild environmental conditions during the field test, we could not consider the reduction in heat stress as a primary factor in evaluating the systems. Under hotter conditions, this factor would have been given more significant weight. Based on subjects' overall preference, the ILC system was the overwhelming favorite, with 26 of 29 votes for the number one rating. The reasons stated for the high preference were its low profile, simple operating characteristics, and significant cooling. The least preferred system was the LSSI backpack system. The weight, bulkiness, and interrupted cooling (i.e., operational difficulties) of the LSSI system were reasons for its unpopularity.

HUMAN LABORATORY STUDIES

Study #3 Effectiveness of a Vortex Tube Microclimate Cooling System.

Introduction

A number of shipboard and industrial personnel working in hot spaces have access to compressed air, which can be connected to air-cooled MCS. Air-cooled systems are lightweight and have fewer mechanical components than do liquid cooled systems. They may, therefore, be advantageous as inexpensive, reliable MCS for shipboard use.

Test Method

NCTRF evaluated the effectiveness of a microclimate cooling vest supplied with compressed air (80 psig) cooled by a vortex tube (4). Seven males attempted heat exposures for 120 min while wearing either a work uniform (clo = 1.1, i_m = 0.6) or a chemical protective ensemble (clo = 1.6, i_m = 0.5). With the work uniform, environmental conditions were 43°C db, 29°C dp; metabolic rate was approximately 425 W. With the protective clothing, conditions were 35°C dp, 26°C dp; metabolic rate was approximately 400 W. Volunteers were tested without cooling (CONTROL) and while wearing a vest supplied with 11.5 cfm of cooled air (VORTEX).

Results

All subjects wearing the work uniform (CONTROL and VORTEX) completed the 120 min of exposure. Final rectal temperatures were 39.0 $\pm$ 0.3°C for CONTROL and

37.9 ± 0.2°C for VORTEX ($p<0.05$). Final heart rates were 159 ± 21 beats per minute for CONTROL and 115 ± 12 beats per minute. Sweating rates were 700 (± 120) and 440 (±60) g/m^2/h for CONTROL and VORTEX, respectively ($p<0.05$).

With the protective clothing, tolerance times were significantly higher (120 min) for the VORTEX compared to the control tests (103 ± 18 min). At 90 min, rectal temperatures were significantly higher in the control condition (38.7 ± 0.2°C) compared to the cooled state (37.4 ± 0.2°C). Heart rates were also significantly higher with no cooling (148 vs 98 beats per minute for CONTROL and VORTEX, respectively). The average sweating rates of the volunteers when the cooling device was used was significantly lower (220 ± 80 g/m^2/h) than when there was no air cooling (700 ± 120 g/m^2/h).

Discussion/ Conclusions

The vortex cooling system has been shown to be effective in reducing heat stress of volunteers wearing both a lightweight and a heavier, protective ensemble. Advantages of a vortex cooler include its low cost, extreme low weight, reliability (few moving parts), and ease of operation. The major disadvantage of the cooler is the fact that an individual must be tethered to a low pressure line. While this may not be problematic for some shipboard applications, such as boiler watch, it may be impractical for many other tasks requiring mobility. Additionally, because of the ever-present danger of fire in an engine space, the tethering could pose a significant safety problem. Quick release, breakaway fittings and/or mulitple sites for attaching the air hose to increase mobility may make the vortex a more feasible option for shipboard use.

Study #4 Microclimate Cooling Systems: A Physiological Evaluation of Two Commercial Systems

Introduction

The Navy Clothing and Textile Research Facility conducted a laboratory evaluation to compare two commercially available liquid microclimate cooling systems for: 1) their effectiveness in reducing heat strain and increasing tolerance time to work in the heat; and 2) their operational characteristics (5). The systems evaluated were the Model 1905 Cool Vest manufactured by ILC Dover, Inc. (ILC), and the Cool Head manufactured by Life Support Systems, Inc. (LSSI). Both are portable, battery-powered, circulating liquid cooling systems. The ILC system includes a torso vest; the LSSI system includes a torso vest and a head cap.

Test Method

Each of nine male volunteers performed a heat test without a cooling system (CONTROL) and with each of the two cooling systems. During each test, volunteers attempted to complete a 3-hour heat exposure in a 43°C dry bulb, 29°C dew point environment (wet bulb globe temperature 36°C). During each heat exposure, subjects wore the Navy utility uniform (clo = 1.1; i_m = 0.6), and walked on a level treadmill at 1.6 m/s (metabolic rate, 360 W).

Results

Only four of the nine subjects were able to complete the CONTROL test. In most cases, use of either of the two cooling systems enabled subjects to complete the 3-hour heat exposures. Rectal temperature responses were similar when either cooling system was used ($p>0.05$); final rectal temperature averaged 38.1 °C. Changes in rectal temperatures are presented in Figure 1.

The ILC system elicited slightly lower heart rates than the LSSI system, by an average of 7 b/min ($p<0.05$). Heart rate responses are presented in Figure 2. Total body sweat rates were similar for the two systems and averaged 566 g/m^2/h ($p>0.05$). Body sweat rates are presented in Figure 3.

The ILC cooling system experienced many fewer operational difficulties and system failures than the LSSI system.

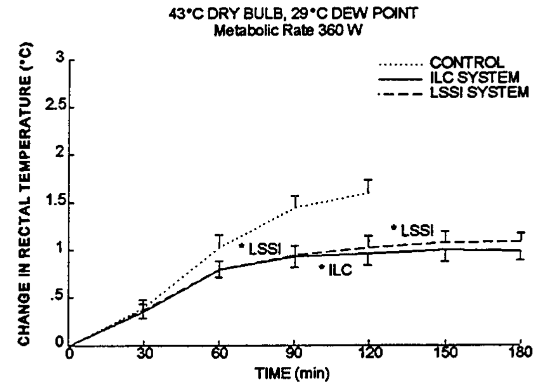

Figure 1. Change in rectal temperature from initial value for the control and cooling tests. T indicates SE; * indicates average time of cooling system ice change.

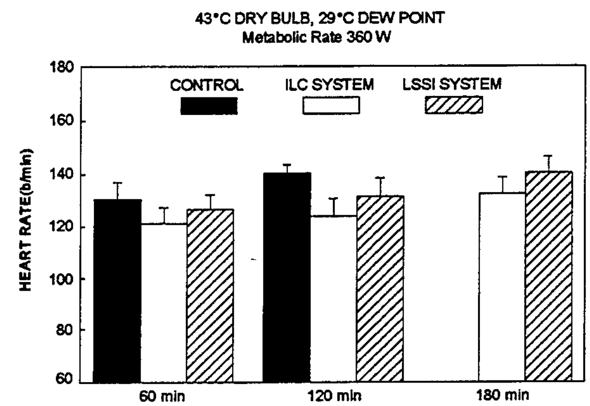

Figure 2. Heart rate at 60, 120 and 180 min for the control and cooling tests. T indicates SE.

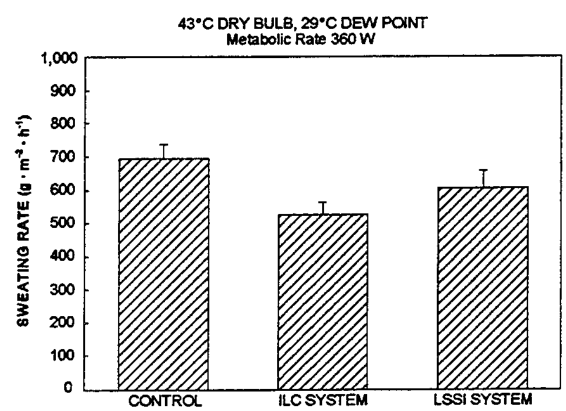

Figure 3. Total body sweating rate for the control and cooling tests. T indicates SE.

Discussion/Conclusions

Under the conditions tested, the ILC Dover Cool Vest and the LSSI Cool Head were similarly effective in reducing physiological strain and increasing tolerance time to work in the heat. Most participants rated the ILC system as cooler, lighter, less bulky, and better overall than the LSSI system. Very few operational difficulties occurred with the ILC system. The LSSI system, however, experienced a significant number of failures and operational difficulties. There is a dramatic cost difference between the two systems: $359 for the ILC Dover Model 1905, compared to $2,376 for the LSSI Cool Head.

Study #5 Effectiveness of Three Portable Cooling Systems in Reducing Heat Stress

Introduction

NCTRF conducted a laboratory evaluation to examine a battery-operated, circulating liquid cooling vest and two "passive", frozen gel pack vests for their effectiveness in reducing heat strain (6). The battery-operated system was the Model 1905 Cool Vest, manufactured by ILC Dover. Inc. (ILC). The passive systems were the SteeleVest, manufactured by Steele, Inc. (STEELE) and the Stay Cool Vest, manufactured by American Vest Co. (AMERICAN).

Test Method

Eight test participants attempted four, 3-hour heat exposures, one without cooling (CONTROL) and one with each of the three cooling systems (ILC, STEELE, and AMERICAN). During the heat exposures, subjects wore the Navy utility uniform and exercised at 360 W in a 43°C dry bulb, 45% humidity environment.

Results

Of the eight volunteers, only three completed the 3-hour CONTROL test. Six completed the AMERICAN test; all eight completed the ILC and STEELE tests. Two of the cooling systems, the ILC and the STEELE, were similarly effective in reducing heat strain. The third system, the AMERICAN, reduced rectal temperature compared with the CONTROL, but not skin temperature, heart rate or sweat rate. Figures 4, 5, 6, and 7 present data on change in rectal temperature, mean weighted skin temperature, heart rate and sweating rate respectively.

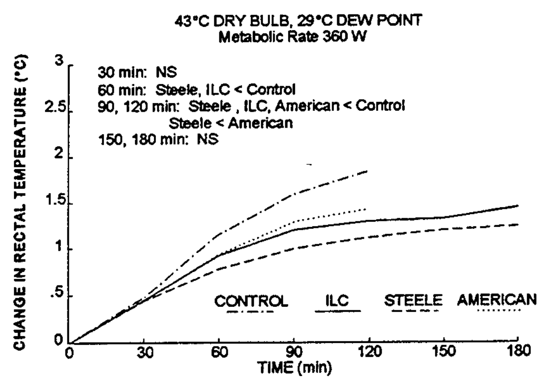

Figure 4. Change in rectal temperature from initial value for the control and cooling tests.

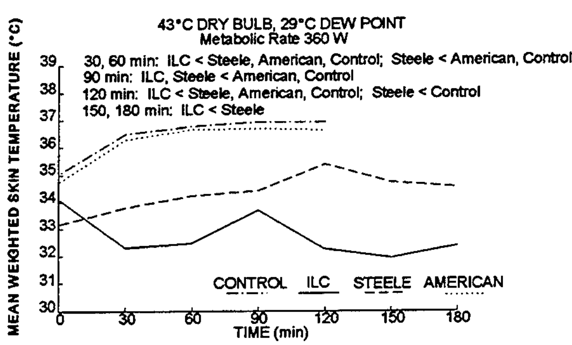

Figure 5. Mean weighted skin temperature for the control and cooling tests.

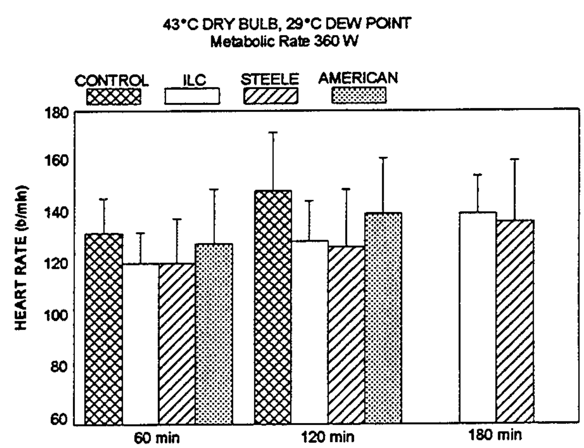

Figure 6. Heart rate at 60, 120 and 180 minutes for the control and cooling tests. T indicates SD.

Discussion/Conclusions

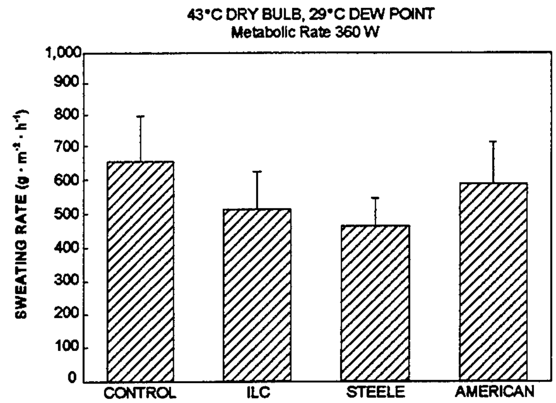

Figure 7. Total body sweating rate for the control and cooling tests. T indicates SD.

Two of the three portable cooling systems tested in this evaluation - the ILC Dover Cool Vest and the Steele, Inc. SteeleVest - were similarly effective in reducing thermal strain when used by volunteers exercising in a 43°C, 45% rh environment. The third cooling system - the American Vest Stay Cool Vest - reduced body core temperature compared to no cooling, but was not nearly as effective as the other two systems.

The surface area available for cooling in the ILC vest (1710 cm^2) is only 62% of that in the Steele vest (2761 cm^2); however, in this evaluation, chest temperatures with the ILC system were 6°C lower than the Steele. This may be because the ILC's design allows for better contact of the vest to the body, and there is very little insulation between the body and the circulating liquid. The net result was that, despite a large difference in surface areas, the ILC and the SteeleVest were similarly effective in reducing heat stress.

The poor results of the American cooling system in reducing heat strain may be due to two reasons. First, the surface area available for cooling in the American vest is only 81% of that in the ILC and 50% of that in the Steele. Second, the American vest cannot be tightened to make good contact between the body and the gel packs; evidence for this was seen in the high chest temperatures measured even when the gel packs were completely frozen.

While both the ILC Dover Cool Vest and the SteeleVest were effective in reducing heat strain, with either system there are logistical concerns which must be addressed for shipboard use. When adjusted for duration between coolant changes, the SteeleVest used 70% more coolant by weight and approximately 20% more coolant by volume than the ILC. In that respect, the ILC may be considered a more efficient cooling system than the Steele. Because of its mechanical nature, however, the ILC may require more maintenance than the passive cooling system. The ILC batteries require storage space and must be recharged for a minimum of 8 hours after every 2-3 hours of use. Ship's personnel must evaluate the logistical burdens of the additional freezer capability required by the SteeleVest and the maintenance and battery support required by the ILC.

Study #6 -Effectiveness of a Prototype Microclimate Cooling System for Use with Chemical Protective Clothing

Introduction

NCTRF conducted a laboratory evaluation to determine the effectiveness of a prototype, portable microclimate cooling system (MCS) designed by NCTRF for use with chemical protective clothing (7). The U.S. Navy has two configurations of chemical protective clothing: the chemical protective overgarment (Mark III) and the Mark III worn with the Navy Wet Weather ensemble. The Mark III is a semi-permeable, two-piece garment (trousers and smock with attached hood), with a clo value of 2.0 and an i_m value of 0.42 measured at 0.3 m/s wind velocity. Under conditions of potential liquid chemical contamination or exposure to ocean spray, the Navy Wet Weather ensemble may be worn over the Mark III, thereby making the clothing ensemble impermeable. The Wet Weather ensemble consists of bib front overalls and a parka constructed of cholorprene-coated nylon twill. The clo and i_m values of the Wet Weather ensemble worn over the utility uniform and Mark III are 2.4 and 0.24, respectively.

The purpose of this evaluation was to determine the effectiveness of the prototype circulating liquid MCS in reducing physiological strain of volunteers working in the heat while wearing the Navy chemical protective ensembles.

Test Method

The MCS circulates chilled liquid through a torso vest. A backpack unit contains an ice pack. A pump and motor assembly and a rechargeable battery are mounted on a chest or waist strap. Total weight of the MCS is 9.3 kg. To examine the effectiveness of the system in reducing heat strain, seven male test volunteers participated in a laboratory heat stress evaluation.

The volunteers attempted 120-min heat exposures in a 35°C, 60% humidity environment while exercising at a time-weighted rate of approximately 300 watts. They were tested four times: with and without the MCS while they wore the semi-permeable and the impermeable chemical protective ensemble.

Results

Exposure time in all cases was 120 min, except when the impermeable ensemble was worn without the MCS (mean tolerance time = 96 min). Use of the MCS significantly reduced rectal temperature by an average of 0.5°C after 120 min with the semi-impermeable ensemble and by 1.3°C after 100 min with the impermeable ensemble. Mean weighted skin temperature was significantly lower by an average of 3.3°C when the MCS was used. Rectal temperature and mean weighted skin temperature data are presented in Figures 8 and 9, respectively.

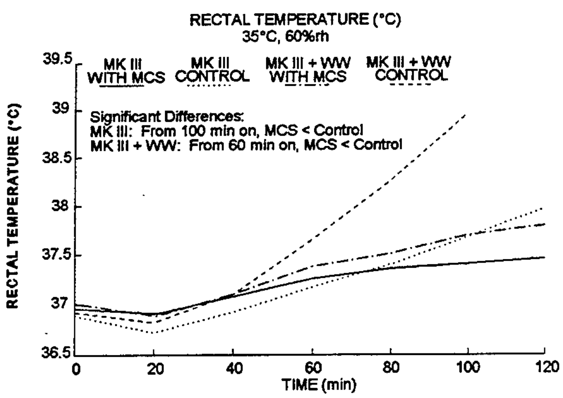

Figure 8. Rectal temperature responses with and without the cooling system.

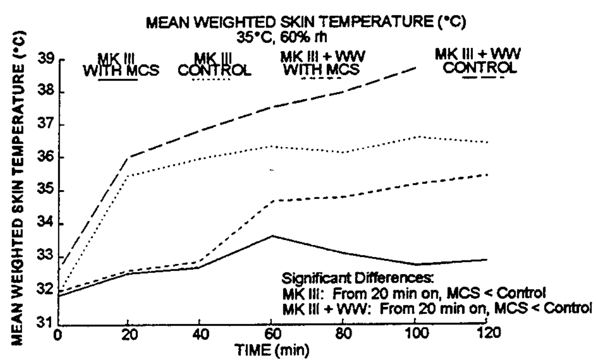

Figure 9. Mean weighted skin temperatures with and without the cooling system.

As seen in Figure 10, use of the MCS significantly reduced heart rate by 30 and 42 b/min with the semi-impermeable and impermeable ensembles, respectively. Sweating rate was also significantly reduced, by an average of 37% (Figure 11).

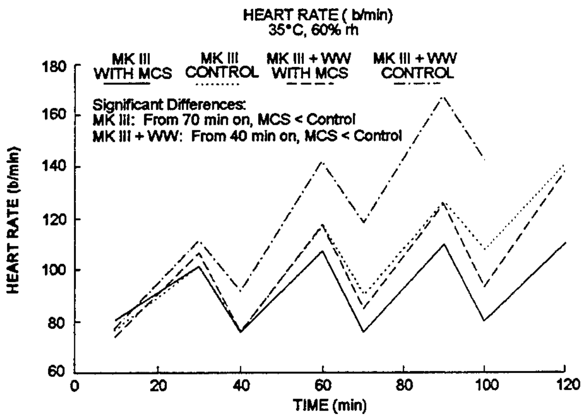

Figure 10. Heart rate responses with and without the cooling system.

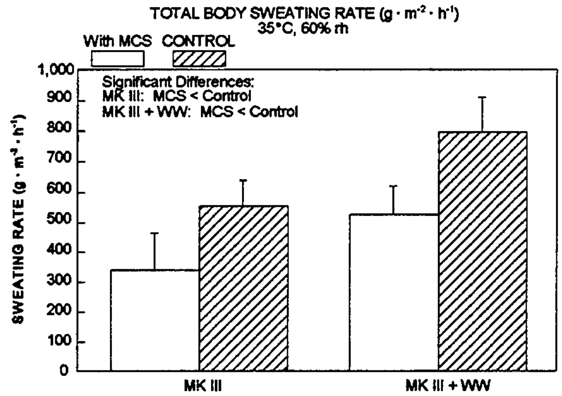

Figure 11. Total body sweating rates with and without the cooling system. T indicates SD.

Discussion/Conclusions

The prototype MCS was effective in alleviating heat strain and enabled volunteers wearing chemical protective clothing to complete a 2-hour heat exposure in a 35°C environment. As currently designed, however, the system is not operationally reliable or rugged enough for near-term Navy use. Further development and/or modifications to the prototype system are required.

Study #7 -Effectiveness of a Selected Microclimate Cooling System in Increasing Tolerance Time to Work in the Heat - Application to Navy Physiological Heat Exposure Limits (PHEL) Curve V

Introduction

On board U.S. Navy ships, whenever dry bulb temperature in a work space exceeds 38°C, or under conditions of "unusually high heat or moisture" or "arduous work", wet bulb globe temperature (WBGT) is measured. The WBGT is then applied to a series of Physiological Heat Exposure Limits (PHEL) curves (8). The PHEL curve chart consists of six curves (I-VI), each of which represents a different time-weighted metabolic rate ranging from 177 to 293 W. For all curves, it is assumed that the Navy utility uniform or work coverall is worn. Based on the work rate and the WBGT, the PHEL curves establish maximum safe exposure times for shipboard personnel. If the scheduled duration of a duty period exceeds the safe exposure time established by the curve, personnel must be rotated out of the heat stress area and given prescribed recovery periods. The PHEL curves are strictly adhered to onboard ship; only under operational emergencies may the ships Commanding Officer waive the curves.

Previous research has shown that various types of microclimate cooling systems - including dry ice, liquid, gas and passive systems - can be used to reduce heat strain and increase tolerance time to work in the heat (e.g. 1,4,5,6,7). Due in large part to the results of these studies, a number of passive MCSs were used on U.S. Navy ships in the Persian Gulf during the summer of 1988 and were favorably received.

The Navy's widespread use of MCS on board shps will partly depend on the development of a table of recommended safe exposure times which will reflect the increased tolerance times when the MCSs are used. If stay times and/or work efficiency cannot be significantly increased by the use of a cooling system, it is doubtful that the Navy will incur the expense of these systems "merely" to increase personal comfort.

The primary purpose of this evaluation, therefore, was to begin evaluating the increases in tolerance time when a selected microclimate cooling system - the SteeleVest - is used in various environments (8). In this evaluation, one metabolic rate (272 W) was used, which corresponded to PHEL Curve V (the second highest of the six work rates represented by the PHEL curves). Five environments were examined, encompassing WBGT conditions ranging from 36-39°C. Although the WBGT range was small, dry bulb temperatures ranged from 38-49°C, and humidity 25-80%. Because of this, it was expected that within this relatively small WBGT range, there might be large differences in tolerance time with the cooling vest. Some of the tested environments were chosen to simulate environmental conditions typical of ships operating on the Atlantic Coast during the summer months. Under these combinations of WBGT and work rate, the current PHEL curves limit exposure time to 60-95 minutes.

The secondary purpose of the evaluation was to compare thermal responses and tolerance times in equivalent WBGT environments. Maximum exposure times established by the PHEL curves are the same for environments having equivalent WBGT. Some research, however, has shown that physiological responses to equivalent WBGT conditions are not necessarily equivalent, particularly when hot-humid and hot-dry environments are compared. Under the test design, therefore, we chose humid and dry environments that produced equivalent WBGT.

Test Method

The SteeleVest has six pockets (three in front, three in back) which hold 0.8 kg frozen gel packs, consisting of a cornstarch and water mixture. The vest has a cotton canvas shell and the pockets are externally insulated with Thinsulate. The total weight of the system is 5.1 kg. The vest comes in one size only.

Eight heat acclimated, healthy male volunteers participated in the evaluation, which consisted of 10 tests - with and without the cooling vest in five different environments (repeated measures design with each participant serving as his own control). The five environments are listed below. The designation for each environment denotes the WBGT (°C) and "H" for the more humid, and "D" for the drier of the two equivalent WBGT environments.

Dry Bulb	rh	WBGT	Designation
38°C	80%	36°C	WBGT36H
49°C	25%	36°C	WBGT36D
43°C	60%	38°C	WBGT38H
49°C	35%	38°C	WBGT38D
49°C	39%	39°C	WBGT39

Wind velocity was 1.0 m/s

Volunteers attempted to complete 4 hours of heat exposure, during which they walked on a level treadmill at 1.3 m/s for 25 minutes and sat for 5 minutes every half hour. They wore the Navy utility uniform, which has a thermal insulation of 1.1 clo and water vapor permeability (i_m) value of 0.6. When the cooling vest was used, it was worn over the shirt.

Parameters measured included rectal temperature, skin temperatures at three sites, heart rate, total body sweating rate and gel pack temperature. When the gel pack reached approximately 20°C, the packs were replaced. The packs were also checked manually to ensure that they were replaced when almost melted. The time of each coolant change was recorded.

Results

In all environments, the SteeleVest significantly reduced thermal strain, as evidenced by reduced rectal and skin temperatures, heart rate and sweat rate. Changes in rectal temperature data from 36°C, 38°C, and 39°C WBGT environments are plotted in Figures 12, 13, and 14, respectively. In all environments, there were significant differences ($p<0.05$) in the rectal temperatures when the control and the SteeleVest tests were compared.

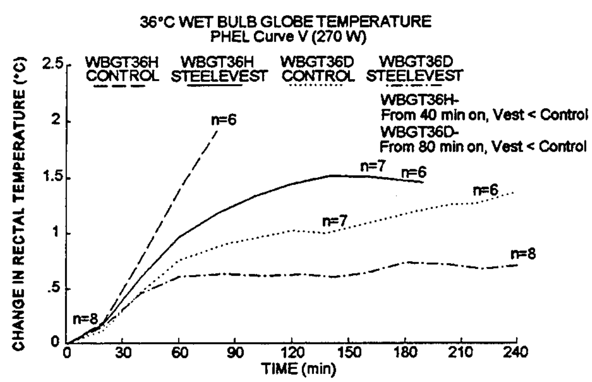

Figure 12. Change in rectal temperature with and without the SteeleVest.

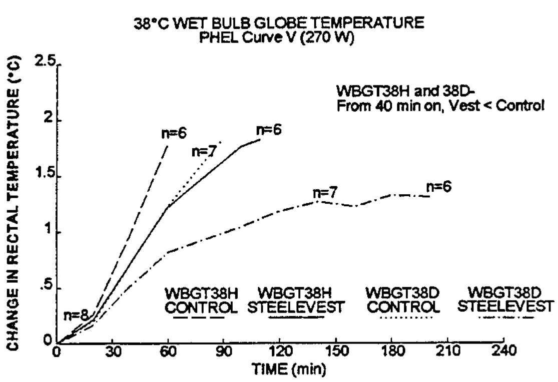

Figure 13. Change in rectal temperature with and without the SteeleVest.

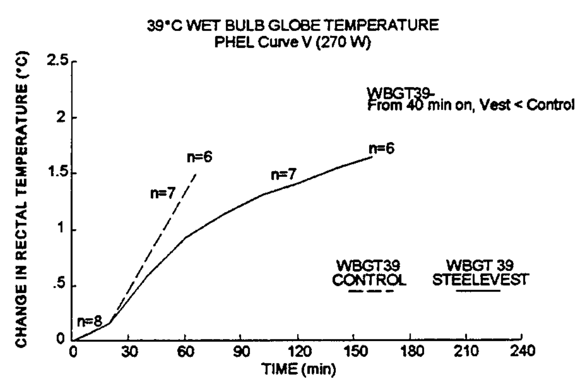

Figure 14. Change in rectal temperature with and without the SteeleVest.

Mean weighted skin temperatures in the 36°C, 38°C and 39°C WBGT environments are shown in Figures 15, 16, and 17, respectively.

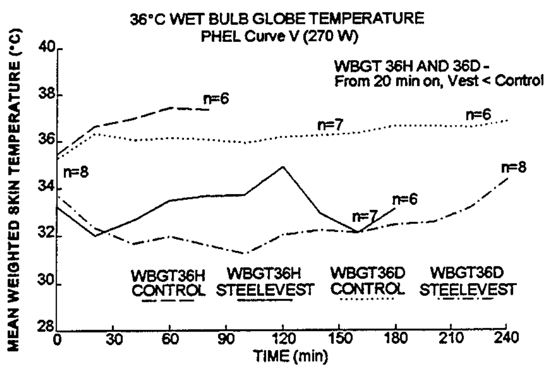

Figure 15. Mean weighted skin temperature with and without the SteeleVest.

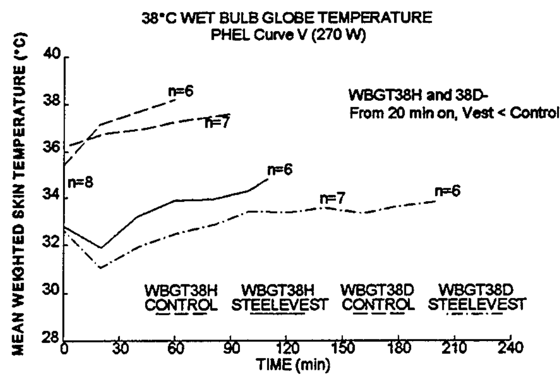

Figure 16. Mean weighted skin temperature with and without the SteeleVest.

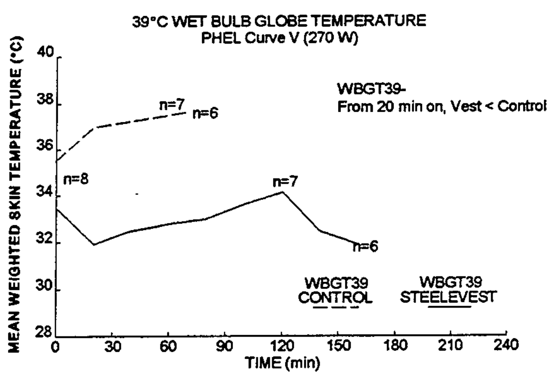

Figure 17. Mean weighted skin temperature with and without the SteeleVest.

There were significant differences ($p<0.05$) in the mean weighted skin temperatures in all environments when the control and the SteeleVest tests were compared. Heart rates during each of the heat exposures are presented in Figures 18-20. As with the rectal and mean weighted skin temperatures, the heart rate was significantly ($p<0.05$) lower when the SteeleVest was used than during the control tests in all environments. Figure 21 illustrates total body sweat rates with and without the SteeleVest in each of the five environments. In each environment, sweat rate was lower when the SteeleVest was used than during the control test ($p<0.05$).

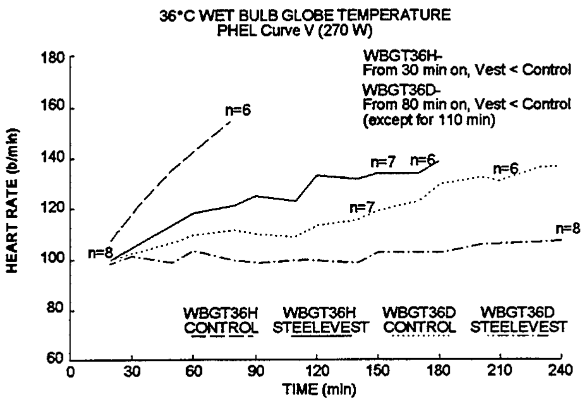

Figure 18. Heart rate over time with and without the SteeleVest.

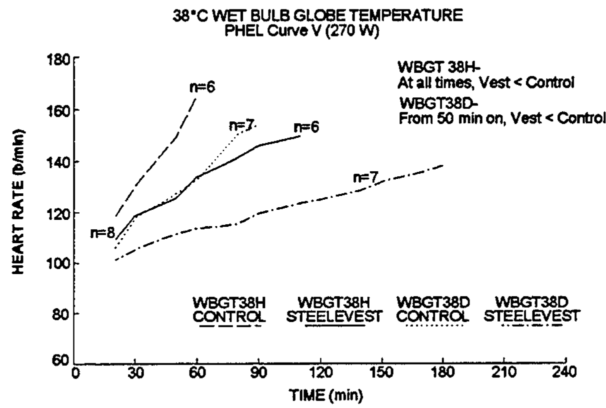

Figure 19. Heart rate over time with and without the SteeleVest.

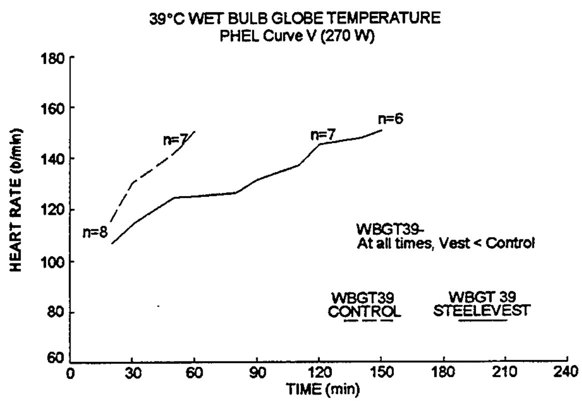

Figure 20. Heart rate over time with and without the SteeleVest.

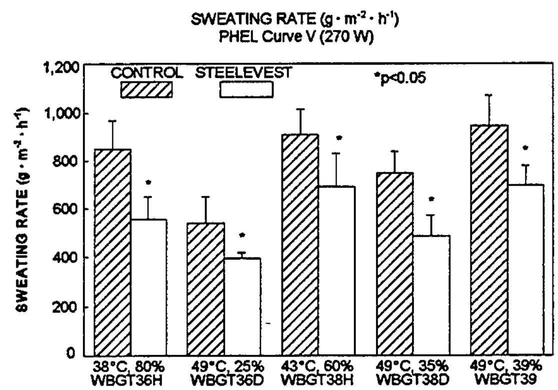

Figure 21. Total body sweating rate with and without the SteeleVest. T indicates SD.

Discussion/Conclusions

In all environments, the SteeleVest significantly reduced thermal strain, as evidenced by reduced rectal and skin temperatures, heart rate and sweat rate. Use of the SteeleVest approximately doubled tolerance times compared with tests without the vest. The gel packs lasted approximately 2 hours before they required replacement. When the hot-humid and hot-dry environments having equivalent WGBTs were compared, thermal strain was higher in the more humid environments.

In addition to its effectiveness in reducing heat strain, the SteeleVest is relatively lightweight, has a low profile, requires little maintenance and is not susceptible to mechanical problems. These characteristics make it very desirable for shipboard use.

Study #8 Ability of a Passive Microclimate Cooling Vest to Reduce Thermal Strain and Increase Tolerance Time to Work in the Heat.

Introduction

Based on its ability to reduce thermal strain as well as its ease of operation and low maintenance, a "passive" cooling system was recommended for U.S. Navy shipboard use. The selected system consists of an insulated, fire-retardant cotton canvas vest with six pockets (three on the front, three on the back) which each hold a frozen gel strip against the torso. The total weight of the system is 5.1 kg.

A previous NCTRF study (9) had evaluated the passive MCS at a metabolic rate of 272 W, which represents the fifth of six curves comprising the Navy's Physiological Heat Exposure Limit (PHEL) curves. This study (10) describes the physiological responses to the environment-work combination described by PHEL curve III (metabolic rate = 208 W).

Test Method

Fourteen male volunteers (average age, 21 yr; height, 179 cm; weight, 80.2 kg) underwent 8 days of heat acclimation followed by six heat stress tests. The heat stress tests were conducted in three different environments: environment A = 44°C dry bulb (db) temperature, 46°C black globe (bg) temperature and 49% relative humidity (rh); environment B = 51°C db, 53°C bg and 33% rh; environment C = 57°C db, 59°C bg and 25% rh. In each environment, each volunteer performed two heat stress tests: once while using the cooling vest and once without (control test). During each test, volunteers attempted to complete a 6-hour exposure while alternating 20 minutes of treadmill exercise (at a speed of 1.1 m/s on a 3% grade) with 40 minutes of seated rest. This resulted in a time-weighted metabolic rate of 208 watts. Subjects wore the U.S. Navy utility work uniform (thermal insulation = 1.1 clo; water vapor permeability (i_m) index = 0.6). When the cooling vest was used, it was worn over the T-shirt and work shirt. Physiological measurements included rectal temperature; chest, upper arm, calf and thigh skin temperatures; heart rate; and total body sweating rate. Because of voluntary attrition during the control tests, statistical comparisons were made up to the following times: 200 minutes in environment A, 80 minutes in environment B, and 60 minutes in environment C.

Results

In environment A, five of the 14 volunteers were able to complete the 6-hour heat exposure during the control test. When the cooling vest was used, all 14 volunteers completed the exposure. In environments B and C, use of the cooling vest more than doubled tolerance time compared with the control tests. The increase in tolerance time due to the vest averaged approximately 3 hours in environment B, and over 1.5 hours in environment C. In all three environments, use of the vest resulted in significant reductions in rectal temperature, chest temperature, heart rate and sweating rate compared with the control tests ($p<0.05$). Upper arm, calf and thigh skin temperatures were not significantly different between the cooling vest and the control tests ($p>0.05$). The reduction in rectal temperature when the vest was used averaged 0.4°C in environment A (after 200 minutes of heat exposure), 0.7°C in B (after 80 minutes of heat exposure), and 0.8°C in C (after 60 minutes of heat exposure). The reduction in chest temperature averaged 8°C in environment A (at 200 minutes), 8°C in environment B (at 80 minutes) and 5°C in environment C (at 60 minutes). Heart rate was reduced by 18, 25 and 20 bpm in environments A (at 200 minutes), B (at 80 minutes) and C (at 60 minutes), respectively. Use of the cooling vest reduced total body sweating rate by 49%, 45% and 38% in environments A, B and C, respectively.

Discussions/ Conclusions

Use of the passive cooling vest significantly reduced thermal strain, as evidenced by reduced rectal temperature, chest temperature, heart rate and sweating rate. When the cooling vest was used by volunteers wearing a standard work uniform and performing light exercise in extreme hot environments, work time was more than doubled compared with control tests. Use of the vest reduced total body sweating rate by an average of over 40%. Drinking water requirements, therefore, would also be lowered.

The significant increases in tolerance times demonstrated in references (9) and (10), clearly show the advantages of MCS use in the Navy. With the doubling of stay times, fewer personnel would be required to man the hot engine spaces; and therefore, more personnel would be available for other duties. Also, because the sailors would sweat less and core temperatures would rise less during their watches, they would presumably be in better physical and mental status at the end of their duty periods.

Study #9 Heat Stress Induced By the Navy Fire Fighter's Ensemble Worn in Various Configurations.

Introduction

The Navy Fire Fighter's Ensemble (NFFE) including the non-aluminized damage control coverall was introduced to the Fleet in 1988. During the following year and a half, some instances of heat stress problems related to use of the NFFE were reported. Problems with heat stress occurred primarily during main space fire drills when personnel were fully dressed out in the NFFE and, in some cases, were also using an Oxygen Breathing Apparatus. When the heat injuries occurred, the average length of time the NFFE had been worn was 36 minutes. The injuries occurred mostly during training drills when personnel completely dressed out in the NFFE were engaged in very low levels of physical activity.

In response to these reports of problems with heat stress when the NFFE was worn, NCTRF conducted a laboratory evaluation of the NFFE (11). The primary purpose of the evaluation was to measure heat strain when the NFFE is worn in a "buttoned up" configuration and to determine to what extent wearing the NFFE in a more relaxed or standby configuration alleviates this heat strain. The secondary purpose of the study was to examine the effectiveness of a selected cooling vest in reducing heat strain used with the NFFE.

Test Method

NCTRF conducted a laboratory evaluation to compare heat stress when the NFFE is worn, with and without a cooling vest, in three configurations: 1) coverall "buttoned up" with anti-flash hood, helmet and gloves worn, 2) coverall unzipped with hood around neck and no helmet or gloves worn, and 3) coverall down around the waist with hood around neck and no helmet or gloves worn. The cooling system was a cotton canvas vest which holds 4.5 kg of frozen gel packs (Steele, Inc.). Nine test volunteers underwent six, 2-hour heat exposures (three NFFE configurations with and without the cooling vest). Environmental conditions were 32°C dry bulb temperature with 60% relative humidity. During the heat exposures, the test volunteers alternated seated rest with walking 1.56 m/s on a treadmill every 15 minutes. These conditions were chosen to simulate a drill during which the level of physical exercise is low.

Results

When the NFFE was worn buttoned up, and when it was worn in the unzipped configuration, use of the Steele cooling vest significantly reduced thermal strain. When the cooling vest was worn, the increase in core temperature after 2 hours of heat exposure was only half that of the uncooled conditions. Mean weighted skin temperature was significantly reduced, and heart rate was reduced by 21-36 b/min.

Total body sweating rate was reduced by approximately 40%. When the coverall was worn around the waist, however, and overall thermal strain was only moderate, the vest further reduced heat stress only slightly. In that condition, the logistics involved in freezing and storing the gel packs probably do not warrant use of the cooling system.

Discussion/Conclusions

The study demonstrated that, if the U.S. Navy Fire Fighter's Ensemble (NFFE) is worn with the coverall down around the waist, heat stress is greatly reduced compared with wearing the coverall just unzipped, or with wearing the ensemble completely buttoned up. While personnel may need to practice donning and wearing the complete ensemble, in warm weather it should be worn in this configuration for very limited tme periods only. If the coverall cannot be worn down around the waist, thermal strain can be significantly reduced by using the Steele cooling vest. While the vest may be effectively used to reduce heat strain during training drills, use of the vest may be an unsafe practice in an actual fire fighting situation. Because of the potential for a burn injury, exposure times for fire fighting personnel may be limited to very short periods during high intensity fires. In this case, use of an auxiliary cooling device such as an ice vest may reduce overall thermal strain but does not decrease the potential for a burn injury. Because of this, the added comfort provided by the cooling vest may result in a false sense of well-being if worn during actual fire fighting. Further evaluation of MCS needs to be done during actual firefighting scenarios to determine its applicability to high intensity heat.

THERMAL MANIKIN STUDIES

Study #10 Passive Cooling for Encapsulating Garments

Introduction

Personnel wearing encapsulating clothing will more readily suffer heat stress under certain conditions due to the added insulation and reduced vapor permeability of such ensembles. Passive cooling vests (e.g. the SteeleVest) are useful for reducing heat stress when worn with general utility clothing (6,9,10) and have found widespread use in both the military and industry. These vests are not practical for use with encapsulating ensembles, however since wearing the vest over the ensemble reduces the cooling effect, and wearing the vest under the ensemble prevents changing of the cooling packs. Increasing the number of cooling packs and incorporating the pockets for the packs directly into the ensemble may be a relatively easy way to provide cooling in encapsulating clothing. The purpose of this study was to test this concept on a Thermal Manikin (TM) (12).

Test Method

TM testing was conducted on a prototype U.S. Navy Chemical Protective Overgarment (CPO) and the Toxicological Agent Protective (TAP) suit. The CPO is a semi-permeable ensemble whereas the TAP is impermeable. Both ensembles were tested with three cooling variations: a passive MCS (the SteeleVest) under the ensemble (U), over the ensemble (O), and the ensemble modified by adding exterior pockets for the cooling packs to the torso and thigh surfaces (M). The M-CPO and

M-TAP contained 29 cooling packs (7.4 kg of gel) compared to 18 (4.6 kg) in the SteeleVest. The gel packs were frozen at approximately -15°C prior to the test. Tests were run at 35°C, 60% relative humidity, 0.9 m/s wind speed, and 35°C TM temperature. TM power was measured without cooling packs (baseline) and at 1-min intervals after the cooling packs were inserted. Cooling results were determined by the average of 120 consecutive power readings less the baseline.

Results

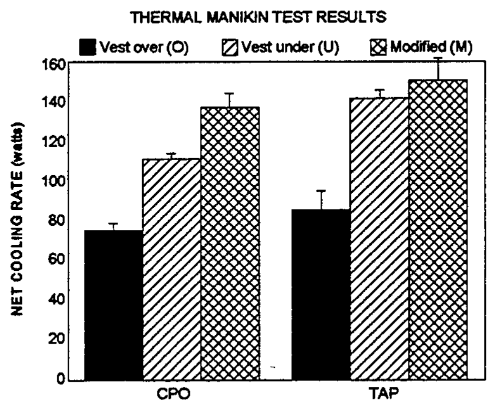

Figure 22. Thermal manikin test results.

The test results are illustrated in Figure 22. The cooling provided by M-CPO (137 W) was significantly greater than U-CPO (112 W) and O-CPO (75 W). The cooling provided by M-TAP (151 W) was equivalent to U-TAP (142 W) and significantly greater than O-TAP (86 W).

Discussion/Conclusions

These results demonstrate that external passive cooling packs may be a viable solution to heat stress problems in both semi-permeable and impermeable encapsulating clothing ensembles. If 29 external packs (7.4 kg gel) are used, the cooling provided is at least equal to the use of the SteeleVest under the ensemble.

Study #11 Effectiveness of a Prototype Microclimate Cooling System for Use with Chemical Protective Clothing - (Thermal Manikin Evaluation)

Introduction

The purpose of this thermal manikin (TM) evaluation was to assess the theoretical and actual cooling capabilities of a prototype MCS for use with chemical protective overgarments. This prototype MCS was also evaluated in a human laboratory test as described in study #6 of this report and in reference (7). Brief descriptions of the chemical protective overgarments (the Mark III (MKIII) and the Mark III with the Navy Wet Weather ensemble (MKIII+WW)) and the prototype MCS may be found in study #6 of this report.

Five parameters were evaluated. The theoretical cooling capacity identifies the maximum cooling potential of the MCS. Actual cooling capacity describes the amount of cooling provided to (i.e., the amount of heat actually removed from) the user. The efficiency of the system provides a representation of how close the actual capacity comes to its theoretical capacity. The last two parameters, ice reserve life and average cooling rate, indicate how long the system will last, and how quickly it removes heat. These parameters are valuable since they indicate in a practical way the cooling that a user of the system should expect.

Test Method

The conditions during the tests were 35°C ambient temperature, 60% relative humidity, 0.9 m/s wind speed, with the manikin surface temperature maintained at 35°C and a fully wetted sweating skin. The MCS vest was worn under the chemical defense garment.

Each test was conducted in two phases, a control (no cooling) phase followed by a cooling phase. During the control phase, the TM was allowed to reach thermal equilibrium with the cooling system turned off, and no ice reserve in the backpack. Once thermal equilibrium was reached, the amount of power required by the TM to maintain surface temperature was noted. At this point, an ice reserve was placed into the backpack, and the cooling system was turned on. This began the cooling phase of the test. The power required by the TM was recorded at one minute intervals during the cooling phase. The difference between the power consumed during the control phase and power consumed during the cooling phase indicates the cooling power of the MCS. The temperature of the fluid entering the vest was monitored until it reached 18°C, at which point the test was ended.

A computerized data acquisition system was used to collect circulating fluid temperature data from the MCS. Thermocouples were placed in the circulating lines of the MCS at four points: entering and exiting the ice pack, and entering and exiting the vest itself.

The required calculations included theoretical cooling capacity, actual cooling capacity, efficiency, and average cooling rate. The theoretical cooling capacity of the MCS is based on the amount of ice or water in the ice reserve and the allowable temperature rise. There are two equations which govern the theoretical cooling capacity of the MCS. The first equation describes the cooling associated with heat absorption by the ice (before melting) as it rises from its initial frozen temperature to 0°C. The first equation also describes the cooling associated with the heat absorption by the water (after the ice has melted) as it rises from 0°C to its final temperature.

$$Q = MC(Tf-Ti) \qquad (1)$$

Where:

Q = heat absorbed
M = mass of ice or water in the ice pack
C = heat capacity of ice or water
Tf = final temperature
Ti = initial temperature.

Any consistent set of units may be used in this equation.

The second equation describes the heat absorption of the ice as it melts at 0°C.

$$Q = MH \qquad (2)$$

Where:

H = latent heat of fusion of ice and other variables are defined above.

The theoretical cooling capacity was calculated by using the first equation to calculate the heat absorbed by the ice as it rose to its melting point (0°C) followed by use of the second equation to calculate the heat absorbed by the ice as it melted. Next, the first equation was used again to calculate the heat absorbed by the water as its temperature rose above 0°C. Finally, the three heat absorption values were summed to determine the theoretical cooling capacity of the MCS.

Before the theoretical cooling capacity could be calculated it was first necessary to establish initial (ice) and final water temperatures in the ice pack. The ice packs were frozen to approximately -15°C. However, by the time the ice packs were transferred from the freezer to the backpack, the hoses connected, and the system started, the temperature of the ice in the backpack had risen to approximately -10°C. Therefore, it seemed reasonable to select -10°C as the starting temperature for the theoretical cooling power calculation. As described earlier, the TM tests were discontinued when the temperature of the fluid entering the vest reached 18°C, therefore this temperature was selected as the final temperature for the theoretical cooling capacity calculation. The time required to reach this end point was termed the ice reserve life of the MCS.

The actual cooling capacity was calculated from the power input to the TM. The power input was recorded every 60 seconds. The control (no cooling) was subtracted from each of the 60-second power input readings taken during the cooling phase. This yielded the rate of heat absorption by the vest from the TM for each 60-second interval. To convert the rate of heat absorbed during each 60-second interval to the quantity of heat absorbed during each interval, the rates were multiplied by time. These results were then summed for the full length of the test to derive the actual cooling capacity of the MCS. Efficiency was calculated by dividing the actual cooling capacity by the theoretical cooling capacity, and multiplying by 100 to obtain percent. Average cooling rate was calculated by dividing the actual cooling capacity by the ice reserve life of the system.

Results

The theoretical cooling capacity of the ice reserve was 538 watt-hours. Most of the cooling (78%) was provided by the heat of fusion of the ice as it melted.

The average actual cooling capacity of the MCS when worn under the MKIII was 326 watt-hours. When worn under the MKIII+WW, the average actual cooling capacity was 308 watt-hours. This represented MCS efficiencies of 61 and 58%, respectively.

The average ice reserve life of the MCS when worn under the MKIII was 163 minutes (2.7 hours). When the WW was added, the average ice reserve life was 123 minutes (2.0 hours). The average cooling rates of the MCS worn with the MKIII alone and worn with the MKIII+WW were 122 and 151 watts, respectively.

Discussion/Conclusions

The actual cooling capacities of 326 and 308 watt-hours translate into efficiencies of 61% and 58%, respectively. It is theorized that the actual cooling capacity and efficiency of the MCS can be increased by reducing heat absorption from the environment. During the TM tests, the temperature of the circulating fluid rose by 5 to 10°C as it flowed from the ice reserve to the vest through uninsulated tubing that was exposed to the environment. Insulating these flow lines should result in a significant improvement to the actual cooling capacity and efficiency of the system. Adding insulation to the backpack itself should also reduce heat gain from the environment.

Conclusion

The Navy Clothing & Textile Research Facility has been involved in the development and testing of MCS for Navy applications for many years. Commercial and prototype systems have demonstrated that MCS significantly reduce heat strain in hot environments. Commercial systems generally require some modification (such as covering the exterior of the MCS with a fire retardant material) before they can be used on board ship.

Studies have demonstrated that both portable ice-based liquid circulating and passive cooling systems have proven effective for use with general utility clothing for US Navy applications. The Model 1905 Cool Vest manufactured by ILC Dover, Inc. and the SteeleVest manufactured by Steele, Inc. demonstrated overall superior performance in terms of cooling effectiveness, logistics, cost, reliability and maintainability when compared to other commercial systems. However, because of logistics problems associated with battery storage and recharging, portable ice based liquid MCS has not been well received on board ship. Only the passive cooling system has been widely used and can be procured through the supply system with a commercial item description (13).

Passive MCS has been shown to significantly increase the stay times of individuals working in hot environments at metabolic rates described by Navy Physiological Heat Exposure Limit curves III (208 W) and V (272 W). For Navy applications, the increase in stay times over those described by the PHEL curves implies that fewer personnel should be required for some watch duties. Further, because sweating is reduced with use of a MCS, the hydration status of the sailor completing the watch in a hot space should be better when a MCS is used.

The passive MCS are of limited use with encapsulating garments such as the Navy Chemical Protective Overgarment and Fire Fighter's Ensemble. Once the ice packs melt, cooling is no longer provided and an additional thermal burden may be incurred. Replenishment requires doffing the ensemble, which may not be practical in contaminated environments. However, NCTRF has demonstrated that under some fire fighting applications, such as training drills, MCS may be useful in reducing the thermal burden of individuals completely outfitted in a fire fighter's ensemble. NCTRF is currently developing and evaluating prototype MCS for impermeable applications. Preliminary laboratory work has shown the prototypes to be effective in signfiicantly reducing heat strain.

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