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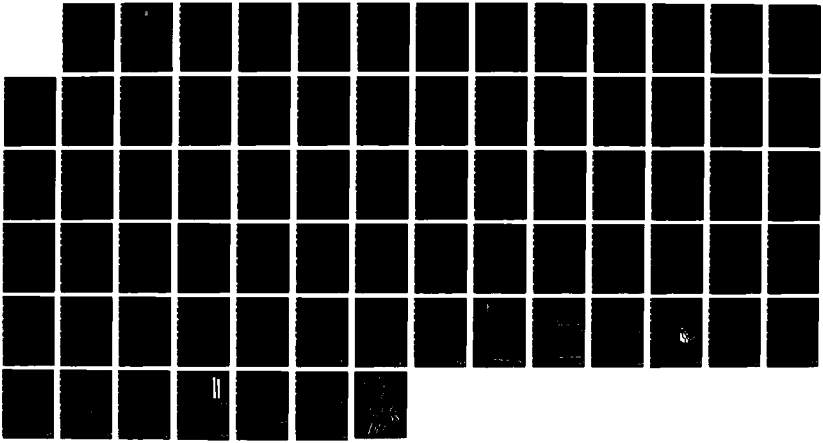

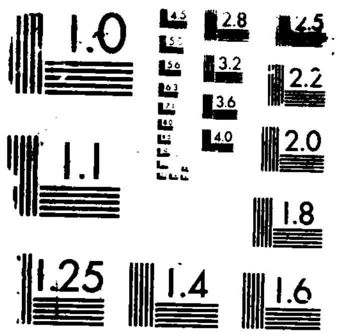

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low metabolic rates with optimal combinations of air flow rates and dry bulb/dew point temperatures, resulting in the extension of tolerance time. The application of these findings to industrial work situations is apparent.

PERSPECTIVES IN MICROCLIMATE COOLING INVOLVING PROTECTIVE CLOTHING IN HOT ENVIRONMENTS

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ABSTRACT

The effectiveness of microclimate cooling systems in alleviating the thermal burden imposed upon soldiers by the wearing of chemical protective clothing under varying environmental conditions has been examined in a series of studies conducted by the U.S. Army Research Institute of Environmental Medicine on the copper manikin, in the climatic chambers and in the field. Liquid-cooled undergarments (LCU) and air-cooled vests (ACV) were tested under environmental conditions from 29° C, 85% rh to 52° C, 25% rh. These parameters were chosen to simulate conditions which may be encountered in either armored vehicles, or in desert or tropic climates. We have reviewed seven studies using LCU (including two ice-cooled vests) and six studies using ACV. LCU tests investigated the effect on cooling when the proportion of total skin surface covered by the LCU was varied. ACV tests examined the effects on cooling during different combinations of air temperature, humidity and air flow rates. Additionally, these combinations were tested at low and moderate metabolic rates. The findings from these LCU and ACV studies demonstrate that a) cooling can be increased with a greater body surface coverage by a LCU and b) evaporative cooling with an ACV is enhanced at low metabolic rates with optimal combinations of air flow rates and dry bulb/dew point temperatures, resulting in the extension of tolerance time. The application of these findings to industrial work situations is apparent.

INTRODUCTION

High temperature and humidity in the work place have been of major concern to diverse industries ranging from coal mining to space exploration. Cognizant of the problem of heat stress on soldiers working in heat outdoors, military commanders have also become aware of the effects of heat on soldiers on maneuvers in enclosures such as tanks and airplane cockpits or encapsulated inside nuclear-biological-chemical (NBC) protective clothing. Characterized by low moisture permeability and high insulating properties (clo ~2.6; i_m/clo ~0.1), NBC clothing, while necessary to prevent noxious agents from reaching the skin, also prevents the normal dissipation of body heat generated metabolically or gained from the environment. NBC protective clothing includes a chemical protective overgarment, overboots, mask with hood and protective gloves. Each of these articles of clothing in various combinations constitutes a given MOPP (Mission Oriented Protective Posture) Level, designated as I, II, III or IV. MOPP I is characterized by the overgarment being worn while the overboots, mask/hood and gloves are carried; MOPP II is characterized by the overgarment and overboots being worn while the mask/hood and gloves are carried; MOPP III is characterized by all but the gloves being worn and; MOPP IV is characterized by all protective clothing articles being worn (also referred to as "complete NBC protective clothing"). In addition, the very bulk of the protective clothing renders the individual less efficient in movement due to the "friction-drag" between the layers, and actually increases the metabolic heat generated by the wearer on a given task, increasing the need to dissipate the heat (29). The intent of this paper is to review the ongoing research program concerning microclimate cooling which is being conducted by the Military Ergonomics Division at the U.S. Army Research Institute of Environmental Medicine (USARIEM).

Initial studies documenting the thermal burden imposed on the wearer of NBC clothing were done by Joy and Goldman in 1968 (13). They studied men in protective clothing who walked for 50 min on an outdoor course exposed to various ambient temperatures (>24° C), humidities, and solar radiative loads. The short length of time that subjects could tolerate such conditions was found to depend more upon impaired heat dissipation than upon the ambient thermal load (9). In fact, they estimated that protective clothing in environments above 24° C decreases tolerance times for continuous moderately heavy physical work to only thirty min (11).

Joy and Goldman's investigations were continued in a 1969 study of an amphibious landing of marines in protective clothing on a Caribbean shore. None of these encapsulated men were able to complete the mission; the study concluded that "it is medically unfeasible to operate in a tropical environment in any of the protective uniforms which were tested" (31). It was clear that even when rest breaks were provided, those in protective wear continued to gain heat. Similar thermal stress on men wearing protective clothing inside an XM-1 tank, parked in the desert sun, was documented by Toner in 1981 (27). Outside the tank, WBGT ranged from 25.7° C to 31° C while inside the tank, the range was 26.8° C to 35° C. When the tank was sealed under these conditions, the men could only remain inside for 80-124 min before heat strain ensued.

Two approaches have been developed to alleviate heat stress in the working individual: macroclimate and microclimate cooling. Before these, in the early twentieth century, the only means available to industry were to ensure heat acclimation, high aerobic fitness, to encourage water consumption, and to provide adequate work-rest cycles. The rationale behind this practice is the fact that heat acclimation and euhydration allow for optimal thermoregulation in the human; however, the thermal problems imposed by protective clothing are biophysical rather than biological (16, 18, 23). Therefore, the ultimate solution is to provide a system for the removal of heat from the body surface to the environment since a consideration of the transfer of heat from the body core to the body surface is not the issue when protective clothing is worn. Later, cooling of the entire working environment (macroclimate cooling) was developed with the use of fans and air-conditioners. However, in such cases as outdoor work, mining or space travel, macroclimate cooling is impractical, ineffective, or too expensive, necessitating the study of microclimate cooling systems. Such systems provide the individual with a portable cooling system in direct contact with the skin. While military research on microclimate cooling has focused on the thermal problems presented by NBC clothing, the concepts and knowledge gained from these studies can be applied to any industrial situation in which the worker must be protected from his environment while surrounded by a barrier to heat dissipation.

BACKGROUND WORK

A resting human has a metabolic rate of about 105 watt (W), and can routinely increase his metabolic rate during light exercise. At low ambient temperatures, such heat may be dissipated as needed by the body's thermoregulatory mechanisms of conduction, convection and radiation. Higher ambient temperatures necessitate evaporative cooling as well. Protective clothing impairs these normal cooling mechanisms. Particularly, when the metabolic rate is high the reduced potential for heat dissipation can result in extreme elevations in body temperatures during moderate ambient conditions (secreted sweat soon saturates the air inside the garment, the added vapor cannot adequately permeate the suit and evaporation stops). Likewise, the insulation of the clothing raises the local ambient temperature around the wearer so that it approaches skin temperature and reduces the potential for dry heat exchange.

Microclimate cooling systems using ice-packet vests, circulating cooled air or liquid in tubes over the skin allow improved removal of body heat from the skin and reduce body heat storage. Some of the environmental heat is also absorbed by the system, decreasing the device's effectiveness at very high ambient temperatures. Microclimate cooling systems also facilitate heat loss by maintaining the temperature gradient between the body core and the cooled skin. In fact, maintenance of this gradient is the essential concept behind the use of microclimate cooling because internal heat conduction by blood from the body's core to the periphery for dissipation depends upon this gradient and the resulting cutaneous vasomotor adjustments.

The amount of heat transferred to any microclimate system is dependent on several factors. The amount and location of body area covered by the device is critical as cutaneous vasomotor adjustments and skin blood flow are not uniform. It is also important to isolate the device from high ambient temperatures to increase effectiveness. Finally, microclimate cooling systems that depend on circulating air or liquid require a power source and connecting tubes to control inlet temperature and flow rate to maximize heat transfer. The length and insulation of these connecting tubes will alter the cooling capacity of the conditioned air or liquid reaching the vest. Each microclimate cooling device has advantages and disadvantages depending on the environment in which it is to be employed.

In summary, the microclimate cooling studies conducted at USARIEM have investigated the effectiveness of the three different systems (i.e., liquid, ice and air-cooled) through testing which has been performed in the field, in climatic chambers or on a sectional copper manikin, under either or both desert and tropic environmental conditions. An overview of the work done in each area is presented in the following pages.

METHODS

Liquid-cooled Systems

The high specific heat of water makes it an ideal medium for microclimate cooling. Cooled liquid circulating in tubes over the skin surface conducts heat away from the body. Heat is also removed from the air around the tubing thereby decreasing the heat received at the skin surface. As the temperature of the water can be maintained at or below the dew point, condensation of moisture around the tubes augments heat loss from the skin as it may be wicked to the semipermeable clothing to enhance evaporative cooling (5).

These aspects of liquid-cooled undergarments (LCU) have been carefully considered and quantified through copper manikin laboratory studies and human chamber and field studies. From the initial prototype LCU (of 40 polyvinylchloride tubes attached to long underwear) developed by the British in 1962, the LCU has undergone multiple design modifications in order to optimize the heat removed while preserving thermal comfort. The liquid microclimate cooling system developed by the U.S. Army Natick, Research, Development and Engineering Center (NATICK) is a vest consisting of three panels constructed of polyurethene coated nylon layers sealed such that the flow channels for the liquid coolant are located within the layers. The vest provides cooling to the torso surface and covers approximately 17% of the total body surface area. Additional panels may be added to provide cooling to the upper and lower body muscle groups. The vest is attached by an umbilical cord to a refrigeration-control unit that maintains precise control of the temperature and flow rate of the cooling liquid which is usually either water or a mixture of 10% propylene glycol and water.

Manikin Studies

Experiment 1

An electrically heated copper manikin was used in this study to evaluate the effectiveness of five LCU over various body surface areas: both the total cooling and the amount of cooling over each individual section were directly measured and electrical power is expressed in watt. The five LCU tested were: 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 LCU provided cooling to the hands or feet. The environmental conditions were either 29.4° C, 85% rh, (26° C dp) or 51.7° C, 25% rh, (26° C dp). The heat exchanges in these two hot environments from a non-sweating and also from a maximally sweating manikin surface to the cooling water flowing through the tubing of a LCU were examined. Each of these five LCU were worn with the Combat Vehicle Crewman (CVC) ensemble, and complete NBC clothing minus the overboots. A detailed description of these methods is provided in a technical report (5).

Experiment 2

The electrically heated copper manikin was used to make a physical evaluation of the effectiveness of four different LCU and a water-cooled cap. The manikin was dressed in a standard hot weather clothing ensemble and the study was conducted in an environmental chamber at air temperatures ranging from 35° C to 49° C. The four LCU included: a+b) 2 garments which provided cooling over the torso-arms-legs (Apollo and British); c) a vest which provided cooling only over the torso and, d) an undergarment consisting of tubing without backing material (Tubing) which provided cooling over all areas except the face. These LCU were operated over a range of cooling inlet water temperatures of 6.7° C to 32° C and water flow rates of 0.7 to 1.8 $\ell \cdot min^{-1}$. The methods employed in this study are provided in greater detail in a technical report (4).

Experiment 3

An electrically heated sectional copper manikin was used to evaluate two portable LCU. The cooling period provided by these LCU is limited by the operating time of the battery supplying power for the pump motor which runs the heat exchanger. One LCU (#1) provided cooling over the torso while the other LCU (#2) provided cooling over the torso and the head. The manikin was dressed in a NBC suit in MOPP IV configuration and cooling rates in watt were determined versus time for a maximally wet (i.e., sweating) skin condition. Chamber environmental conditions were either 32° C, 56% rh,(23° C dp) or 45° C, 46% rh, (31° C dp). Duplicate tests were made in each of these conditions. A detailed description of these methods is provided in a technical report (8).

Chamber Studies

Experiment 4

Experiment 4 examined the effect of varying the body surface area being cooled by a liquid microclimate cooling system in order to alleviate heat stress associated with the performance of physical work by different muscle groups. Although increasing surface area improves heat loss on a manikin, this may not be necessarily true in humans. In humans, regional heat loss appears to be dependent upon the type of exercise performed (24). For example, for a tank loader who uses upper body muscle groups as opposed to an infantry soldier who uses lower body muscle groups, different patterns of regional cooling may, therefore, be needed. This study was undertaken to determine an optimal configuration for cooling various body surface areas during upper and lower body exercise under heat stress conditions of 38° C, 10% rh, (2° C dp). Subjects were heat acclimated and completed a total of six experimental heat stress tests, each one employing a different combination of exercise mode and regional cooling configuration. Four tests employed coolant chilled to an inlet temperature (T_i) of 20° C and two tests employed T_i of 26° C. The four test combinations at 20° C were: a) upper-body exercise with torso cooling (U-T-20); b) upper-body exercise with torso and upper-arm cooling (U-TA-20); c) lower-body exercise with torso cooling (L-T-20) and; d) lower-body exercise with torso, upper-arm and thigh cooling (L-TAT-20). Additionally, lower-body exercise at 26° C with: e) torso (L-T-26) and; f) torso, arm and thigh cooling (L-TAT-26) were repeated. All tests consisted of a 150 min exposure (i.e., three repeats of 10 min rest, 40 min exercise) to the hot environment. Exercise entailed either arm cranking or treadmill walking at the same metabolic rate. Subjects were attired in CVC uniform, ballistic armor vest and NBC protective clothing (minus the mask) plus the LCU. A detailed description of these methods is provided in an open literature paper (28).

Experiment 5

This study evaluated two commercial microclimate cooling systems (MCS) which provide portable liquid cooling. The commercial cooling systems were the ILC Dover and LSSI model vests. Water is utilized as the coolant fluid in the ILC; whereas an aqueous propylene glycol solution is utilized as the coolant in the LSSI system. Both vests operated by circulating their respective coolant fluid from a backpack-mounted heat exchanger (including pump, battery and flow controller) through the liquid garment and back to the heat exchanger. The vests were fabricated from polyurethane coated nylon and had contact cooling surface areas of 0.135 m^2 for the ILC as opposed to 0.184 m^2 for the LSSI (which additionally had a cap with a contact surface area of 0.042 m^2). Subjects were eight male soldiers who were dressed in MOPP IV plus one of the two MCS and on eight occasions they attempted to complete a 180 min heat exposure in a desert (49° C, 20% rh, (20° C dp); 70 W radiant heat load) or a tropic (35° C, 75% rh, (30° C dp)) environment. During the tests, subjects either rested (metabolic rate of 105 W) or performed intermittent treadmill exercise (average metabolic rate of 340 W). The cooling vests were worn under the CVC body armor and were connected via an umbilical line to their backpack unit which was worn over the MOPP IV ensemble. A detailed description of the methods is provided in a technical report (3).

Field Study

Experiment 6

This study evaluated a LCU for its potential in alleviating the heat stress imposed upon active, heat-acclimated crewmen in a closed hatch, unventilated, stationary XM-1 tank, in the desert. The crewmen wore standard CVC uniform plus various configurations of chemical protective clothing; i.e., MOPP I-IV. All testing was performed in September at Yuma Proving Ground, Arizona between 1330 and 1700 hours. The environmental conditions varied throughout the testing and differed both inside and outside the tank. The temperature averaged 35±1.1° C with 26±2% rh, (14° C dp); winds were from 4 to 13 knots and cloud cover was between 13 and 30%. Throughout the duration of a given heat exposure, each crewman had specific tasks to perform which were done at low to moderate exercise levels. A detailed description of these methods is provided in a technical report (27).

Ice-cooled Systems

Manikin Study

Experiment 1

The electrically heated copper manikin was used to assess the cooling provided by each of two ice packet vests. The manikin was dressed in CVC ensemble, complete NBC protective clothing (minus the overboots) plus ice packet vest. The heat exposures were to three environments: 29° C, 85% rh, (26° C dp); 35° C, 62% rh, (26° C dp); and 52° C, 25% rh, (26° C dp). Cooling rates (watt) versus time were determined for a maximally sweating skin condition. Ice packet vest #1 contained a maximum of 72 ice packets while ice packet vest #2 contained a maximum of 91 packets which presented a continuous interface between ice and torso. The ice packets varied somewhat in size; however, each packet had a contact surface area of ~64 cm^2 and contained ~47 gms of water. One experiment was conducted with fewer than the maximum number of packets that the vest could hold to investigate the effect on torso cooling. A detailed description of these methods is provided in a technical report (6).

Air-cooled Systems

Manikin Study

Experiment 1

In this study, the electrically heated, sectional copper manikin was used to determine the rates of cooling provided by 3 different air cooled vests (ACV) and a ventilated XM-29 Face Piece. Cooling rates were measured for the sweating and non-sweating skin conditions. The ACV were worn with the CVC ensemble and NBC MOPP IV level clothing in environments that ranged from 29° C and 85% rh, (26° C dp) to 52° C and 25% rh, (26° C dp). Ventilating air flow rates to the vests ranged from 1.5 to 15 cfm while inlet cooling air temperature and rh varied over the range of 10° C, 20% rh, (-12° C dp) to 43° C, 14% rh, (10° C dp). The three ACV were: two NATICK vests which covered only the torso (but cooling air at higher ventilating air flows could travel over the arms and legs) and one commercial model which was fabricated to direct cooling air up the back of the neck and down the back and front of each leg. The NATICK ACV provide torso cooling via a hose/manifold system that is mounted on an open weave fabric. The vest is attached by an umbilical cord to a control unit which precisely maintains the temperature and flow rate of the air being supplied to the vest. A detailed description of the methods is provided in a technical report (7).

Chamber Studies

Experiment 2

In this experiment, the NATICK ACV was studied to evaluate its effectiveness under severe heat stress conditions. The vest was tested on soldiers working for three hours at a metabolic rate of 340 W under desert conditions of 49° C, 19% rh, (19° C dp), radiant load 70 W, and a wind speed of 1.5 $m \cdot s^{-1}$. The vest was also tested in these environmental conditions without the radiant load at a lower metabolic rate of 240 W for an extended duration of 12 hours. Subjects were heat acclimated and wore CVC uniform, body armor, helmet and NBC MOPP IV level clothing along with the ACV. The cooling air supplied to the vests was 16° C, 20° C dp. The vest delivered 15 cfm of conditional air to the chest, neck and back and 3 cfm to the face. A detailed description of these methods is provided in a technical report (21).

Experiment 3

This study determined the effectiveness of the NATICK ACV using selected air temperature and humidity combinations to determine the minimal air conditioning requirements for several military vehicles. Heat acclimated soldiers dressed in CVC uniform and NBC, MOPP IV level clothing attempted 300 min heat exposures (49° C, 20% rh, (20° C dp)) at metabolic rates of 175 and 315 W, each with five different cooling combinations. The 175 W metabolic rate was attained by resting for 45 min and walking at 1.01 $m \cdot s^{-1}$ for 15 min per hour while 315 W was accomplished by walking at the above speed for 45 min and resting for 15 min per hour. At each of these two metabolic rates, five combinations of temperatures ranging from 20-27° C, 40-58% rh and 7-18° C dp were supplied to an ACV at 15 cfm. During each of the two control tests, the subjects did not wear the ACV; however, the face piece to the mask was ventilated with 3 cfm of ambient air. A detailed description of these methods is provided in an open literature publication (22).

Experiment 4

This study evaluated the effectiveness of the NATICK ACV which was supplied with each of four different combinations of dry bulb and dew point temperatures and air flow rates, to further extend the work done in Experiment 3. Subjects were heat acclimated and exercised at metabolic rates of 175 or 315 W, attempting 300 min exposures on four occasions, while dressed in CVC uniform, Kevlar vest and NBC MOPP IV level clothing. Environmental conditions were constant at 49° C, 20% rh, (20° C dp). Air flow rate to the vest was either 10 or 14.5 cfm. This ACV is designed to provide chest (40%), neck (20%) and back (40%) cooling via a hose and manifold system mounted on an open weave fabric. These methods are provided in detail in a technical report (15).

Experiment 5

The effectiveness of an air shower and the NATICK ACV vest was evaluated in this study on tank crewmen dressed in CVC uniform with Kevlar (i.e., fragmentation) vest and NBC clothing in MOPP III and IV configurations. The tank was stationary in a climatic chamber with environmental conditions of 33° C, 50% rh, (24° C dp) (WBGT index of 28° C) and minimal wind speed. The crewmen performed standard tank exercises at metabolic rates of 146 to 360 W in the closed hatch tank for 165 min. Cooling was provided by either individual vest cooling to the torso or an "air shower" of 47 cfm to each of the crewmens' areas. One crew also attempted the heat exposure with usage of the M13A1 particulate filter in operation but without microclimate cooling; this exposure was discontinued following the incapacitation of two crewmen within 84 min. Vest cooling supplied about 15 cfm of air distributed to the chest (5-6.5 cfm), neck (2-3 cfm) and back (6.5-7 cfm). Additionally, 3 cfm was supplied to the M25 gas mask. A more detailed description of these methods is provided in a previously published technical report (28).

Field Study

Experiment 6

This study evaluated the thermal responses of tank crewmen wearing the NATICK air-cooled system (vest and ventilated face piece) while dressed in CVC uniform, Kevlar vest and NBC MOPP IV level clothing. Testing took place in the field in desert (Yuma Proving Ground, Arizona) and tropic (Tropic Test Center, Republic of Panama) environments. Ambient temperatures during the two desert tests ranged from 23-38° C, 20-64% rh, (1-30° C dp); ambient temperatures during the tropic tests ranged from 27-36° C db and 40-81% rh, (13-32° C dp). The crewmen performed continuous operations for up to 12 hours exposure time. The microclimate cooling system provided a total of 20 cfm of conditioned air with each crewman receiving 18 cfm (15 cfm to the vest and 3 cfm to the face piece) with the remainder bulk dumped into the driver's compartment. A technical report (2) describes this system and the methods in detail.

RESULTS

Liquid-cooled systems

Experiment 1

The range of cooling in watt, provided by each of the five LCU as a function of the cooling water inlet temperature, is presented in Figure 1. These curves show that at cooling water inlet temperatures above 10° C, the water-cooled cap could not provide 100 watt of cooling even for a completely wet skin condition; the water-cooled vest would require a completely wet skin condition; and the water-cooled cap with water-cooled vest could provide 100 watt of cooling even for a dry skin. With the LCU, short, the skin would have to be completely wet if there was a requirement for it to provide 400 watt of cooling, but the LCU, long, could provide this amount of cooling even if the skin were dry. A "comfortable" cooling water inlet temperature of 20° C should provide 46 watt of cooling using the water-cooled cap; 66 watt using the water-cooled cap with the water-cooled vest; 264 watt using the LCU, short; and 387 watt using the LCU, long. As expected, these results support the conclusion that cooling in watt increases with greater body surface coverage from the LCU and illustrates the importance of biophysical assessments of the heat transfer characteristics concerning prototype microclimate cooling systems using the heated copper manikin.

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INSERT FIGURE 1 HERE

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Experiment 2

Experiment 2 demonstrates the importance of the proportion of the total skin area covered by a given LCU (and the thickness of this garment) in assessing the effectiveness of the LCU in shielding the body from a hot environment. The findings reveal the Tubing LCU to be most effective in reducing the total amount of heat received by the body from the hot environment; this LCU reduces the total heat gained by about 70%. The water-cooled vest (covering only the torso) showed the lowest reduction in total heat gain; ~7%. The British LCU reduces the total heat gained by about 38% while the reduction with the Apollo is slightly less at ~30%. When the heat received from a hot environment is restricted to the torso area only, the aforementioned values change to 65% for the Tubing LCU, 50% for the water-cooled vest and 44% for the British and Apollo LCU.

Figure 2 shows the dependence of manikin heat loss on the temperature difference between the manikin surface and the inlet water temperature (T_s - W) and the cooling water flow rate ($\ell \cdot min^{-1}$) of a LCU for these four LCU. These curves show the increase in watt of cooling with increasing skin to water temperature gradient (Part A) and the increase in watt of cooling with increasing water flow rate (Parts B and C). The increase in cooling with increasing T_s - W is dramatic. This increase in cooling is almost directly proportional to the temperature difference; i.e., doubling the temperature difference will nearly double the heat transfer between a LCU and the manikin surface. In contrast, although cooling increases with increasing water flow rate, this increase in cooling is not directly proportional to water flow rate.

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INSERT FIGURE 2 HERE

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Figure 3 shows that the quantity of cooling provided by the water-cooled cap decreases continuously over time with the steepest decrease occuring after ~90 min of cooling. The addition of an aircrew helmet provides a 30% increase in insulation over the head from the hot environment, and therefore, the benefit of such a practice increases with increasing air temperature. At 47° C and 37% rh, (29° C dp), the total heat removed from the head using this water-cooled cap/helmet system would be about 42 watt (since heat transfer between the head and the cap is increased by up to 13 watt when the helmet is worn). Under these environmental conditions, the quantity of heat removed from the head by the water-cooled cap would equal about 1/3 of the metabolic heat production for a seated person.

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INSERT FIGURE 3 HERE

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These findings, taken in combination with the rates of cooling provided by the LCU against metabolic heat gain demonstrate that whereas these LCU do not completely isolate the skin surface from gaining heat from a hot environment, they do (in addition to removing internally generated heat) remove one-half or more of the potential for heat gain from the environment. In this manner, the

LCU and water-cooled cap are effective measures in alleviating the heat stress of personnel working in the enclosed crew compartments of aircraft or armored vehicles in hot environments.

Experiment 3

The cooling period for the LCU of Experiment 1 is limited by the operating time of the battery, i.e., about two hours. However, battery replacement after two hours of operation apparently did not affect the cooling rate since the curves do not show any abrupt changes in slope after two hours as seen in Figure 4. Under the conditions of these experiments, there is no leveling off of the cooling rate with time; all curves reach a maximum rate of cooling of 126 to 150 watt (LCU #2 and #1, respectively), then decrease with time as shown in Figure 5. The average torso cooling rate for LCU #1 over the first hour is -94 watt at 45° C, and -83 watt at 32° C (Fig.4). These values decrease to -46 watt at 45° C and -26 watt at 32° C over the second hour of cooling. Some torso cooling is provided for up to three hours. The average torso plus head cooling for LCU #2 over the first hour is about 81 watt at 45° C, and 67 watt at 32° C (Fig.5). These values decrease to 67 watt and 43 watt respectively, over the second hour of cooling. As with LCU #1, LCU #2 provides some cooling to the torso and head for up to three hours. Over a two hour cooling period, about 78% of the cooling is provided over the torso and 22% over the head with these percentages being about the same as the percentages of total tubing covering the torso and head, respectively.

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INSERT FIGURES 4 AND 5 HERE

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Experiment 4

Figure 6 depicts changes in rectal temperature (T_{re}), relative to the initial value, during each rest/exercise cycle of the two upper-body exercise-heat stress tests of Experiment 4. There were no significant differences between U-T-20 and U-TA-20 in the change in T_{re}. Figure 7 presents pooled data to show the effect of the amount of surface area cooled on changes in T_{re} during lower-body exercise-heat stress tests as there was no effect of T_i on changes in T_{re} under these conditions. The microclimate cooling system was more effective in alleviating heat stress during lower-body exercise when the surface area for cooling was increased to include the thighs. T_{re} changes as well as heart rates and sweating rates were all lower with torso and thigh cooling when compared to torso-only cooling. This improvement in cooling was probably due to the large increase in amount of active muscle available for conductive heat transfer. A comparison between upper-body (U-T-20) versus lower-body (L-T-20) exercise revealed no difference in metabolic rate, sweating rate, and T_{re} changes. The data from this study indicates that cooling arms in addition to the torso during upper-body exercise provides no thermoregulatory advantage, while cooling the thigh surfaces in addition to the torso during lower-body exercise does provide an advantage.

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INSERT FIGURES 6 AND 7 HERE

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Experiment 5

For the two commercial cooling systems of Experiment 5, there were no statistical differences ($P>0.05$) between systems in any of the experimental conditions for cooling capacity, endurance time, T_{re}, skin temperature, heart rate, sweating rate or water intake (Figures 8 and 9). All subjects completed the resting tests but were unable to complete the exercise tests in either commercial cooling vest (mean exposure times were 98 and 169 min for the desert and tropic tests, respectively). An excessive amount of maintenance was required to keep the vests operational. A common problem included crimping in the vests which would cause the flow to become blocked which in turn resulted in disengagement of the pump. A serious logistical drawback was the improbability of successful utilization of a "buddy" system to maintain the commercial cooling vests. All flow controls and indicators for each system were mounted on the soldier's back so that they were inaccessible to him for regulation and monitoring. Batteries and ice packs would be too difficult for a buddy dressed in MOPP IV inside or outside a tank under battle conditions to change. Finally, the greatest logistical problem was posed by the ice cartridges used in the commercial vests. The maximum cooling that either system could produce would be 180 watt necessitating ice cartridge changes every 20 min. Furthermore, this study demonstrates some of the problems encountered in the application of commercially suitable cooling systems to military use.

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INSERT FIGURES 8 AND 9 HERE

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Experiment 6

Figure 10 graphically depicts the contrast in humidity buildup with the closed versus open hatch tank conditions of Experiment 6. In the closed hatch condition, although there was not much temperature buildup inside the tank, the interior relative humidity rose dramatically to approach 95% on the sixth day of testing. This rise in relative humidity inside the tank was the direct result of the crew's sweat production. Also notable is the fact that on Day 4, the interior WBGT rose ~6° C within 45 min: the effects of this heat stress on the crew is evidenced by steeply rising skin temperatures and more slowly responding but nonetheless increasing rectal temperatures of the crew as seen in Figure 11. In contrast, on Day 5 (with essentially similar exposure conditions) when the men wore a water-cooled vest, there was little or no rise in rectal temperature despite the buildup of interior humidity as shown in Figure 12, and skin temperatures were extremely low. The vest removed heat at a rate of about 75 watt from each of the men who were able to complete the full exposure time without difficulty.

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INSERT FIGURES 10, 11, 12 HERE

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The physiological data from this study fully reflects the relative strains of heat exposure when subjects are in MOPP IV gear, and in tanks with closed hatches. The overall study findings are summarized in Table 1, where average values for skin and rectal temperature, heart rates and sweating rates are presented. Note that sweating rate on Day 4 averages 2.05 $\ell \cdot hr^{-1}$ in contrast to the average 0.63 $\ell \cdot hr^{-1}$ produced when microclimate cooling was available. Clearly there is a reduction in the requirement for drinking water of between 0.9 and 1.4 $\ell \cdot hr^{-1}$ with microclimate cooling. In addition, the mission can be accomplished with microclimate cooling, it but can not be accomplished without it, when the hatches are closed and the ventilating system is off.

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Ice-cooled Systems

Experiment 1

In Experiment 1, the heat losses from the torso of the manikin equalled the actual watt of cooling supplied to the torso during a given experiment. The decrease in torso watt with torso cooling time for ice packet vest #1 is shown in Figure 13, for each of the hot environmental exposures. The total heat losses from the torso during each cooling period were: 381 W at 29° C; 362 W at 35° C; 278 W for 52° C; and 187 W at 52° C when 40% of the ice packets were removed from the vest. No cooling is provided when the ice is completely melted and then the torso receives a net heat gain from a hot environment of 52° C, 25% rh, (26° C dp). This heat gain results in skin temperature rising above 35° C.

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INSERT FIGURES 13 AND 14 HERE

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Figure 14 shows the decrease in torso watt with cooling time for ice packet vest #2 during exposure to each of the three hot environments. The total heat losses were: 522 W at 29° C; 491 W at 35° C; and 444 W at 52° C The relationships among these curves are similar to those seen in Figure 13; the effect of increasing the temperature of the environment from 29° C to 52° C is to decrease the torso heat loss by ~50%. The effect of increasing the number of ice packets on the vest by 26% (i.e., from 71 to 91 packets) is to increase both the heat removed from the torso during the cooling period and the length of time during which some benefit would be obtained from the vest. The total heat exchange over a four-hour cooling period when 91 ice packets are attached to a vest are: 760 W at 29° C; 690 W at 35° C; and 370 W at 52° C. Expressed another way, each kilogram of ice which is initially at a temperature of -20° C, has the potential of providing 145 W of cooling to the torso surface and/or a hot environment before the melted ice temperature reaches the average torso skin temperature of 35° C. The efficiency of cooling provided over a four hour torso cooling period by an ice packet vest (based on the potential cooling provided by a kilogram of ice) is 73% when 91 packets are used with the vest, 69% when 72 packets are used and 63% when 44 packets are used. These approximate calculations indicate that the cooling efficiency of an ice packet vest should increase with the number of ice packets attached to the vest, up to the limit of total torso surface area coverage. Said another way, when ~50% of the torso surface area is covered by ice packets, each additional ice packet added to the vest increases the torso cooling to a greater degree than an ice packet added to a vest with less than 50% torso surface area coverage. Also, with less than full coverage, the cooling is dependent upon the temperature of the hot environment whereas with full coverage, torso cooling over a four hour heat exposure is independent of the temperature of the hot environment. Finally, since ice packet vests do not provide continuous and regulated cooling over an indefinite time period, exposure to a hot environment would either be time limited, or else involve backup ice packet vests which would require redressing every 2 to 4 hours when the ice in the packets was completely melted and water temperature approached skin temperature.

Air-cooled Systems

Experiment 1

Cooling rates (watt) for the ACV #1 of Experiment 1 are given in Table 2 for cooling air flow rates of 6, 8 and 10 cfm. Inlet cooling air temperatures were either 10° C at 20% rh, (-12° C dp) or 21° C at 10% rh, (-12° C dp). Less cooling was obtained in a 29° C environment than under comparable conditions in a 52° C environment. Considering all twelve cooling rates in Table 2, the average percentage of difference in the cooling rates between 29° C and 52° C is about 22%. Without ventilation, the skin (at 35° C) loses heat to the environment at 29° C but gains heat at 52° C. Thus, the potential for change in heat loss (i.e., cooling) is greater at 52° C. Increasing the ventilating air flow rate from 6 to 10 cfm (a 67% increase) increases the cooling rate by ~67%, suggesting that over this air flow range, the cooling rate increases in proportion to the ventilatory air flow rate. The average value of the cooling efficiency of this ACV was 32%; i.e., about 1/3 of the cooling potential of the ventilating air was being utilized.

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INSERT TABLE 2 HERE

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When ACV #1 was worn with the XM-29 Face Piece as shown in Table 3, cooling air to the vest ranged from 3 to 15 cfm and to the inlet of the face piece either 3 or 4.5 cfm. Exposure was in two hot environments: 32° C, 26% rh, (10° C dp) and 49° C, 11% rh, (11° C dp). At the low air flow rate, cooling to the face accounted for ~34% of the total cooling rate with this cooling falling to ~16% at the higher ventilating air flow rates. The efficiency of cooling of the air supplied to the face piece alone was ~18% as compared to ~28% for ACV #1 (vest alone) under these experimental conditions.

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INSERT TABLE 3 HERE

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Cooling rates for the ACV #2 are given in Table 4 for cooling air flow rates ranging from 1.5 to 10.0 cfm. Inlet cooling air temperatures were either 21° C, 16% rh, (-6° C dp) or 21° C, 60% rh, (13° C dp) in two hot environments of 29° C, 85% rh, (26° C dp) and 52° C, 25% rh, (26° C dp). The cooling curves in Figure 15 show a reduction in the cooling rate with increasing relative humidity of the inlet air. However, for two inlet cooling air conditions of constant temperature but different relative humidity, the cooling efficiency of the one with the initially higher relative humidity will always be equal to or greater than the cooling efficiency of the one with the lower relative humidity. When comparing the cooling efficiencies of different ACV, not only the flow rate and temperature of the inlet cooling air have to be the same, but also its relative humidity. At air flows of ~4 cfm or less, the cooling curve for the 52° C environment consistently shows higher cooling rate values than the others above 4 cfm. This is consistent with the finding for ACV #1. Under the same cooling air flow rate, temperature and relative humidity, cooling provided by air supplied to these vests is greater in the higher air temperature condition; i.e., a given quantity of ventilating air is more efficient. The cooling efficiency of ACV #2 is ~74% for air flow rates of 3 cfm. This is nearly double the cooling efficiency of ACV #1. At these air flows, a decrease in flow rate results in an increase in cooling efficiency.

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INSERT TABLE 4 AND FIGURE 15 HERE

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Comparing the cooling rates over the torso-arms-legs in Table 3 for ACV #1 with the cooling rates in Table 5 for ACV #3 shows very little difference at the low ventilating air flows (3 or 6 cfm); i.e., only ~5% difference is noted. At an air flow rate of 10 cfm, the cooling rate for ACV #3 is ~50% greater than the rate for ACV #1. At the higher air flows, both ACVs provided ~55% of their cooling over the torso; however, at these higher flow rates, the contribution of the legs to total cooling increases. The cooling efficiency of ACV #3 is ~31% as compared to 28% for ACV #1 and the face piece is ~18% with ACV #1 as opposed to 22% with ACV #3.

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INSERT TABLE 5 HERE

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Experiment 2

All subjects were able to complete both the 3 and 12 hour heat exposures in Experiment 2. T_{re} during exercise for both tests increased over time ($p<0.05$). T_{re} at the end of the final exercise bout averaged 38.0±0.3° C for the 12 hour test and 38.5±0.6° C for the 3 hour test, representing an average increase of 1.1° C and 1.7° C, respectively, over the initial resting values. In the extreme environment (i.e., 49° C) of those tests, the ACV significantly reduced physiological strain and increased tolerance time to over 12 hours using a 1:1 work to rest ratio.

Experiment 3

All subjects demonstrated a rapid rise in T_{re} during the control test (metabolic rate of 175 W) which involved no ACV but NBC protective clothing, and they were unable to complete the proposed 300 min heat exposure of Experiment 3. Average endurance time was only 118 min. A rapid rate of rise in T_{re} is associated with increased body heat storage and therefore this variable appears to be a good prognosticator of exercise-heat tolerance (19).

In contrast to the T_{re} attained during the control test in this experiment, all five cooling combinations (presented in Table 6) allowed for the maintenance of a near constant body temperature while subjects were dressed in NBC, MOPP IV level protective clothing. Additionally, among the five cooling combinations during the various rest or exercise periods, there were no significant differences in T_{re} responses ($p>0.05$). However, at 315 W, the ACV at all five cooling combinations was less effective in maintaining T_{re} as illustrated in Figure 16. T_{re} decreased during the rest periods but increased significantly ($p<0.05$) over time with all five cooling combinations. After the fourth exercise bout (~235 min), peak T_{re} averaged 38.0° C for A, 38.2° C for B, 38.3° C for D, 38.5° C for E and 38.6° C for C. Nevertheless, all five combinations were more effective in lessening the rate of rise in T_{re} than the control tests (i.e., no cooling).

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INSERT TABLE 6 and FIGURE 16 HERE

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Figure 17 presents endurance times for each of the five combinations, A, B, C, D and E and for the control tests at 175 and 315 watt. At 175 watt, all subjects were able to complete the 300 minute heat exposure for all five cooling combinations; however, without the cooling vest, endurance time was limited to an average of 118 (±27, SD) min. At 315 watt, endurance times did not differ significantly ($p>0.05$) among the five combinations (range, 242 - 300 min); however, with no microclimate cooling, the endurance time averaged only 73 (±19, SD) min.

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INSERT FIGURE 17 HERE

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Experiment 4

Table 7 presents the cooling vest test combinations for Experiment 4. Figure 18 graphically depicts the endurance times for the four cooling combination tests. At 175 watt, between vest conditions H and I, there was no significant difference and all six subjects completed the 300 min test in cooling vest H. At 315 watt, again there was no significant difference between conditions F and G; however, no subject was able to complete the 300 min heat exposure using either vest F or G.

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INSERT TABLE 7 AND FIGURE 18 HERE

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The rectal temperature response at 175 watt for vests H and I is given in Figure 19. After the second walk, T_{re} did not increase significantly ($p>0.05$) over time with either cooling combination. In contrast, it can be seen from Figure 20, that at 315 watt for vests F and G, T_{re} was higher ($p<0.05$) at the end of each exercise bout compared to each preceding bout. The average T_{re} exceeded 39.0° C prior to terminating the heat stress for both vest trials.

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INSERT FIGURES 19 AND 20 HERE

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The air-cooled vest combinations tested in this study reduced but did not prevent body heat storage. Table 8 presents the cooling capacity, mean endurance times and mean rectal temperatures for the control and five vest conditions tested in Experiment 3 and the four vest combinations of Experiment 4. Vests H and I of Experiment 4 yielded longer endurance times (300±0 and 272±68 min, respectively) which suggests that these combinations of air flow rate and db/dp temperatures were effective in reducing the thermal strain of the subjects. Referring to Table 8, it can be seen that the potential cooling of vest H (218 watt) with the lower air flow rate was ~66% lower than vest A and B from Experiment 3 which had previously demonstrated to be the most physiologically effective in reducing thermal strain. It is possible that at the lower air flow rate (10 cfm), vest H was rendered more efficient by the improvement in heat transfer which was due to the increased transit time across the skin.

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INSERT TABLE 8 HERE

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At 315 watt, vest F allowed the longest endurance time, which was 220±78 min. This time is shorter than the previously reported values listed in Table 8, and it was associated with a greater thermal strain than the prior vest conditions in Experiment 3. In addition, none of the subjects in the present study were able to complete the five hour heat exposures whereas in the aforementioned study, subjects completed the heat exposures 70% of the time. Lastly, use of the microclimate cooling vest combinations F, G, H and I reduced sweating rates which prevented dehydration and the accompanying heat storage due to exercise.

Experiment 5

No differences ($p>0.05$) were found in tank environmental conditions between the air shower and vest tests of Experiment 5. Table 9 presents the final physiological responses of the two crews (combined) during these tests. It can be seen that rectal, skin and mean body temperatures and heart rates were statistically higher during the air shower as compared to vest tests. A substantial gradient ($\bar{X}$, 6.3° C; range, 5 to 7° C) was established between the mean skin and rectal temperatures during the vest tests. By contrast, a much smaller gradient between these variables occured during the air shower test, and these smaller gradients probably contributed to the slight increase in rectal temperatures noted. The heart rate responses are lower during the vest test compared to both the air shower and M13A1 tests: in fact, the final values during the air shower test are statistically higher ($p<0.05$) than the vest test. Finally, total sweat loss values were nearly twice as high during the air shower test as compared to the vest test. This substantiates earlier findings (27) which have demonstrated the benefits of water conservation provided by vest cooling. Therefore, despite the fact that the environmental conditions were substantially improved with the air shower, the combination of insulation and low permeability of the CVC and NBC protective clothing prevented sufficient heat dissipation via this mode (i.e., air shower) to maintain normal core temperatures.

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INSERT TABLE 9 HERE

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Experiment 6

Figure 21 shows the mean T_{re} response of the four tank crewmen during the 12 hour tropic test of Experiment 6. During the first hour in the tank, these crewmen displayed a group decrease in T_{re} followed over the next 11 hours by a mean increase in T_{re} of 0.5° C. T_{re} did not approach the physiological safety limit but did show a statistically significant increase ($p<0.05$) over the 12 hour duration time of this test. Mean T_{re} at the start and finish of this tropic test were 37.2±0.05° C and 37.4±0.4° C, respectively. At the low metabolic rates generated in this test, 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 of 7.5 and 12 hours in desert environments. No significant body heat storage occured in any of the four tank crewmen during either test. Figure 22 shows that the average rise in T_{re} during the 12 hours was 0.1±0.4° C and during the 7.5 hour test, T_{re} increased by no more than 0.2° C.

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INSERT FIGURES 21 AND 22 HERE

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DISCUSSION

Liquid-cooled systems

The amount of cooling provided by a water-cooled garment can be precisely measured on an electrically heated sectional copper manikin. The increase in electrical power required to maintain the manikin's surface temperature constant when the water-cooled garment is in place corresponds to the amount of heat transferred to the circulating cooled water. The difference between the total heat removed from the manikin by the water, and the heat transferred to the manikin from the environment, represents the total heat gained or lost. Fonseca has documented (5) that the cooler the inlet water temperature used, the more heat removed. In fact, the rate of cooling provided by a LCU is proportional to the difference between the skin and inlet water temperatures (12). Fonseca also shows that the more body surface area covered by the LCU, the more cooling occurs. Heat transfer is also increased by increasing inlet flow rates but not in direct proportion. Interestingly, more cooling is provided by a LCU when the skin is wet from sweat. A continuous condensation-evaporation cycle is established from the skin to the tubing to the outer clothing potentiating heat loss (5). Cooling inlet water temperatures studied have ranged from 7° to 28° C depending on the garment used. Thermal comfort dictates that cooling inlet water temperatures less than 10° C are unacceptable to the wearer.

Consideration of regional cooling is important when dealing with a water-cooled garment. Cooling to the head with a water-cooled cap, to the torso with a vest and to the arms and legs using long underwear have been evaluated (5). With the exception of exercising muscles, cutaneous vessels under the LCU may constrict decreasing conductive heat transfer. Placing the LCU over working muscles has been found to be of benefit. Cooling thigh surfaces during leg exercise, in addition to cooling the torso, decreased heat strain in men wearing protective gear more effectively than just torso cooling alone (32). Conduction of heat from the active leg muscles was enhanced by the cooling device. During upper body exercise, however, additional cooling to the arms was not helpful (32), probably due to the regional differences for the vasoomotor response (24). In subjects exercising on a treadmill while wearing an evenly distributed LCU, heat stress was reduced overall but subjectively the torso felt chilled while the legs remained hot (17). Therefore, depending upon the workplace and activity of the wearer, the LCU can be customized to the type of work and environment.

Portable LCU with the heat sink, battery and pump strapped to the back are available (8), and stationary prototypes with the wearer tethered to the cooling unit by long inlet tubes have been designed (4,5,26,32). All provide continuous and controlled cooling. Problems with the LCU or any microclimate system which uses liquid as a medium are diverse; LCU are heavier than those using air-cooling, adding to the wearer's workload, and interruption of flow, if the tubes are compressed, has also been documented (8). As water has such a high heat capacity, it is ideally suited for microclimate cooling where heat loads greater than 465 watt need to be removed. Conversely, if the cooling requirement decreases, as with decreasing metabolic activity, the wearer can become rapidly chilled causing cutaneous vasoconstriction and unwanted body heat loss and thermal discomfort (17).

A study of commercial cooling vests involving the use of ice cartridges was performed in climatic chambers under desert and tropical environmental conditions. Physiological data confirmed that there were no differences between the two commercial vests tested in their ability to reduce thermal strain. Likewise, engineering data concluded that the two vests produced statistically identical cooling capacities. The maximum cooling capacity that could be generated with either system was ~180 watt; however, to offset the metabolic heat loads, typical of many combat scenarios, a microclimate cooling system that will deliver ~350 watt of cooling is required. To put it simply, neither system was sufficient to enable subjects to complete a three hour heat exposure and too much maintenance was required to keep the systems practically operational.

The ideal water-based microclimate cooling system has yet to be developed. However, the concept of providing variable cooling over different regions of the body would allow for optimal cooling. While variable regional cooling would be ideal, particularly in situations of intense physical work, most liquid-based systems are unwieldy, require large amounts of energy and often malfunction in field use (8).

Ice-cooled systems

Ice packets of water or dry ice may be positioned on the body, such as in an ice-packet vest under the protective gear, to provide conductive cooling (6). This method of microclimate cooling allows the wearer to move without being tethered or carrying the cooling unit as is required in other portable systems. No continuous energy source is needed to provide cooling, although a source of refrigeration is necessary. Local skin temperatures of 10-15° C under the ice do not cause undue discomfort (14). Critical aspects of ice-cooling are the actual body surface in contact with the ice at a given time, and the insulation of the ice packets from the environment. As ice melts, its shape changes and its direct contact with the body surface will also change. Consequently, heat is not removed at a constant or controllable rate and is limited to a finite period of time, i.e., until the melting ice reaches body temperature. Once the ice is completely melted, the water temperature continually increases and approaches the temperature of the torso surface. There is no condensation of moisture onto these ice packets from the surrounding air trapped within the clothing layers once the temperature of the plastic ice packets exceeds the dew point of this surrounding air. This is a different experimental condition than when a LCU is worn. The surface of the tubing of a LCU can constantly be maintained at or below the dew point temperature of the surrounding air. Condensation of moisture from the air trapped within the clothing augments the heat loss from the skin surface by continually wicking and blotting this moisture onto the larger surface areas of the clothing. With the ice packet vest, cooling rates are high when the ice first contacts the skin and decrease as the ice melts. Copper manikin studies using environments of 29.4° C, 85% rh, (27° C dp) and 35° C, 62%

rh, (26° C dp) documented that ice packet vests worn under the protective clothing provided some cooling for up to four hours. At a higher ambient temperature of 51.7° C, 25% rh, (26° C dp), cooling from the vest was negligible after three hours (6). As ice-based microclimate cooling decreases the rate of heat storage but does not prevent it, this system would be useful for short duration physical work only.

Air-cooled systems

The essential difference between liquid-cooled and air-cooled microclimate systems is the mechanism of heat transfer employed. While liquid-cooled devices use conduction, air-cooled systems potentiate convective cooling and depend on the evaporation of sweat to be completely effective as a cooling device (25). In air-cooled devices, dry-cool air permeates under the protective clothing and exits after exchanging heat and moisture with the air inside the clothing. The design of an air-cooled vest can increase the efficiency of cooling of the ventilating air by maximizing the proportion of cooling air that diffuses over the surface of the body and minimizing the proportion of cooling air that exits the air-cooled vest directly through the clothing to the hot environment. Maximum cooling to the body has been provided when the ventilating air passes over the skin surface and then exits to the hot environment saturated with moisture at the temperature of the skin. The cooling efficiency in this case would be 100% as opposed to the situation where saturation occurs partly within the clothing layers (rather than strictly along the skin surface) in which case cooling efficiency would be less than 100%. In other words, the cooling air flow rate must be sufficient to ensure that the ventilating air does not reach moisture saturation before it completes its passage over the skin since warm, saturated air will not provide any cooling of surfaces over which it passes (7). By increasing the air flow rate or decreasing the air temperature, cooling is modulated. In three ACVs studied by Fonseca on the copper manikin, cooling rates increased in proportion to increasing air flow rates and decreasing inlet cooling air temperature (7). These cooling rates were dependent upon the particular hot environment in which the exposure occured as the ventilating air moving from the surface of the skin outward through the clothing apparently did not provide the thermal isolation from a hot environment that a water-cooled undergarment does.

While air is not as efficient as water due to the difference in specific heat, air-cooled systems are effective in reducing heat strain (22) and in some environments are felt to be as effective as water-cooled devices (25). In addition, air-cooled vests provide drier skin conditions thereby increasing the level of thermal comfort afforded by this system as opposed to that provided by liquid-cooled systems. Soldiers wearing protective clothing, generating metabolic rates of either 175 watt or 315 watt in 49° C, 20% rh, (20° C dp) were unable to tolerate more than 118 min or 73 min of work, respectively. Wearing the air-cooled vests, subjects' rectal temperatures, heart rates, and sweating rates were effectively reduced and endurance time extended for both work loads, to 300 min. The vest provided 15 cfm of conditioned air to the chest, neck and back and 3 cfm to the face, with supplied air temperatures ranging from 20-27° C, 40-58% rh (7-18° C dp). While air circulation and heat transfer is not uniform in these devices making some skin surfaces drier than others, cooling is still effective since convective cooling in the drier area does occur.

In environments uncontaminated by biological and/or chemical agents, ambient air can be employed to circulate under the protective clothing. However, less sweat will be evaporated to provide cooling if ambient humidity is high and local skin irritation results if the ambient humidity is low and the air temperature too hot (25). Cooling of the air just before it enters the clothing is essential as air rapidly warms in long inlet tubes, decreasing maximal cooling. In contaminated environments, compressed fresh air can be provided.

Air-cooled garments are lighter to wear, keep clothing drier and, when face ventilation is also provided, are more comfortable than their water-cooled counterparts. Importantly, air-cooled devices rely on the body's own mechanism for heat loss, i.e. the evaporation of sweat, making excessive body cooling unlikely. Furthermore, they are adequate in removing moderate amounts of generated heat.

CONCLUSIONS

Over the last decade, the Military Ergonomics Division of our Institute has maintained an active research program evaluating the thermal burden imposed upon men by the wearing of NBC protective clothing ensembles during exercise in the heat. Through the use of a life-size sectional copper manikin, measurements have been made of the insulation characteristics (clo) and evaporative impedance (i_m/clo) of these low permeable or impermeable clothing ensembles. The length of time that men could tolerate heat stress under the aforementioned conditions has been demonstrated through studies performed in the climatic chambers and the field. Tolerance time has been determined to be more dependent upon impaired heat dissipation than upon the ambient thermal load. To alleviate thermal stress to the individual, therefore, the approach has been to develop a system of microclimate cooling where the microenvironment immediately surrounding the person is cooled versus his macroenvironment (i.e., his working area). 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 chemical protective clothing in hot-wet and/or hot-dry environments. Studies performed on LCU have revealed the relative importance of the proportion of total skin surface covered by the undergarment not only in providing cooling to the body, but also in shielding the body from heat gain from a hot environment. As the percentage of total body surface area covered by the LCU increases, cooling in watt increases. Furthermore, there is an increase in watt of cooling with increasing skin to water temperature gradient as well as an increase in watt of cooling with increasing water flow rate. Whereas the LCU studied do not completely isolate the skin surface from gaining heat from the environment, they do remove half or greater of this potential for heat gain. Upper versus lower body exercise was also examined in assessing the effectiveness of LCU to alleviate heat stress during physical work in a hot environment. The findings supported the above conclusion that the proportion of total skin surface covered by a LCU was an important consideration in providing cooling since the LCU was more effective in alleviating heat stress when the surface area for cooling was increased to include the thighs. Lastly, when men wore LCU inside closed hatch, unventilated armored vehicles under desert or tropic environmental conditions, they were able to complete their missions whereas without microclimate cooling they were unable to complete their missions.

Microclimate cooling systems which utilize ice as the cooling medium are not as effective as either liquid or air-cooled systems. Once the ice has completely melted, cooling is no longer provided and the torso receives a net heat gain from the hot environment resulting in skin temperatures in excess of 35° C. The cooling efficiency of one ice packet vest was increased by increasing the number of ice packets attached to the vest (up to the limit of total torso surface area coverage). With less than full coverage, cooling by ice packets was dependent upon the temperature of the hot environment. The logistical problems rendered by ice-cooled systems make them impractical for use as cooling devices in all but very short duration situations.

Since the most important factor affecting thermal strain appears to be the level of metabolic energy expenditure, 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 ACV; therefore, work/rest periods also need to be employed. At a metabolic rate of 315 W using five selections of air temperature, humidity and air flow rate combinations to an air-cooled vest, cooling was less effective in maintaining a near constant T_{re} (endurance time averaged 73 min) than at a metabolic rate of 175 W (endurance time achieved was 300 min). At low metabolic rates, ACV aid the evaporative cooling capabilities of men during extended (i.e., 7.5 to 12 hours) operations in desert and tropic environments.

ACV, in contrast to WCU in which there is an increase in watt of cooling with increasing water flow rates, provide an increase in cooling with decreasing air flow rates. Whereas upon initial consideration, these statements may appear to be contradictory, the idea makes sense that a lower air flow rate renders a vest more efficient through improved heat transfer by increasing the transit time of the air across the skin. Furthermore, since ACV are dependent upon the body's ability to evaporate sweat, excessive body cooling by an ACV is unlikely while this has been an inherent problem in LCU.

The Military Ergonomics Division of our Institute has developed the ability to predict through the use of modeling, the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in chemical protective clothing or other low permeable clothing ensembles in a variety of hot environments. The determination of work/rest ratios can be used in conjunction with microclimate cooling to enable the individual to perform at high metabolic rates while wearing protective clothing in the heat. 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 (19).

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TABLE 1

XM-1 HEAT STRESS AT YUMA PROVING GROUND

SEPTEMBER 1980

DAY	MOPP/HATCH	t_a o	t_a i	RH o	RH i	WBGT o	WBGT i	TOLERANCE min	t_{sk}	t_{re}	HEART RATE $b \cdot m^{-1}$	SWEAT RATE $\ell \cdot m^{-1}$	COMMENTS
1	I/OPEN	38.7° C	39.1° C	39%	31%	31.9° C	30.5° C	>172	35.4° C	37.6° C	92	0.64	TRAIN #1
2	III/OPEN	28.6	31.4	66	60	25.7	26.8	>163	34.9	37.3	76	0.30	TRAIN #2 (CW under)
3	IV/OPEN	37.6	36.6	29	33	30.0	28.1	>177	36.5	37.8	114	0.99	
4	IV/CLOSED	36.0	38.8	30	57	29.9	35.0	(80)	38.3	38.9	162	2.05	T.C. ERRORS <60'
5	IV/CLOSED (w/cooling)	36.1	35.7	25	66	27.4	32.5	>208	32.6	38.1	113	0.63	DOUBLE DRILLS
6	IV/CLOSED	34.4	35.3	29	91	28.9	33.4	(124)	38.1	38.5	147	1.69	T.C. ERRORS ~60'

o outlet
i inlet

TABLE 2

COOLING RATES (WATT) PROVIDED BY THE IPL #1 AIR-COOLED VEST

Completely Wet (Maximal Sweating) Skin Surface at 35° C

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY (DB/DP)	FLOW RATE (FT^3/MIN) AIR-COOLED VEST	COOLING RATES (WATT) TORSO-ARMS-LEGS	CHAMBER ENVIRONMENTAL CONDITIONS
10° C at 20% RH* (10.0/-11.8)	6	95 (15.8)**	29° C at 85% RH (29.0/26.3)
10° C at 20% RH (10.0/-11.8)	8	137 (17.1)	29° C at 85% RH (29.0/26.3)
10° C at 20% RH (10.0/-11.8)	10	158 (15.8)	29° C at 85% RH (29.0/26.3)
10° C at 20% RH (10.0/-11.8)	6	122 (20.3)	52° C at 25% RH (52.0/26.2)
10° C at 20% RH (10.0/-11.8)	8	169 (21.1)	52° C at 25% RH (52.0/26.2)
10° C at 20% RH (10.0/-11.8)	10	203 (20.3)	52° C at 25% RH (52.0/26.2)
21° C at 10% RH (21.0/-11.7)	6	82 (13.7)	29° C at 85% RH (29.0/26.3)
21° C at 10% RH (21.0/-11.7)	8	120 (15.0)	29° C at 85% RH (29.0/26.3)
21° C at 10% RH (21.0/-11.7)	10	137 (13.7)	29° C at 85% RH (29.0/26.3)
21° C at 10% RH (21.0/-11.7)	6	103 (17.2)	52° C at 25% RH (52.0/26.2)
21° C at 10% RH (21.0/-11.7)	8	130 (16.2)	52° C at 25% RH (52.0/26.2)
21° C at 10% RH (21.0/-11.7)	10	167 (16.7)	52° C at 25% RH (52.0/26.2)

*Relative Humidity
**Watts/Ft^3/Min

TABLE 3

COOLING RATES (WATT) PROVIDED BY THE IPL AIR-COOLED VEST WORN WITH A COOLING AIR VENTILATED XM-29 FACE PIECE

Completely Wet (Maximal Sweating) Skin Surface at 35° C

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY (DB/DP)*****	FLOW RATE (FT³/MIN) Air-cooled VEST	FLOW RATE (FT³/MIN) XM-29 FACE PIECE	COOLING RATES (WATT) TORSO-ARMS-LEGS	COOLING RATES (WATT) HEAD	COOLING RATES (WATT) TOTAL***	CHAMBER ENVIRONMENTAL CONDITIONS
24° C at 41% RH* (24.0/9.4)	3	3	44 (14.7)****	23 (7.7)****	67 (22.4)****	32° C at 26% RH*(32.0/9.8)
32° C at 26% RH (32.0/9.8)	6	NF**	51 (8.5)	0 (0.0)	51 (8.5)	32° C at 26% RH (32.0/9.8)
32° C at 26% RH (32.0/9.8)	15	4.5	142 (9.5)	30 (6.7)	172 (16.2)	49° C at 11% RH (49.0/10.5)
43° C at 14% RH (43.0/9.7)	10	3	76 (7.6)	15 (5.0)	91 (12.6)	49° C at 11% RH (49.0/10.5)

*RH
**No Flow
***Sum of cooling provided over Head-Torso-Arms-Legs
****Watt/Ft³/min
*****DB/DP

TABLE 4

COOLING RATES (WATT) PROVIDED BY THE IPL ACV #2

Completely Wet (Maximal Sweating) Skin Surface at 35° C

		FLOW RATE (FT^3/MIN)	COOLING RATES	
Chamber Environment:	29° C at 85% RH* (29.0/26.32)DB/DP**	1.5	58	(38.7)***
Inlet Cooling Air:	21° C at 16% RH (21.0/5.7)	2.0	71	(35.5)
		2.5	81	(32.4)
		4.0	119	(29.8)
		6.0	138	(23.0)
		10.0	212	(21.2)
Chamber Environment:	29° C at 85% RH (29.0/26.32)	1.5	49	(32.7)
Inlet Cooling Air:	21° C at 60% RH (21.0/12.79)	2.2	67	(30.5)
		3.0	72	(24.0)
		4.6	112	(24.3)
		6.0	146	(24.3)
		8.3	177	(21.3)
		10.0	203	(20.3)
Chamber Environment:	52° C at 25% RH (52.0/26.2)	2.2	75	(34.1)
Inlet Cooling Air:	21° C at 16% RH (21.0/-5.7)	2.6	79	(30.4)
		6.4	209	(32.7)
		8.0	227	(28.4)
		10.0	254	(25.5)

*Relative Humidity
**Dry Bulb/Dew Point
***Watts/Ft^3/min

TABLE 5

COOLING RATES (WATT) PROVIDED BY THE AIR-COOLED VEST #3 WORN WITH A COOLING AIR VENTILATED XM-29 FACE PIECE

Completely Wet (Maximal Sweating) Skin Surface at 35° C

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY (DB/DP)*****	FLOW RATE (FT³/MIN) Air-cooled Vest	FLOW RATE (FT³/MIN) XM-29 Face Piece	COOLING RATES TORSO-ARMS-LEGS	COOLING RATES HEAD	COOLING RATES TOTAL***	CHAMBER ENVIRONMENTAL CONDITIONS
24° C at 41% RH* (24.0/9.4)	3	3	42 (14.0)****	26 (8.7)****	68 (22.7)****	32° C at 26% RH*(32.0/9.8)
32° C at 26% RH (32.0/9.8)	6	3	53 (8.8)	39** (13.0)	92 (21.8)	32° C at 26% RH (32.0/9.8)
32° C at 26% RH (32.0/9.8)	15	4.5	159 (10.6)	36 (8.0)	195 (18.6)	49° C at 11% RH (49.0/10.5)
43° C at 14% RH (43.0/9.7)	10	3	113 (11.3)	21 (7.0)	134 (18.3)	49° C at 11% RH (49.0/10.5)

*Relative Humidity
**Hood not worn over head
***Sum of cooling provided over Head-Torso-Arms-Legs
****Watts/Ft³/min
*****Dry Bulb, Dew Point

TABLE 6

VEST CONDITIONS

CONDITION	TEST DAY	VEST DRY BULB (° C)	VEST DEW POINT (° C)	MAXIMAL EVAPORATIVE (W)	MAXIMAL DRY CONVECTIVE (W)	TOTAL COOLING (W)
A	9-10	20.2	7.2	565	122	687
B	5-6	21.0	12.4	515	116	631
C	1-2	27.0	7.7	555	65	620
D	11-12	27.0	12.9	499	65	564
E	3-4	26.4	18.5	428	70	498
CONTROL	7-8	(VENTILATED FACEPIECE ONLY)				

TABLE 7

COOLING VEST TEST COMBINATIONS

COMBINATION	TEST DAY	VEST DB/DP (rh) TARGET (° C)	VEST DB/DP (rh) OBTAINED (° C)	AIR FLOW RATE (CFM)	METABOLIC RATE (W)	POTENTIAL COOLING* (W)
F	3	26.7/15.5 (52%)	26.1/15.6 (51%)	10	315	196
G	1	29.4/21.1 (60%)	27.5/21.1 (68%)	14.5	315	360
H	2	26.7/15.5 (52%)	22.5/15.5 (64%)	10	175	218
I	4	29.4/21.1 (60%)	24.4/21.1 (80%)	14.5	175	391

*POTENTIAL COOLING CALCULATED FROM OBTAINED DB/DP TEMPERATURES.

TABLE 8

COMPARISON OF COOLING POTENTIAL, MEAN ENDURANCE TIMES AND MEAN RECTAL TEMPERATURES

COMBINATION*	POTENTIAL COOLING	175 W		315 W	
		ENDURANCE	T_{re}**	ENDURANCE	T_{re}***
	(W)	(MIN)	(° C)	(MIN)	(° C)
CONTROL	---	118	39.0	73	39.4
A	687	300	37.4	293	37.9
B	631	300	37.2	300	38.2
C	620	300	37.6	275	38.6
D	564	300	37.5	281	38.3
E	498	300	37.6	242	38.5
F	196	---	----	220	38.9
G	360	---	----	159	39.3
H	218	300	38.1	---	----
I	391	272	37.5	---	----

* DATA FOR CONTROL AND COMBINATIONS A-E FROM PIMENTAL ET AL. (22)
** END OF WALK 5
*** END OF WALK 4

TABLE 9

FINAL PHYSIOLOGICAL RESPONSES OF THE CREWS
DURING VEST AND AIR SHOWER MICROCLIMATE TESTS

		Vest	Air Shower	Diff
Rectal Temperature	(°C)	37.2(0.2)	37.6(0.5)	0.4*
Mean Skin Temperature	(°C)	30.9(5.1)	35.7(1.0)	4.8**
Mean Body Temperature	(°C)	35.1(0.7)	37.0(0.5)	1.9**
Heart Rate	($b \bullet min^{-1}$)	91(16)	112(28)	21*
Sweat Loss	(liters)	0.64(.17)	1.29(.61)	.65**

Values are means (standard deviation); * is $p<0.05$; ** is $p<0.01$.

FIGURE LEGENDS

Figure 1 - Watt of cooling provided by each of the five water-cooled undergarments plotted against the cooling water inlet temperature for a completely wet (i.e., maximal sweating) skin condition.

Figure 2 - Heat removed (watt) from the sections of the manikin covered by one of the water-cooled undergarments as: (A) a function of the difference between the manikin surface temperature and the cooling water inlet temperature (T_s-w); (B) and (C) as a function of the cooling water flow rate in L/min.

Figure 3 - Electrical power (watt) supplied to the head of the manikin versus head cooling time in minutes.

Figure 4 - Cooling rates (watt) versus cooling time (minutes) provided over the completely wet (maximal sweating) skin surface area of the torso by the portable liquid-cooled undergarment (LCU) #1.

Figure 5 - Cooling rates (watt) versus cooling time (minutes) provided over the completely wet (maximal sweating) skin surface areas A. of the torso and B. the head by the portable liquid-cooled undergarment (LCU) #2.

Figure 6 - Effect of cooling different skin surface areas on changes in rectal temperatures (ΔT_{re}) during rest and upper-body exercise ($\dot{V}O_2$-1.2 $\ell \cdot min^{-1}$ [L/min]) under heat stress conditions.

Figure 7 - Effect of cooling different skin surface areas on changes in rectal temperature (ΔT_{re}) during lower-body exercise ($\dot{V}O_2$-1.2 $\ell \cdot min^{-1}$ [L/min]) under heat stress conditions.

Figure 8 - Total exposure time during rest and exercise for two portable commercial cooling systems (desert and tropic).

Figure 9 - Heart rate and rectal temperature during rest and exercise in desert and tropic experiments involving two portable commercial cooling systems.

Figure 10- Relative humidity readings inside the XM-1 averaged over each half hour of exposure from Days 3-6.

Figure 11- Average rectal temperature (T_{re}) and mean-weighted skin temperature (T_{sk}) of the crew on Days 3 and 4.

Figure 12- Average rectal temperature (T_{re}) and mean-weighted skin temperature (T_{sk}) of the crew on Days 5 and 6.

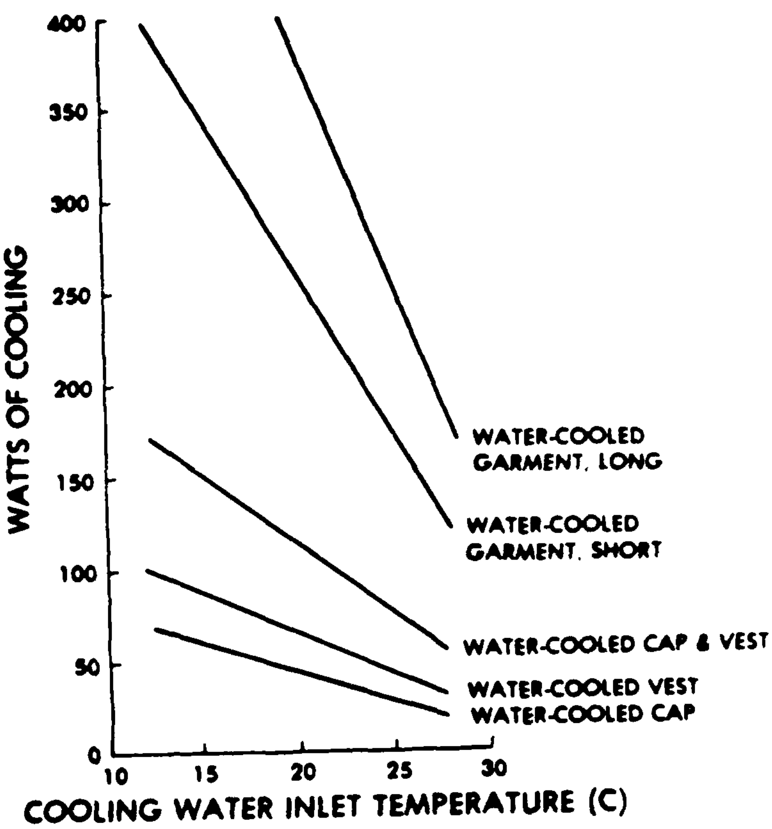
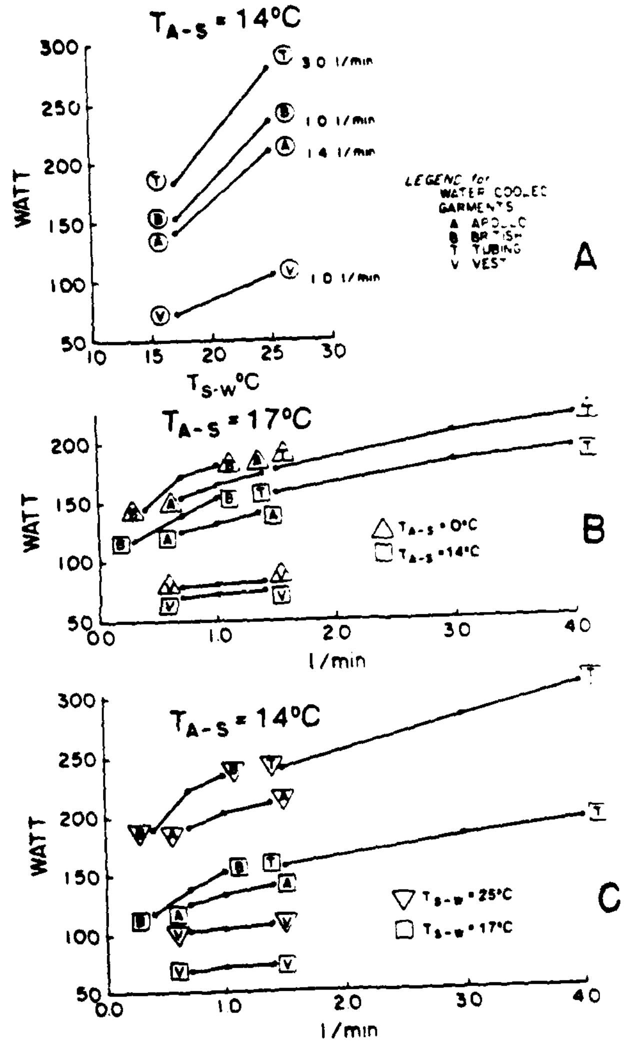
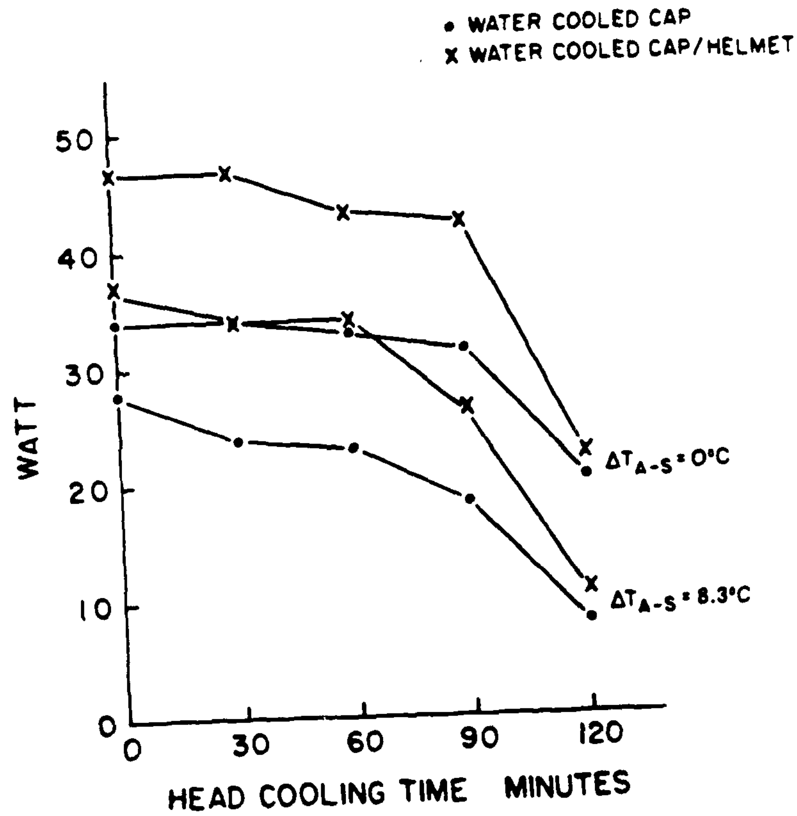

WATTS OF COOLING
400
350
300
250
200
150
100
50
0
10
15
20
25
30
COOLING WATER INLET TEMPERATURE (C)
WATER-COOLED GARMENT, LONG
WATER-COOLED GARMENT, SHORT
WATER-COOLED CAP & VEST
WATER-COOLED VEST
WATER-COOLED CAP

Fig. 1



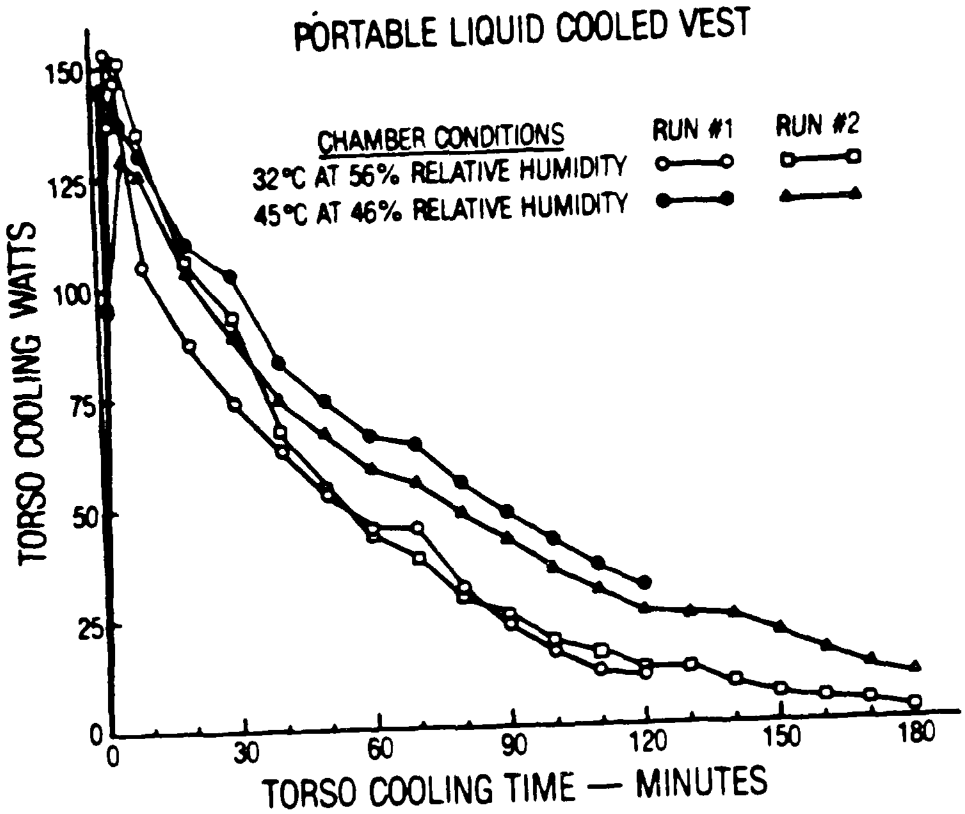
T_{A-S} = 14°C
WATT
T_{S-W}°C
3.0 l/min
1.0 l/min
1.4 l/min
1.0 l/min
LEGEND for WATER COOLED GARMENTS
A APOLLO
B BRITISH
T TUBING
V VEST
A
T_{A-S} = 17°C
WATT
l/min
T_{A-S} = 0°C
T_{A-S} = 14°C
B
T_{A-S} = 14°C
WATT
l/min
T_{S-W} = 25°C
T_{S-W} = 17°C
C

Fig.2



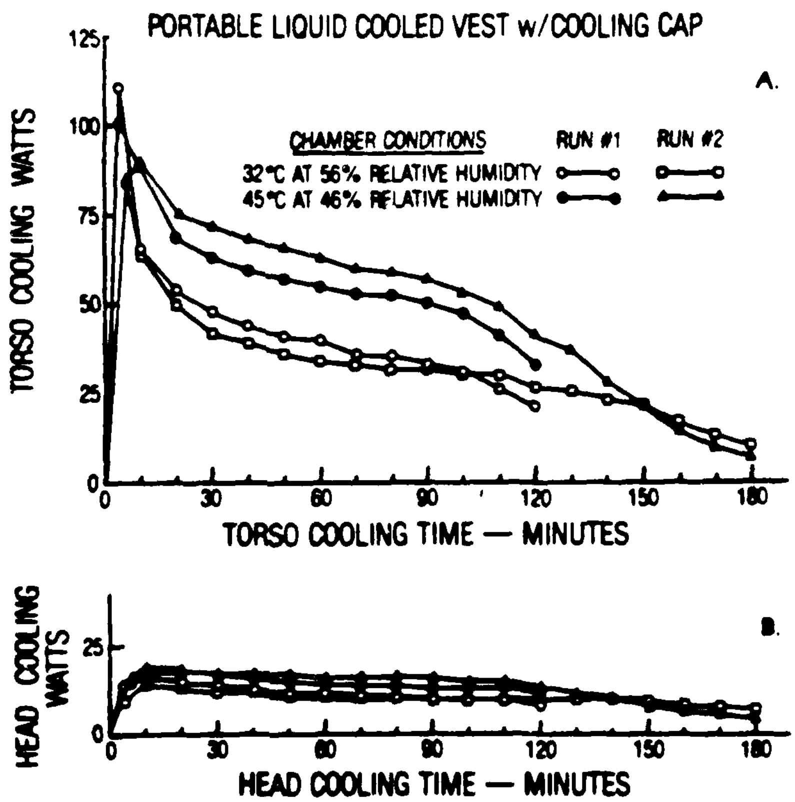
• WATER COOLED CAP
X WATER COOLED CAP/HELMET
WATT
50
40
30
20
10
0
0
30
60
90
120
HEAD COOLING TIME MINUTES
ΔT A-S = 0°C
ΔT A-S = 8.3°C

Fig. 3



PORTABLE LIQUID COOLED VEST
CHAMBER CONDITIONS
RUN #1
RUN #2
32°C AT 56% RELATIVE HUMIDITY
45°C AT 46% RELATIVE HUMIDITY
TORSO COOLING WATTS
150
125
100
75
50
25
0
0
30
60
90
120
150
180
TORSO COOLING TIME — MINUTES

Fig.4



PORTABLE LIQUID COOLED VEST w/COOLING CAP
A.
CHAMBER CONDITIONS
RUN #1
RUN #2
32°C AT 56% RELATIVE HUMIDITY
45°C AT 46% RELATIVE HUMIDITY
TORSO COOLING WATTS
125
100
75
50
25
0
0
30
60
90
120
150
180
TORSO COOLING TIME — MINUTES
B.
HEAD COOLING WATTS
25
0
0
30
60
90
120
150
180
HEAD COOLING TIME — MINUTES

Fig.5

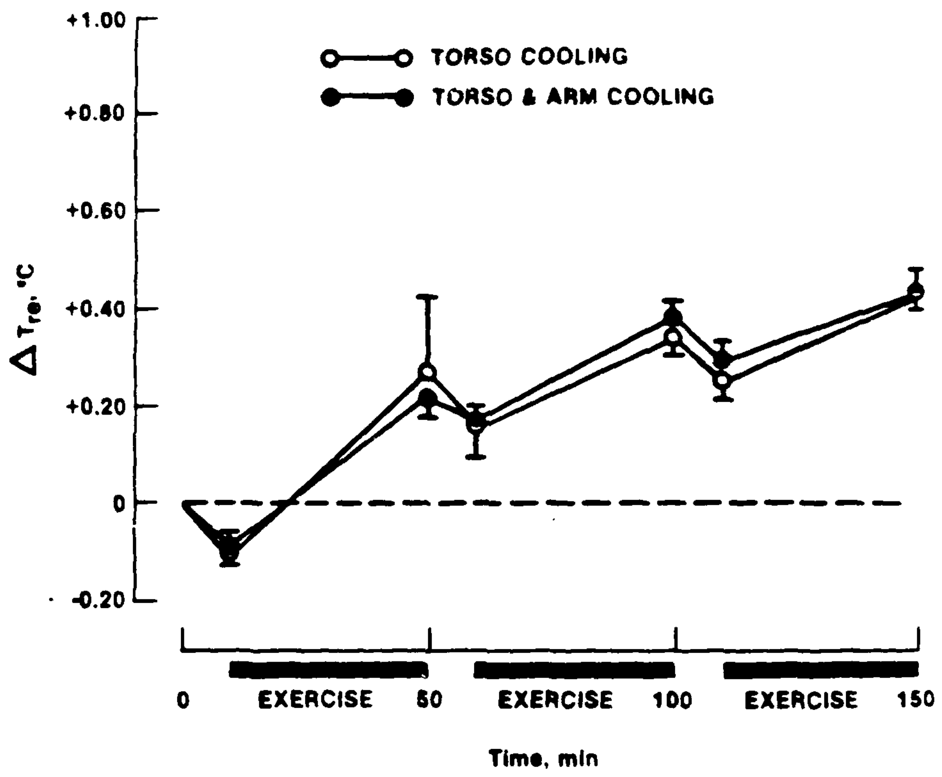

+1.00
+0.80
+0.60
+0.40
+0.20
0
-0.20
Δ Tre, °C
TORSO COOLING
TORSO & ARM COOLING
0
EXERCISE
50
EXERCISE
100
EXERCISE
150
Time, min

Fig. 6

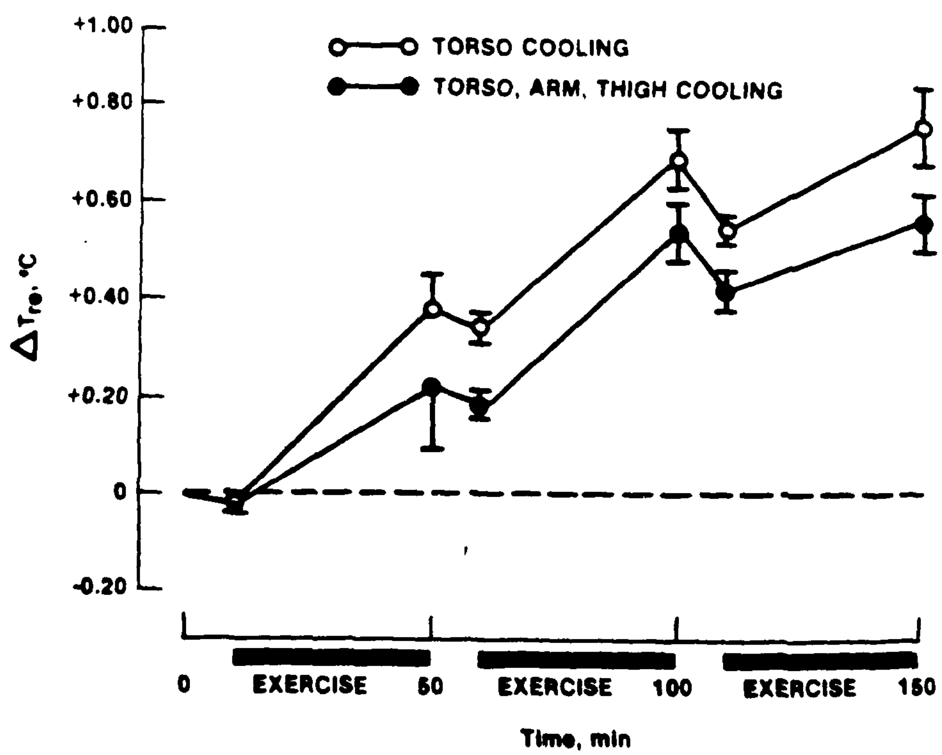
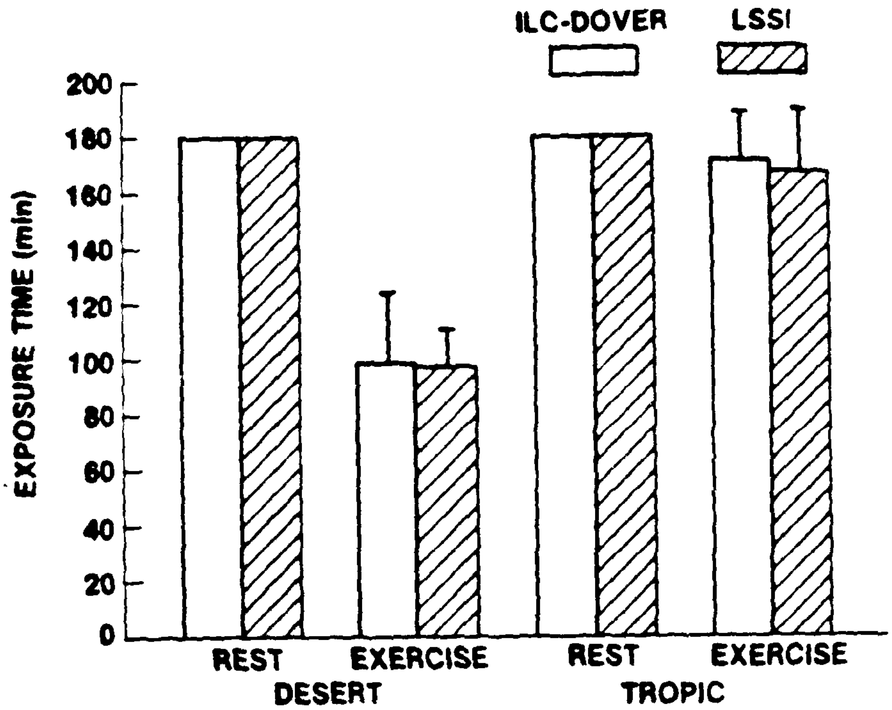
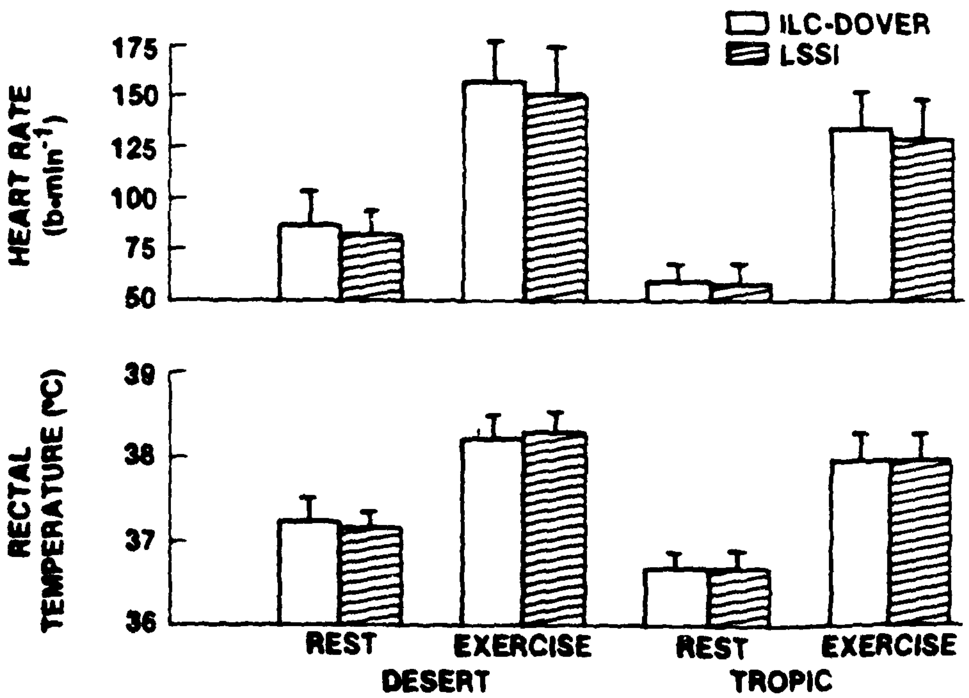

+1.00
+0.80
+0.60
+0.40
+0.20
0
-0.20
Δ Tre, °C
TORSO COOLING
TORSO, ARM, THIGH COOLING
0
EXERCISE
50
EXERCISE
100
EXERCISE
150
Time, min

Fig. 7



ILC-DOVER
LSSI
EXPOSURE TIME (min)
200
180
160
140
120
100
80
60
40
20
0
REST
EXERCISE
REST
EXERCISE
DESERT
TROPIC

Fig. 8



ILC-DOVER
LSSI
HEART RATE (b·min⁻¹)
175
150
125
100
75
50
RECTAL TEMPERATURE (°C)
39
38
37
36
REST
EXERCISE
REST
EXERCISE
DESERT
TROPIC

Fig. 9

XMI TANK

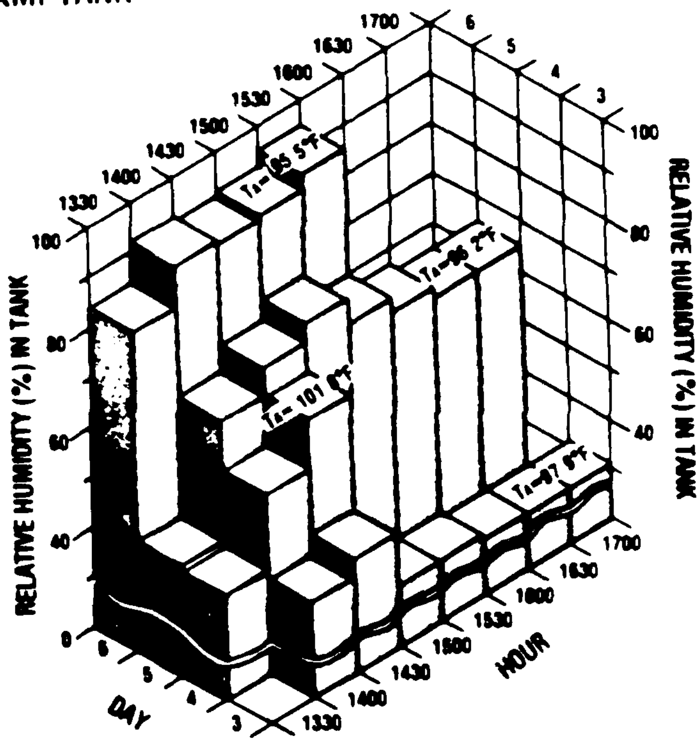


Fig. 10

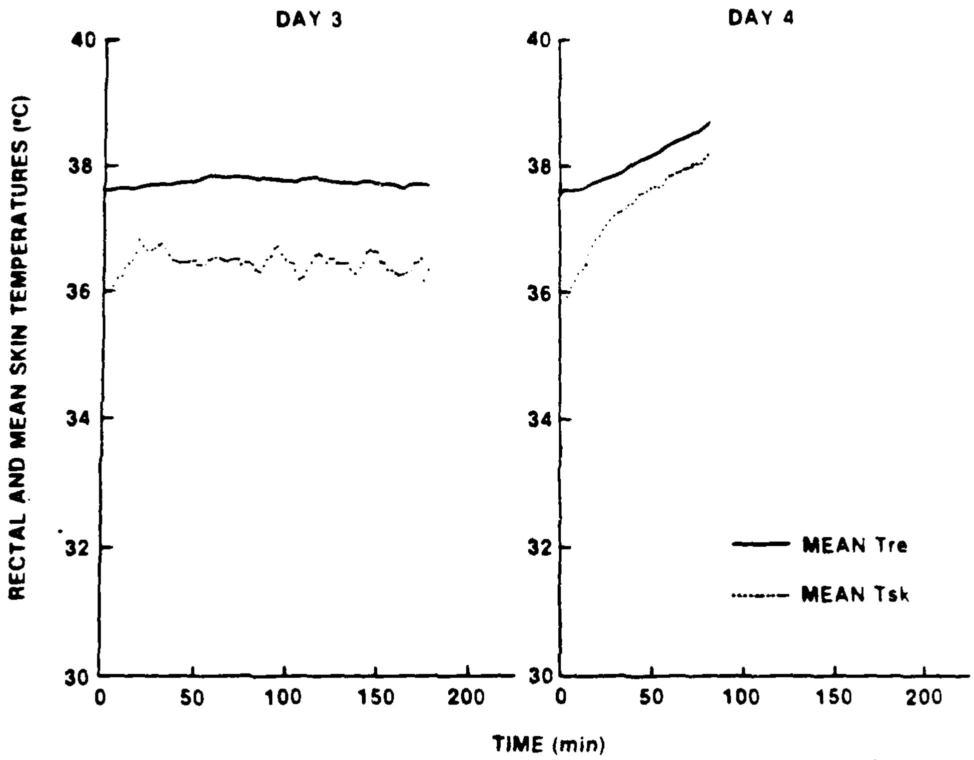

DAY 3
DAY 4
RECTAL AND MEAN SKIN TEMPERATURES (°C)
40
38
36
34
32
30
0
50
100
150
200
TIME (min)
MEAN Tre
MEAN Tsk

Fig. 11

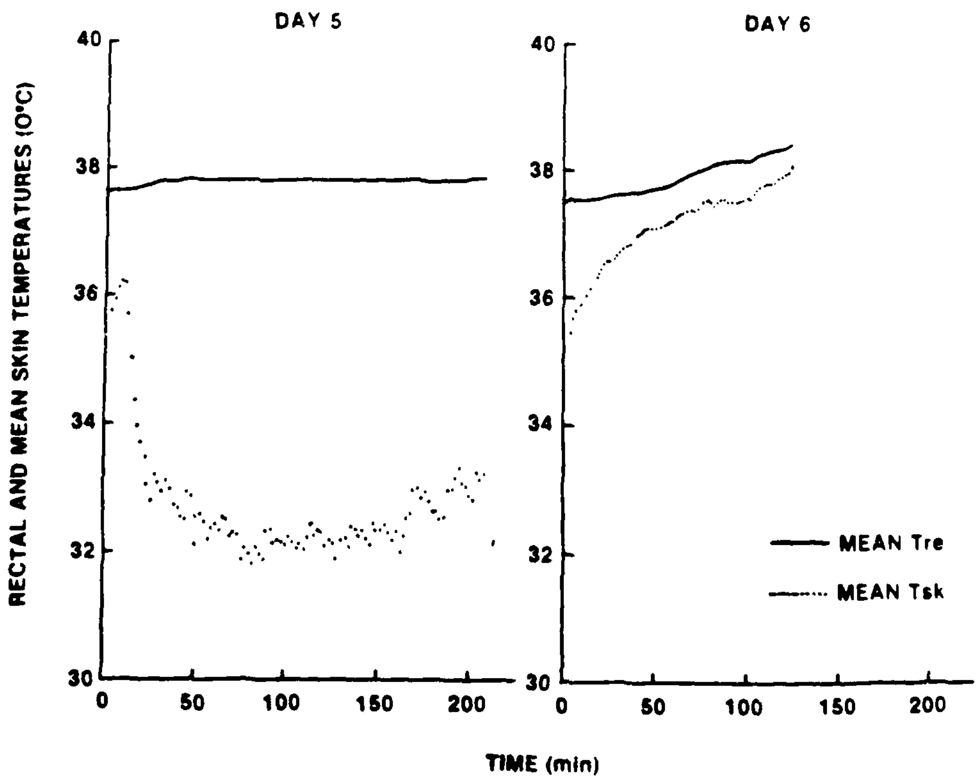

DAY 5
DAY 6
RECTAL AND MEAN SKIN TEMPERATURES (O°C)
40
38
36
34
32
30
0
50
100
150
200
TIME (min)
MEAN Tre
MEAN Tsk

Fig. 12

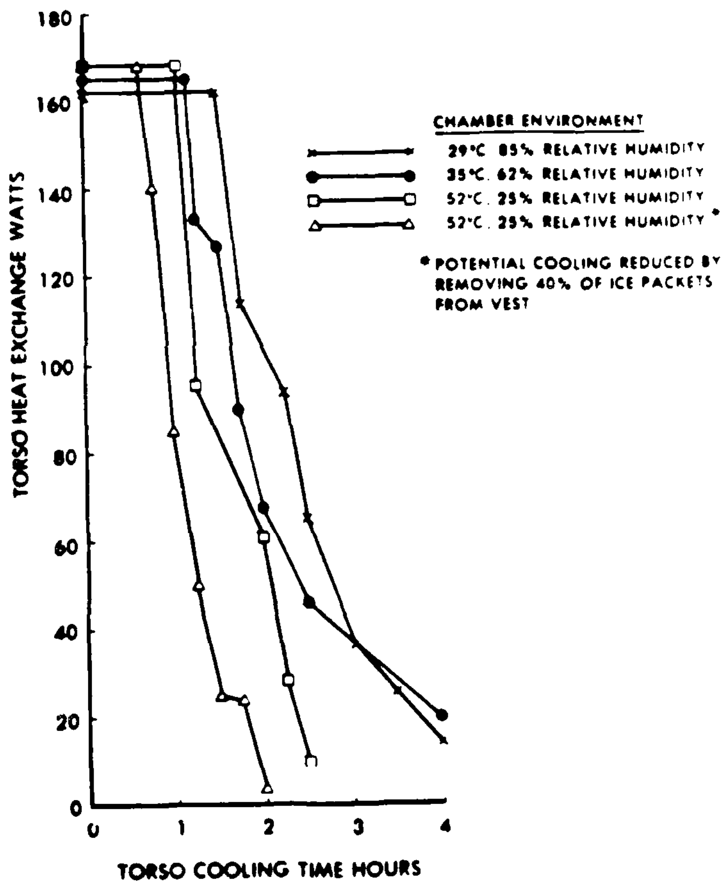

180
160
140
120
100
80
60
40
20
0
TORSO HEAT EXCHANGE WATTS
0
1
2
3
4
TORSO COOLING TIME HOURS
CHAMBER ENVIRONMENT
29°C 85% RELATIVE HUMIDITY
35°C. 62% RELATIVE HUMIDITY
52°C. 25% RELATIVE HUMIDITY
52°C. 25% RELATIVE HUMIDITY *
* POTENTIAL COOLING REDUCED BY REMOVING 40% OF ICE PACKETS FROM VEST

Fig.13

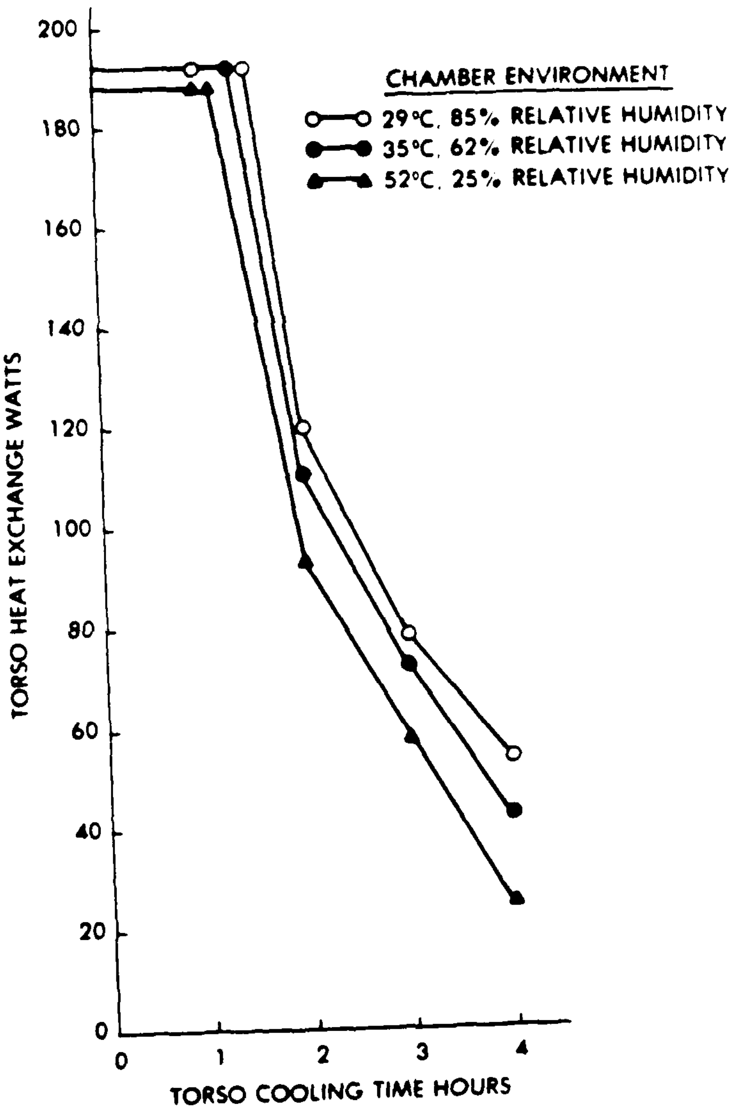

CHAMBER ENVIRONMENT
29°C, 85% RELATIVE HUMIDITY
35°C, 62% RELATIVE HUMIDITY
52°C, 25% RELATIVE HUMIDITY
TORSO HEAT EXCHANGE WATTS
200
180
160
140
120
100
80
60
40
20
0
0
1
2
3
4
TORSO COOLING TIME HOURS

Fig. 14

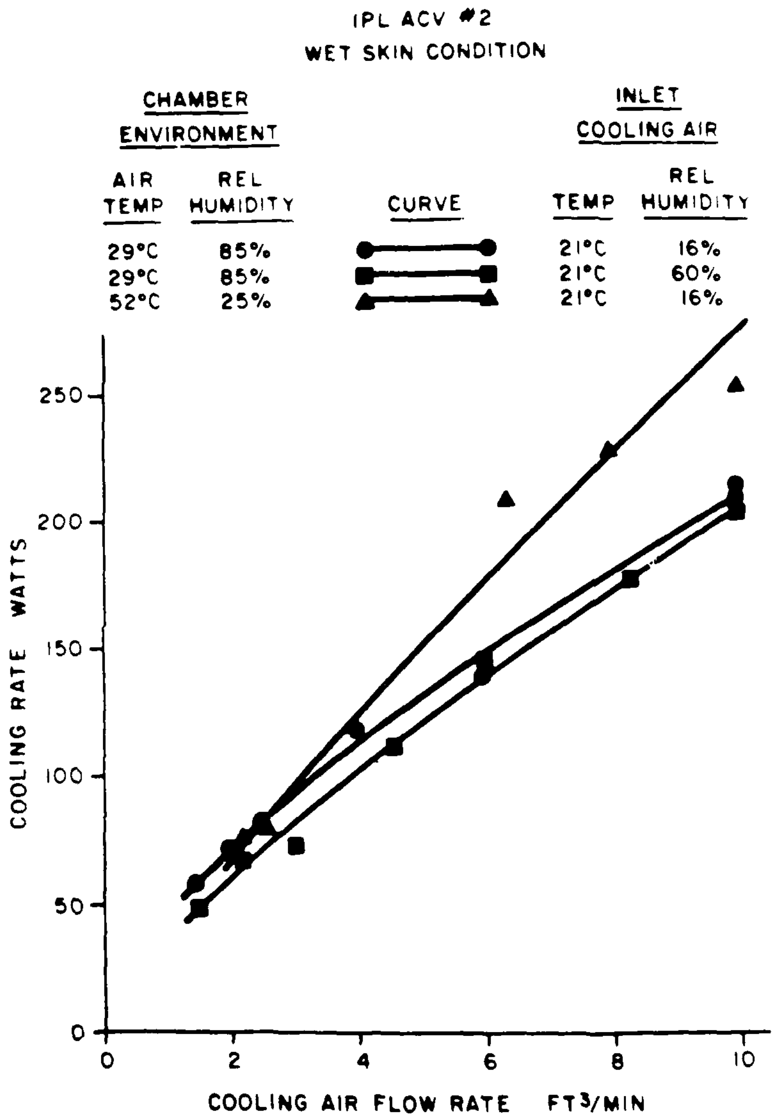

IPL ACV #2
WET SKIN CONDITION
CHAMBER ENVIRONMENT
AIR TEMP
REL HUMIDITY
CURVE
INLET COOLING AIR
TEMP
REL HUMIDITY
29°C 85% 21°C 16%
29°C 85% 21°C 60%
52°C 25% 21°C 16%
COOLING RATE WATTS
0
50
100
150
200
250
0
2
4
6
8
10
COOLING AIR FLOW RATE FT³/MIN

Fig. 15

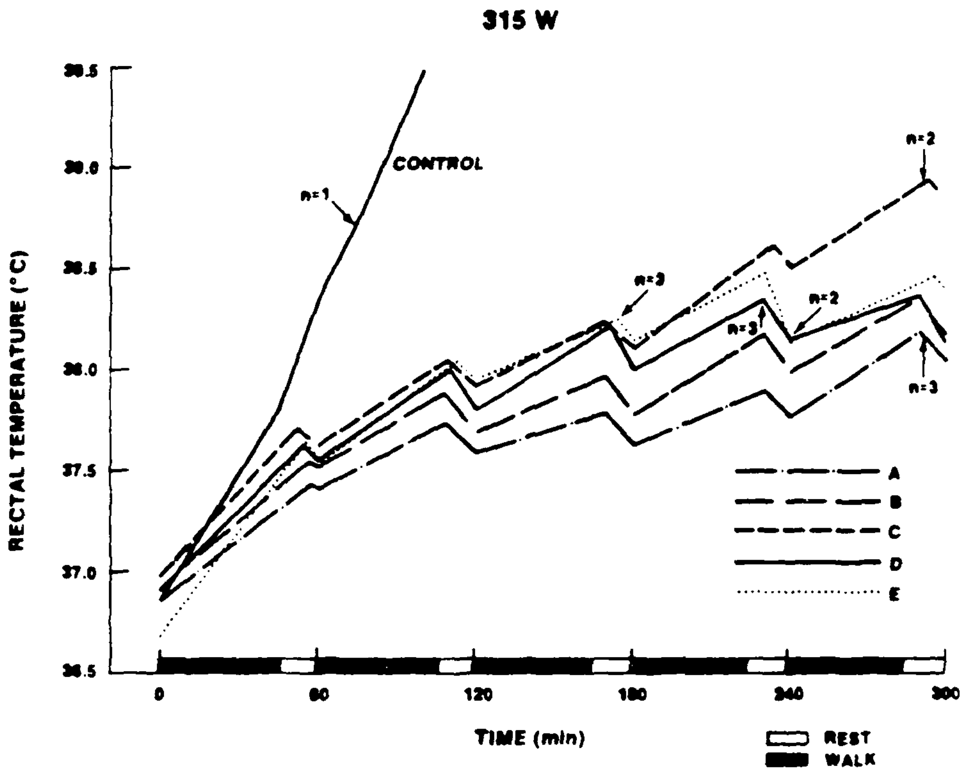

315 W
RECTAL TEMPERATURE (°C)
CONTROL
n=1
n=2
n=3
n=3
n=2
n=3
A
B
C
D
E
TIME (min)
REST
WALK

Fig. 16

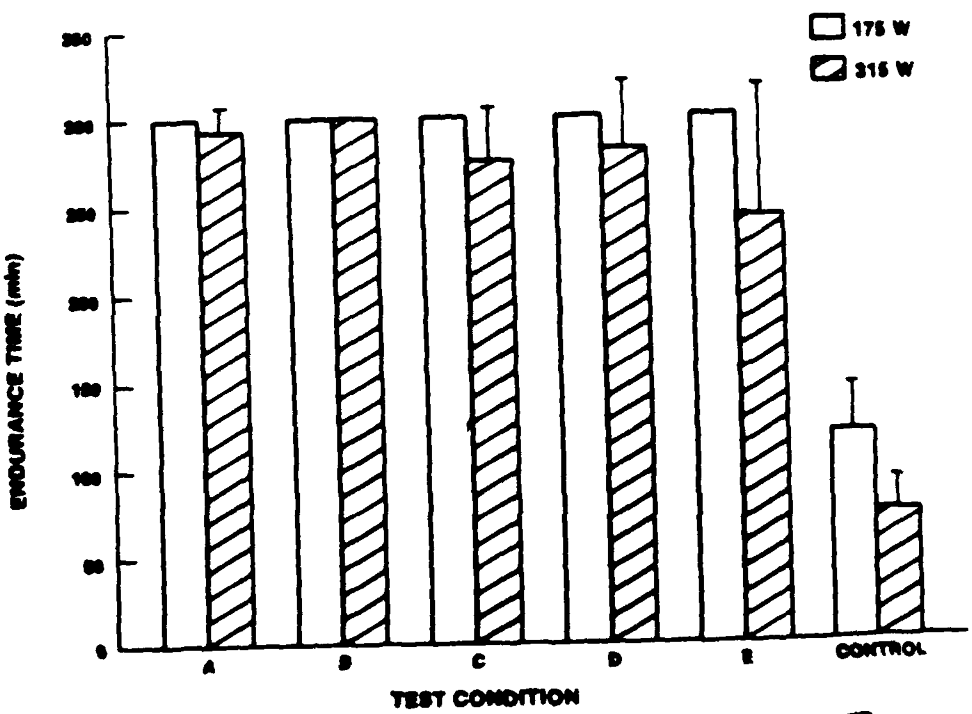
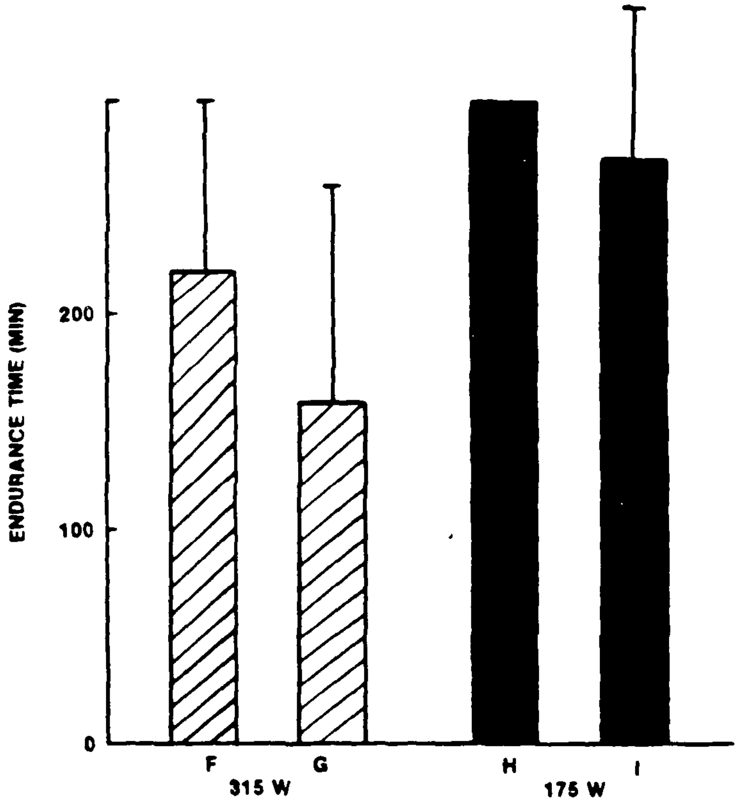
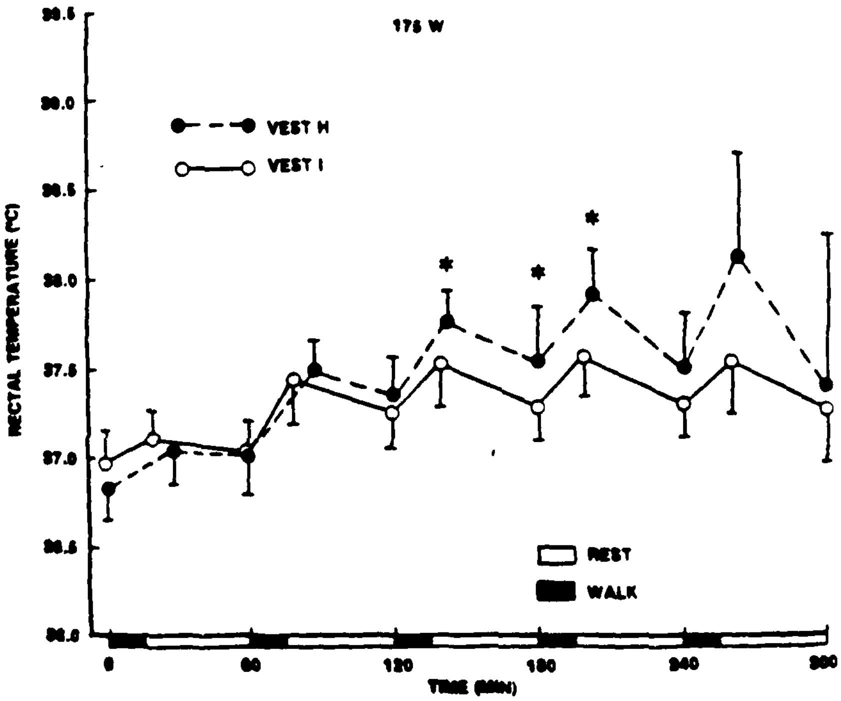

175 W
315 W
ENDURANCE TIME (min)
A
B
C
D
E
CONTROL
TEST CONDITION

Fig. 17



ENDURANCE TIME (MIN)
0
100
200
F
G
H
I
315 W
175 W

Fig. 18



175 W
VEST H
VEST I
RECTAL TEMPERATURE (°C)
37.5
37.0
REST
WALK
0
60
120
240
TIME (MIN)

Fig. 19

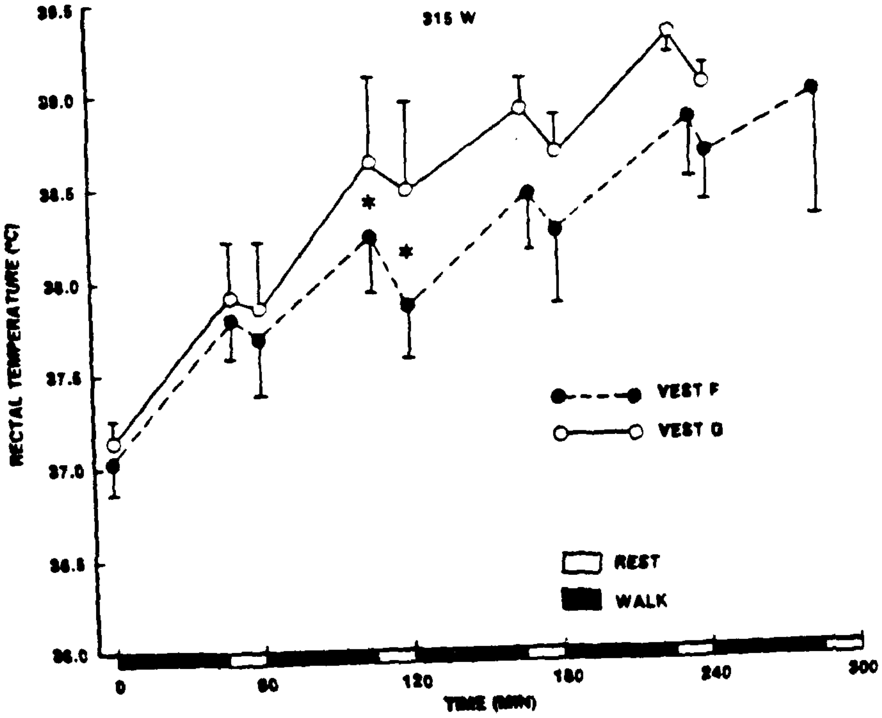

315 W
RECTAL TEMPERATURE (°C)
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
VEST F
REST
WALK
0
60
120
180
240
300
TIME (MIN)

Fig.20

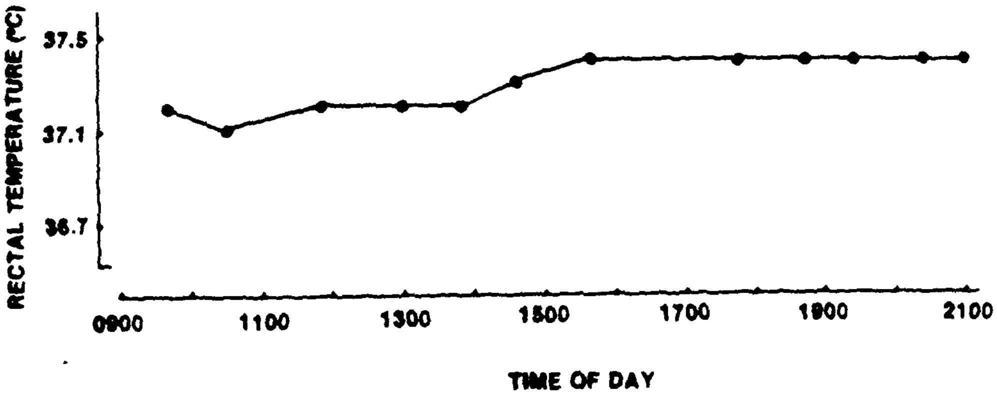

37.5
37.1
36.7
RECTAL TEMPERATURE (°C)
0900
1100
1300
1500
1700
1900
2100
TIME OF DAY

Fig. 21

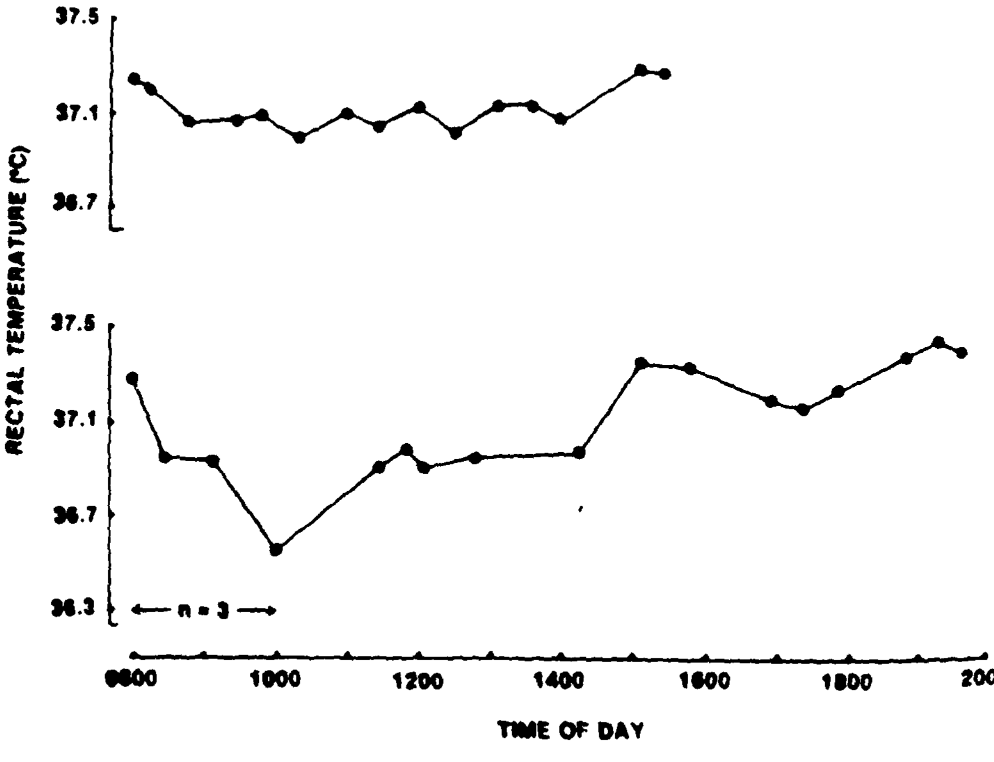

37.5
37.1
36.7
37.5
37.1
36.7
36.3
RECTAL TEMPERATURE (°C)
RECTAL TEMPERATURE (°C)
n = 3
0800
1000
1200
1400
1600
1800
2000
TIME OF DAY

Fig. 2

END
DATE
FILMED
3-88
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