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SYSTEMS IN THE CHEMICAL, BIOLOGICAL,  
RADIOLOGICAL ENVIRONMENT

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T. Derion

R. S. Pozos

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Report No. 93-23

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NAVAL HEALTH RESEARCH CENTER  
P. O. BOX 85122  
SAN DIEGO, CALIFORNIA 92186 - 5122



NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND  
BETHESDA, MARYLAND

# A REVIEW OF MICROCLIMATE COOLING SYSTEMS IN THE CHEMICAL, BIOLOGICAL, RADIOLOGICAL ENVIRONMENT

T. Derion, Ph.D.<sup>1</sup>  
R.S. Pozos, Ph.D.<sup>2</sup>

Naval Health Research Center  
P.O. Box 85122  
San Diego, CA 92186-5122

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Report number 93-23, supported by the Naval Medical Research and Development Command, Department of the Navy, under Research Work Unit 62233N-MM33P30.005-6207. The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. Approved for public release, distribution unlimited.

<sup>1</sup>U.S. Public Health Service, Monterey, CA

<sup>2</sup>Naval Health Research Center, San Diego, CA

## SUMMARY

### Problem

Military personnel may be required to perform tasks in high heat environments (e.g., aircraft cockpits, shipboard engine rooms, or on the battlefield) and under conditions that pose a biological, chemical, or nuclear threat. Chemical protective overgarments, characterized by low permeability and high insulating properties, are worn to prevent contact with toxic agents, but they prevent normal dissipation of body heat.

### Objective

The objective of this report is to summarize the information currently available regarding the effectiveness of various microclimate cooling systems in alleviating the thermal strain imposed upon military personnel encapsulated in chemical protective overgarments during exertion in the heat.

### Approach

In this report, we summarize studies involving the use of various microclimate cooling systems. Particular attention is paid to (active) air and liquid cooling systems and (passive) ice cooling systems, as the majority of the literature is composed of studies in which these systems were tested.

### Results

Conditioned air cooling can increase tolerance time up to four times longer than is possible without cooling, but high ambient temperature air cooling may be dangerous because of possible skin damage at high air velocity. Within an airflow range of 6 to 10 cfm, cooling increases in direct proportion to the increase in airflow. Liquid cooling is effective in reducing heat strain at moderate work loads and provides an added benefit when applied to the thighs during lower-body exercise. Unlike air cooling, an increase in cooling with a liquid (water) system is not directly proportional to the coolant flow rate. Overcooling and ensuing discomfort can occur with a liquid-cooling system due to cutaneous vasoconstriction. Ice cooling is ineffective in prolonging tolerance time during heavy exercise but may be suitable for short-term work.

### Conclusion

All currently available cooling systems have disadvantages. Liquid-cooling systems are heavy, require excessive maintenance, and the tubes contained therein can possibly become compressed resulting in interruption of coolant flow. Passive ice vest cooling is generally not

as effective as either air or liquid cooling, although the wearer can move about untethered. In ice-cooled systems, the cooling rate decreases as the ice melts and changes shape.

The one suitable cooling system for all scenarios may never be developed. The best design approach may be indicated by consideration of the unique cooling needs of personnel performing specific tasks in various environments.

## **INTRODUCTION**

Many military and industrial settings require performance of duties by personnel in hot and hazardous environments. Work in such environments requires use of protective overgarments, which are characterized by low permeability and high insulating properties and are worn to prevent inhalation and skin contact of toxic agents (Speckman et al., 1988a). However, protective overgarments prevent normal dissipation of body heat (evaporation of sweat). Adequate heat dissipation, while essential for individuals wearing such garments, is also imperative under conditions where solar radiation is high and air motion is low, such as in aircraft cockpits and enclosed crew compartments (Shapiro et al., 1982). Impairment of heat dissipation can result in heat strain ranging in severity from discomfort to performance decrements, illness (cramps, exhaustion, stroke), collapse, and even death. Microclimate cooling thus becomes essential for prevention of heat stress, and ideally, maintenance of thermal balance in hot (and noxious) environments.

The objective of this review is to summarize the information currently available regarding the effectiveness of various microclimate cooling systems in alleviating thermal strain and to recommend certain systems for particular scenarios. The literature reviewed herein: predominantly comprises studies involving air, liquid, and (passive) ice-vest cooling systems; however, other cooling methodologies are briefly summarized. The accompanying tables summarize not only the microclimate cooling literature with respect to encapsulation in protective overgarments but also include other studies.

## **AIR COOLING**

### **Human Studies**

The effectiveness of air cooling ensembles has been studied extensively (Cadarette et al., 1986; Muza et al., 1987; Pimental et al., 1985; Pimental et al., 1987b; Shapiro et al., 1982; Speckman et al., 1988a; Speckman et al., 1988b). These cooling ensembles consisted of an air-cooled vest designed to provide chest, neck, and back cooling via a hose and manifold system mounted on an open-weave fabric. The hoses were lightweight, crush-resistant, and when bent, maintained a constant inside diameter. In most of these studies, air was delivered to the cooling vest at flow rates of either 10 or 15 cfm, and at temperatures ranging from 16 to 27.5°C dry bulb (db) and 7 to 21.1°C dew point (dp). Several representative studies are summarized below.

Pimental et al. (1985) showed that soldiers were able to complete 3- and 12-hr repeated bouts of rest and treadmill walking at average metabolic rates of 340 W and 240 W, respectively, while wearing the cooling vest under a chemical protective garment. Ambient conditions were 49°C db, 20°C dp, 49°C black globe temperature, with a 70 W radiant heat load added during

the 3-hr test. Rectal temperature ( $T_{re}$ ) never exceeded 38.5°C (12-hr test) or 39.2°C (3-hr test), and heart rate (HR) during exercise averaged 140 bpm. Sweat rate averaged 275 g/m<sup>2</sup>/hr (12-hr test) and 566 g/m<sup>2</sup>/hr (3-hr test). Tolerance time without cooling was predicted to be 110 min for the 12-hr test and 80 min for the 3-hr test. Thus the cooling vest was effective in reducing physiological strain under these conditions. When 300-min exposures at time-weighted mean metabolic rates of 175 W and 315 W (alternating treadmill rest and walking) were attempted under six different vest air cooling combinations (db and dp combinations) (Pimental et al., 1987b), tolerance times were 2.5 to 4 times as long as without the vest (i.e., with a ventilated face piece only) (Figure 1). Specifically, endurance time was 300 min at 175 W and 242 to 300 min at 315 W with the vest, but only 118 ± 27 min (175 W) and 73 ± 19 min (315 W) without the vest. Thus, at a work rate of 315 W in the heat, endurance time is extended compared to the control (no vest cooling) condition but is limited to approximately 5 hr.

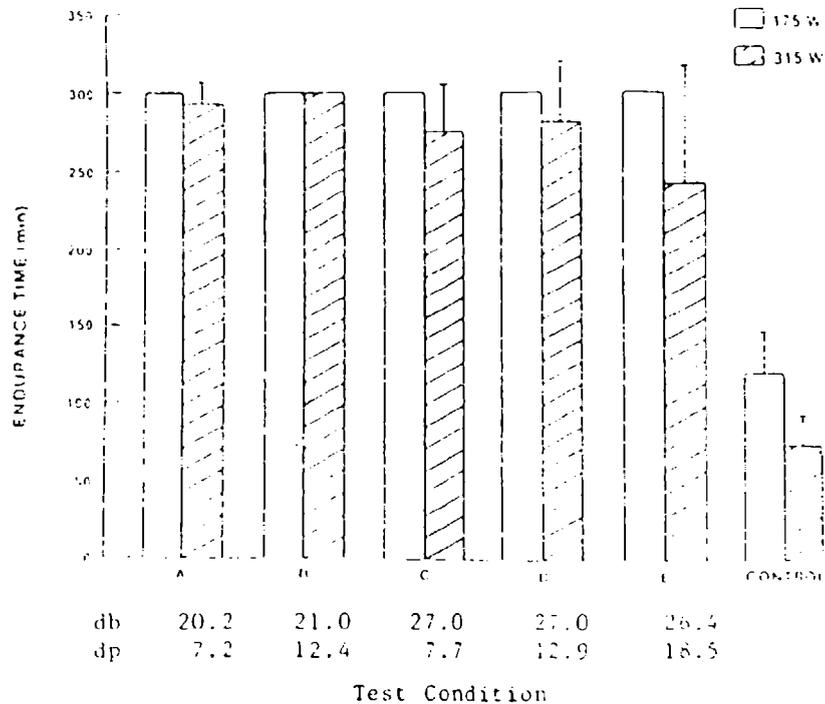


Figure 1. Endurance times at 175 W and 315 W. (From Pimental et al., 1987b. Used with permission.)

$T_{re}$  did not differ across the cooling combinations but was considerably lower overall with cooling than in the control (no cooling) condition (Figure 2). In addition, sweat rates (water requirements) were reduced 59% to 66% by use of the cooling vest. The advantage of this is obvious when drinking water is limited or when the design of the protective gear renders drinking extremely difficult or impossible (Pimental et al., 1987b).

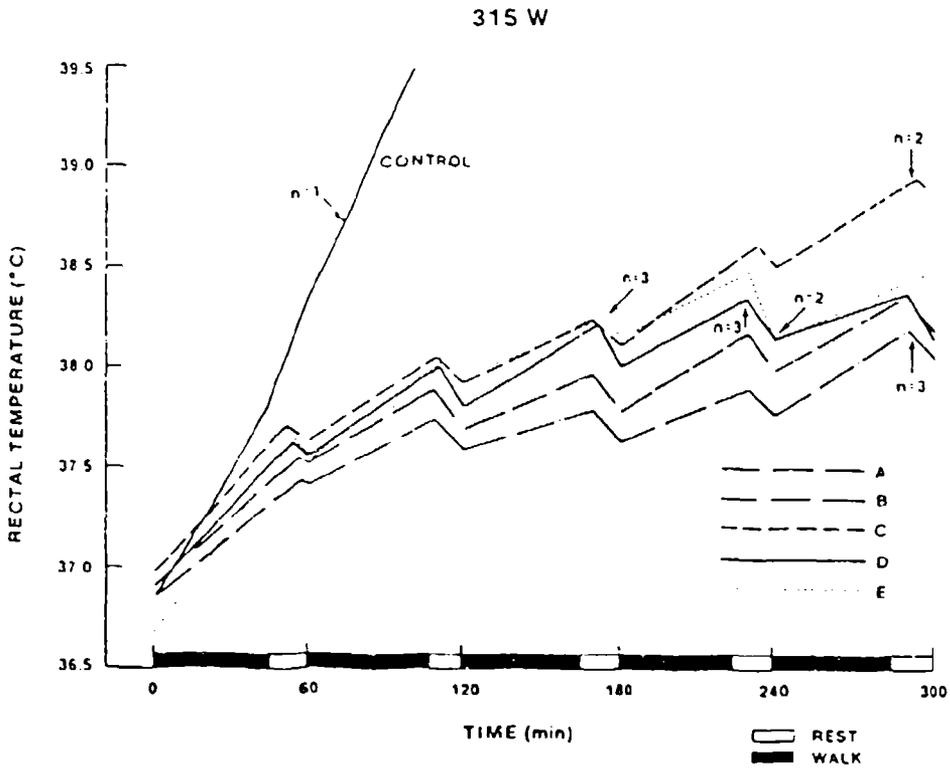
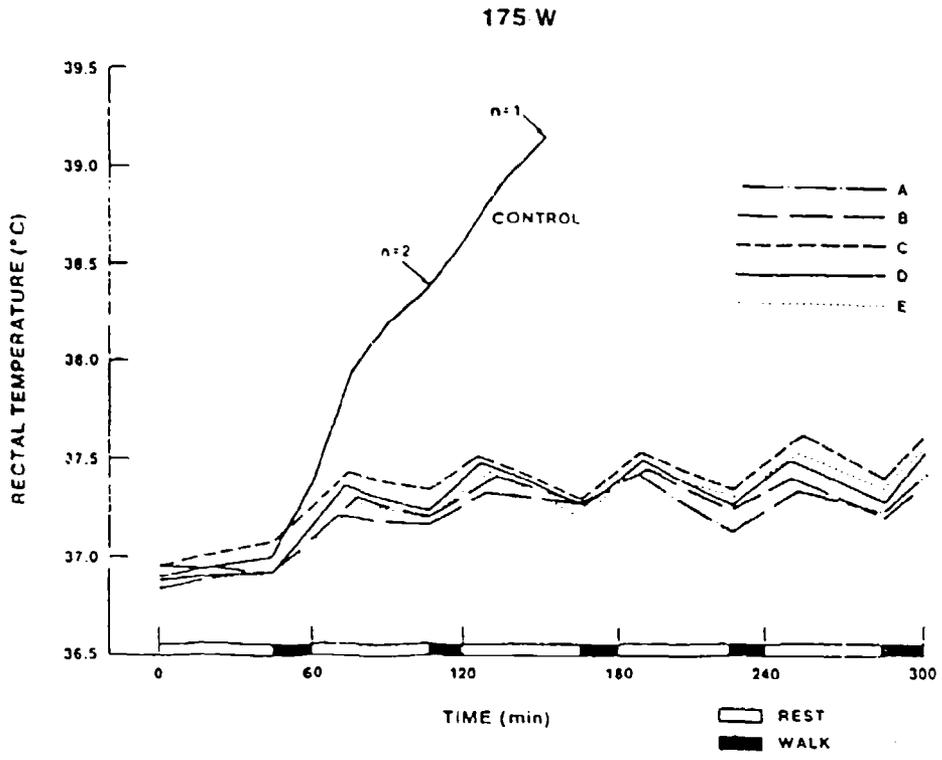


Figure 2. Rectal temperature vs. time for the five cooling combinations and the control test, 175 W, and 315 W. (From Pimental et al., 1987b. Used with permission.)

Shapiro et al. (1982) tested the efficacy of an air-cooled vest and an ambient air-ventilated vest each worn under a chemical protective garment in a hot, wet environment (35°C, 75% relative humidity [RH]). The air-cooled vest was deemed sufficient for cooling, as heat storage rate was only 7 W and final  $T_{re}$  was 37.3°C. With the ambient air-ventilated vest,  $T_{re}$ , skin temperature ( $T_{sk}$ ), sweat rate, and HR were all significantly higher. Although the engineering simplicity of an ambient air-ventilated vest is obvious, and although the vest is somewhat effective in mild heat, the authors concluded that this vest should not be used at very high temperatures because of possible skin damage by hot air at high velocity.

Muza et al. (1988) studied the effectiveness of providing conditioned air cooling during rest and ambient air cooling during exercise on reducing thermal strain. Their subjects wore the cooling vest under chemical protective clothing and alternated treadmill walking with rest for attempted 250-min exposures. In the hot/dry environment (40.6°C db, 1.0°C dp), ambient air cooling significantly extended exercise endurance time and reduced  $T_{re}$ , HR, and sweat rate over the control condition although no difference was found with an inlet airflow rate of 10 vs. 18 cfm. In the hot/wet environment (35.1°C db, 19.7°C dp), tolerance time was lengthened compared to times predicted by a computer model. No differences in physiological response were observed between the environmental conditions.

Table 1 summarizes studies in which air was used to cool subjects during exertion in the heat.

Table 1.

## AIR COOLING IN HUMANS DURING WORK IN THE HEAT

| Authors                 | n  | Exp. Design                     | Work Rate or Metabolic Rate (watts)          | Inlet Flow (cfm)                 | Inlet Temp. (°C) | Inlet RH (% or dp) | Ambient Cond. (°C, %RH)                            | Stay Time                             |
|-------------------------|----|---------------------------------|--|----------------------------------|------------------|--------------------|--|---------------------------------------|
| Vallerand et al. (1991) | 7  | 150 min                         | 240 W  | 10                               | 13°              | 8' dp              | 37°, 50%   | 150 min                               |
| Muza et al. (1988)      |    | walk/rest:<br>250 min           | 420 W (walk)<br>105 W (rest)                 | 10 or 18<br>or ambient           | 22.2°            | 15.0' dp           | 49°, 19%, 70W                                      | 250 min<br>209 min                    |
| Speckman et al. (1988a) |    | 3 hr, 12 hr                     | 340 W (3 hr)                                 | 15                               | 16°              | 20' dp             | 49°, 19%, 70W                                      | 3 hr, 12 hr                           |
| Speckman et al. (1988a) |    | walk/rest<br>300 min            | 175 W, 315 W                                 | 15                               | 20-27°           | 40-58%             | 49°, 20%   | 300 min<br>242-300                    |
| Speckman et al. (1988b) |    | air shower                      | ---  | 47                               | ---              | ---                | 33°, 60%   | not as good<br>as vest                |
| Janik et al. (1988)     |    | normal duty<br>10 day shipboard | ---  | 20 or<br>15 (amb.)               | 33°<br>36°       | ---                | 24° wbgf   | ---                                   |
| Muza et al. (1987)      | 6  | 4 x 300<br>min                  | 175 W, 315 W                                 | 10 or 14.5                       | 22.5-27.5°       | 15.5'-21.1'<br>dp  | 49°, 20' dp  | 272-300<br>159-220                    |
| Pimental et al. (1987b) | 4  | 300 min                         | 175 W, 315 W                                 | 15                               | 20-27°           | 7-18' dp           | 49°, 20' dp  | 300 min<br>242-300                    |
| Cadarette et al. (1986) | 10 | 12-hr field<br>test             | ---  | 0.0085 L/s                       | 29-42°           | ---                | 23-27°, 20-60%<br>26-38°, 22-64%<br>27-36°, 40-81% | 7.5 hr<br>12 hr<br>12 hr              |
| Mitchell et al. (1986)  | 6  | 6-day<br>field<br>test          | 125-150 W<br>simulated flights<br>(aviators) | 5-10                             | < ambient        | ---                | ---  | ---                                   |
| Pimental et al. (1985)  | 4  | 12 hr<br>3 hr                   | 240 W<br>340 W                               | 15                               | 16°              | 3' dp              | 49°, 20' dp  | 12 hr<br>3 hr                         |
| Iacono et al. (1984)    | 12 | walk/rest<br>50/10              | 430 W<br>avg. 180 W                          | 11.4                             | 24-30°           | ---                | 49°, 20%<br>35°, 75%                               | 62 min                                |
| Toner et al. (1983)     | 8  | air shower, vest<br>2.75 hr     | 150-360 W                                    | shower=47<br>vest=15             | ---              | ---                | 33°, 60%   | 84 min (n=2)                          |
| Shapiro et al. (1982)   | 12 | 120 min<br>(avg.)               | 180 W  | 312 L/m (cool)<br>484 L/m (amb.) | 21°, 19°         | ---                | 35°, 75%<br>49°, 20%                               | 120 min                               |
| Crockford et al. (1961) | 15 | ventilated<br>suit              | ---  | 10-25                            | 30-37.8°         | ---                | 81°  | thermal equil. in 1 hr<br>at > 15 cfm |

## **Manikin Studies**

Fonseca (1983b) studied the effectiveness of both an air-cooled vest and a ventilated face piece on an electrically heated sectional manikin. Cooling occurred primarily over the torso at low airflow rates: about 95% of the torso-arms-legs cooling occurred over the torso. The percentage decreased to 55% at higher flow rates. Fonseca concluded that cooling efficiency can be optimized by designing a vest that will maximize the proportion of air that circulates over the body surface and will minimize the amount that exits through the clothing.

Speckman et al. (1988b) used a sectional copper manikin to assess cooling rates provided by three different cooling vests, two of which covered the torso only and one commercial model that directed cool air up the back of the neck and down the legs. Vest airflow rates ranged from 1.5 to 15 cfm, and inlet air temperature and RH ranged from 10°C, 20% to 43°C, 14%. They found that within an airflow range of 6 to 10 cfm, cooling increases in direct proportion to the increase in airflow.

## **LIQUID COOLING**

### **Human Studies**

The first water-cooled garment was fabricated at the Royal Aircraft Establishment in 1962 (Burton & Collier, 1964) as a means of protecting crewmen in hot environments (Nunneley 1970). Since that time, water-cooled suits have been employed in an assortment of industrial, military, aerospace, and laboratory settings.

Cadarette et al. (1990) evaluated three commercial liquid microclimate cooling systems in reducing the stress associated with exercise in the heat. Their subjects wore chemical protective garments over one of each of three cooling vests: ILC Dover Model 19 Cool Vest (ILC); Life Support Systems, Inc. Cool Head (LSSI); or Thermacor Technology, Inc., Thermacor vest (THERM). The ILC vest was composed of two nylon bladders worn as panels on the chest and back. The chest panel contained a pouch with a pump, battery holder, and bag filled with ice and water for circulation at 2.65 l/min. Average inlet water temperature was 5.0°C. The LSSI vest was constructed of nylon and contained channels for the coolant, a propylene glycol mixture, to flow through. The vest panels were connected to a cooling cap, and total flow through the vest and cap was 0.4 l/min. Average inlet coolant temperature was 14.5°C. The THERM vest was composed of 16 hexagonal packets to which pressurized dichlorotetrafluoroethane (R114) was delivered. The wearer was cooled by the heat of vaporization of R114, and the average evaporative temperature measured at two packets was 28.3°C. These systems were all state-of-the-art as of the publication date of the primary source (Cadarette et al., 1990). The ILC provided the highest mean actual cooling rate at 244 W,

followed by the LSSI at 222 W, and the THERM at 108 W. Figure 3 shows the endurance times of subjects' treadmill walking at a metabolic rate of 440 W with each of the cooling systems. It is clear that endurance time was significantly less with the LSSI than with the ILC or THERM; however the cooling rate with the THERM was less than that of the LSSI. Although the subjects' physiological responses did not differ between cooling systems, the short endurance time with the LSSI was attributed to the headaches that all subjects reported shortly after exercise onset; the LSSI was the only system in which a cooling cap was employed. Although the ILC was deemed best for individuals working in hot environments, it was concluded that the cooling provided by all three of the systems was sufficient during only light to moderate work and that the systems would have limited suitability for sustained military operations.

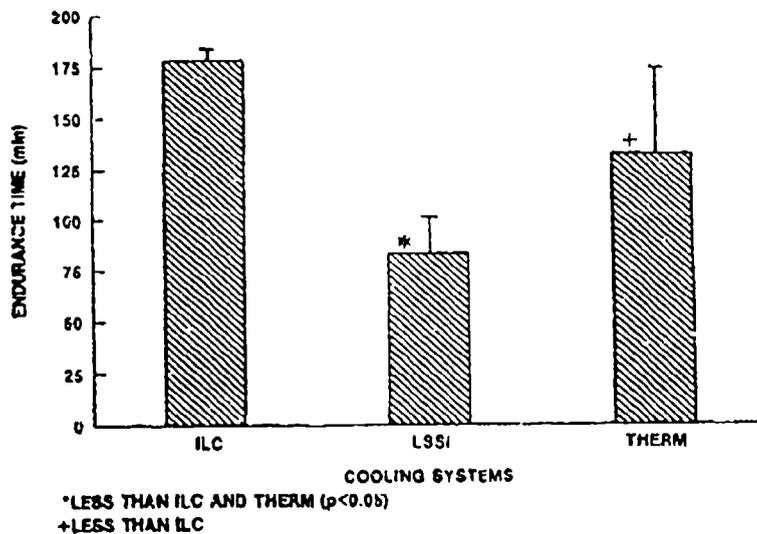


Figure 3. Endurance time of subjects exercising at 440 W wearing the three microclimate cooling systems. (From Cadarette et al., 1990. Used with permission.)

Cosimini et al. (1985) and Speckman et al. (1988a) evaluated the ILC and LSSI on subjects wearing a protective overgarment while at rest (metabolic rate of 105 W) or treadmill walking at an average metabolic rate of 340 W in either a hot/wet (35°C, 75% RH) or hot/dry (49°C, 20% RH) environment. Although all subjects completed 180 min at rest, none of the subjects completed the treadmill tests (target 180 min) with either of the cooling systems (average stay time was 98 min in the hot/dry condition, and 169 min in the hot/wet condition). Cosimini et al. concluded that neither system was suitable for Army field use due to the inability of their subjects to complete the exercise tests and to the excessive maintenance required to keep the systems operational. Pimental et al. (1989) evaluated the ILC on eight subjects' treadmill walking at a metabolic rate of 360 W in a 43°C, 45% RH environment for a target 3-hr exposure. All subjects completed the exposure with the ILC, whereas only three were able to last 3 hr with no cooling. These results reinforce the conclusions of Cadarette et al. (1990) that the ILC is effective in reducing heat strain at light to moderate exercise work loads.

In another study, Pimental et al. (1987a) evaluated the operational characteristics of the ILC and LSSI and their effectiveness in increasing tolerance time in nine subjects who were treadmill walking at a metabolic rate of 360 W in a 43°C db, 29°C dp environment. Sweat rates and final  $T_{re}$  were similar with either system; however, the ILC elicited somewhat lower heart rates. The ILC was recommended over the LSSI for Navy use because of fewer system failures, greater ease of operation, less bulkiness, less weight, and lower cost.

The effect of cooling various body surfaces during upper- and lower-body exercise was investigated by Young et al. (1987). Subjects performed either arm cranking (40 W external work rate) or treadmill walking (1.27 m/s at 0% grade) in a 38°C, 30% RH environment while a cooling mixture (10% propylene glycol and water) was circulated through a garment at 380 ml/min. The authors found that conductive cooling of the upper arms in addition to the torso during upper-body exercise provided no additional cooling advantage. However, thigh cooling in addition to torso cooling during lower body exercise resulted in lower sweat rates and smaller changes in core temperatures. The legs apparently possess a higher capacity than the arms for adjusting sweating and vasomotor responses for local heat transfer (Young et al., 1987).

Table 2 summarizes studies in which liquid cooling was used to cool subjects during exertion in the heat.

Table 2.

## LIQUID COOLING IN HUMANS DURING WORK IN THE HEAT

| Authors                 | n  | Exp. Design                      | Work Rate or Metabolic Rate (watts) | System               | Coolant               | Ambient Cond. (°C, % RH) | Stay Time                                       |
|-------------------------|----|----------------------------------|-------------------------------------|----------------------|-----------------------|--------------------------|---|
| Frim et al. (1991)      | 12 | normal engine room duties        |                                     | EXOTEMP              | water                 | 45-50°                   | ---   |
| Vallerand et al. (1991) | 7  | 150 min                          | 240 W                               | ---                  | ---                   | 37°, 50%                 | 150 min<br>95 min (no cool)                     |
| Cadiette et al. (1990)  | 5  | walk 180 min                     | 440 W                               | ILC<br>LSSI<br>THERM | water<br>PG*<br>R114* | 38°, 10°dp               | 83-178 min                                      |
| Pimental et al. (1989)  | 8  | walk 180 min                     | 360 W                               | ILC                  | water                 | 43°, 45%                 | 180 min   |
| Speckman et al. (1988b) | 8  | walk/rest 180 min                | 340 W                               | ILC<br>LSSI          | water<br>PG           | 29°, 85%                 | 169 min<br>98 min                               |
| Janik et al. (1988)     | 29 | shipboard duty                   | ---                                 | ILC<br>LSSI          | water<br>PG           | avg 24°<br>wbgt          | ---   |
| Pimental et al. (1987a) | 9  | walk 180 min                     | 360 W                               | ILC<br>LSSI          | water<br>PG           | 43°, 29dp                | 148-180 min<br>≤ 180 min                        |
| Young et al. (1987)     | 6  | 2 arm crank tests<br>4 walks     | $\dot{V}O_2=1.2$ l/m                | vest,<br>umb panels  | PG                    | 38°, 30%                 | N/A   |
| Mitchell et al. (1986)  |    | 6-day field ops                  | ---                                 | vest                 | ---                   | < and > 29°              | ---   |
| Nagle et al. (1986)     | 3  | perf. tasks                      | ---                                 | 2 vests              | water                 | 55°, 55%                 | ---   |
| Cosimini et al. (1985)  | 8  | walk 180 min                     | 340 W                               | ILC<br>LSSI          | water<br>PG           | 49°, 20%<br>35°, 75%     | 98 min ILC, LSSI<br>171 min ILC<br>167 min LSSI |
| Iacono et al. (1984)    | 12 | 2 hr                             | avg 180 W                           | vest                 | EG*                   | 49°, 20%<br>35°, 75%     | 2 hr  |
| Nunneley et al. (1983)  | 8  | 10 min cycle<br>then 90 min rest | ---                                 | Acurex vest<br>& cap | water                 | 35°, 26° (svb)           | 90 min  |

Table 2, continued

| Authors                   | n   | Exp. Design          | Work Rate or Metabolic Rate (watts) | System                    | Coolant             | Ambient Cond. (°C, % RH)        | Stay Time   |
|---------------------------|-----|----------------------|-------------------------------------|---------------------------|---------------------|---------------------------------|---|
| Terrian et al. (1983)     | 9   | 160 min walk/rest    | 480 W                               | ILC LSSI                  | water PG            | 45°, 31' (wb)<br>32°, 22' (wb)  | 40-50 min<br>70 min ILC<br>160 min LSSI with ice recharge |
| Brown et al. (1982)       | 6   | two 2-hr rests       | ---                                 | liq. cond. hood           | 50% aq. Thermocal B | 40°, 29' (wb)                   | 2 hr  |
| Nunneley et al. (1982)    | 6   | manikin task         | ---                                 | full suit, cap            | water               | 30°                             | N/A   |
| Shapiro et al. (1982)     | 12  | 120 min work/rest    | 180 W                               | vest                      | water               | 35°, 75%<br>49°, 20%            | ---   |
| Webbon et al. (1981)      | 5   | walk                 | 464 W (avg)                         | 3 garments                | ---                 | 20°                             | ---   |
| Webbon et al. (1978)      | 4   | rest/walk            | avg. 350 W                          | liquid circ. (head, vest) | water               | 32.5° wbgt                      | ---   |
| Kissen et al. (1976)      | 5   | 80 min               | ---                                 | helmet liner              | water               | 46.1°, 30 mmHg P <sub>H2O</sub> | ---   |
| Shvartz, E. (1976)        | 6   | bench step           | 40 W                                | head or neck              | water               | 23° or 39.5°, 30.3' (wb)        | ---   |
| Shvartz, E. et al. (1974) | 3   | moderate work        | ---                                 | regional cooling          | water               | 49.3°, 31.4' (wb)               | ---   |
| Williams et al. (1974)    | 4   | 80 min tracking task | ---                                 | helmet liner              | water               | 46.9°, 37.4%                    | ---   |
| VanRensburg et al. (1972) | --- | ---                  | ---                                 | vest                      | water               | ---                             | ---   |
| Webb et al. (1972)        | 3   | 24-hr calorimetry    | 70 W heat production                | ---                       | water               | ---                             | ---   |
| Benor et al. (1971)       | 7   | walk 2 hr            | 3.5 km/hr                           | cooling suit              | water               | 30-50°                          | ---   |
| Nunneley et al. (1971)    | 3   | 2 hr                 | 50% VO <sub>2</sub> max             | cooling cap               | water               | 20-40°                          | ---   |

Table 2, continued.

| Authors                | n  | Exp. Design              | Work Rate or Metabolic Rate (watts) | System                                | Coolant | Ambient Cond. (°C, % RH)       | Stay Time          |
|------------------------|----|--------------------------|-------------------------------------|---------------------------------------|---------|--------------------------------|--------------------|
| Shvartz, E. (1970)     | 6  | walk 2 hr                | 5 km/hr                             | hood or hood & suit                   | water   | 50°, 20%                       | 2 hr               |
| Webb et al. (1970)     | 6  | ... cooling control..... |                                     | space suit                            | water   | ...                            | ...                |
| Gold et al. (1968)     | 6  | 30 min ea. walk/rest     | 3 or 5 kph + incline                | partial body suit                     | water   | 40°, 50°                       | lower with incline |
| Waingora et al. (1968) | 6  | treadmill exercise       | 315 kcal/hr ≤ 655 kcal/hr           | prototype garment developmental garm. | ...     | ...                            | 2-3 hr             |
| Webb et al. (1968)     | 4  | walk                     | 300-900 kcal/hr                     | suit                                  | water   | ± 1°C from suit temp           | ...                |
| Kaufman et al. (1966)  | 16 | rest 2 hr                | ...                                 | vest                                  | water   | 46.5°, 15mmHg P <sub>H2O</sub> | ...                |

• PG = aqueous propylene glycol; EG = aqueous ethylene glycol

## Manikin Studies

Speckman et al. (1988a) used an electrically heated copper manikin to assess the effectiveness of four liquid cooling systems. Two of the systems provided cooling over the torso-arms-legs, the third cooled the torso only, and the fourth provided cooling over all body regions except the face. The investigators found that the increase in cooling is almost directly proportional to the difference in temperature between the manikin surface and inlet water temperature but is NOT directly proportional to the water flow rate. This finding differs from that with air cooling in that at lower airflow rates (6 to 10 cfm), cooling increases in direct proportion to the increase in airflow (Speckman et al., 1988a).

Fonseca (1983a) determined the cooling rates, for maximally sweating skin, provided by two liquid-cooled undergarments to either the torso only or to the torso and head. Ambient conditions were either 32°C, 56% RH or 45°C, 46% RH. Both systems rapidly reached their maximum cooling rate within the first few minutes, then gradually decreased with time. At no time did the cooling rates level off; at three hours, less than 25 W of cooling was being provided by either system.

Masadi et al. (1991) evaluated the cooling capability of the ILC, LSSI, EXOTEMP (portable active ice system with liquid-cooled undergarment), KT M-10 (thermoelectric system: liquid-cooled shirt and cooling unit), on a heated aluminum manikin in a 35°C, 5% RH environment. The ILC provided the greatest cooling capacity (191 W-hr) of the three systems. The results are summarized in Table 3.

Table 3. THERMAL MANIKIN TEST RESULTS\*

| Cooling System    | Cooling Rate<br>(watts) | Duration**<br>(min) | Cooling Capacity†<br>(watt-hr) |
|-------------------|-------------------------|---------------------|--------------------------------|
| EXOTEMP CD-2      | 160                     | 40                  | 107                            |
| ILC Dover 1905-M1 | 135                     | 85                  | 191                            |
| STEELE Vest       | 135                     | 120                 | 270                            |
| KT M-10†          | 120                     | ----                | ----                           |
| LSSI Mark VII     | 85                      | 90                  | 128                            |

\*data from Masadi and Kinney (1991).

\*\*time between ice change.

†calculated based on one ice change.

‡provided continuous uninterrupted cooling.

## ICE COOLING

Passive protective microclimate cooling ice vests offer numerous advantages over air and liquid cooling systems. Ice vests are lower in cost, easy to don and doff, are relatively lightweight, are passive (i.e., require no external energy), contain no moving parts, and engender virtually no mechanical difficulties. The STEELE ice vest is constructed of cotton canvas, is positively buoyant (important for aircrew and shipboard personnel), and contains six frozen gel thermostrips that are placed in horizontal Thinsulate insulated pockets. The pockets are oriented in parallel rows: three in the front and three in the back. Masadi et al. (1991) found in manikin tests that the STEELE ice vest provided a much greater cooling capacity, 270 W-hr, than the liquid cooling systems they also tested (Table 3). These advantages identify the ice vest as a potentially efficacious method of providing cooling especially for shipboard personnel who can change the melted packs when necessary. However, passive ice vests do not prevent heat storage and may be suitable for only short-term work (Speckman et al., 1988a).

### Human Studies

Banta and Braun (1992) recently evaluated the effectiveness of the STEELE ice vest in reducing heat strain in helicopter aircrew during at-sea, in-flight operations in the Persian Gulf. HR was significantly reduced on-deck and during hover in the aircrew members wearing the vest. Subjective opinions of aircrew members revealed that the vest was beneficial in reducing the thermal load.

Pimental et al. (1989) evaluated the STEELE ice vest and the American Stay Cool vest (nylon vest with six pockets for frozen gel packs, two on the front and four on the back) in eight subjects walking on a level treadmill at 3.5 mph for 3 hr (target exposure) in a 43°C db, 45% RH environment. At 120 min, HR with the STEELE ice vest was significantly lower than HR with the American vest (and also lower than with the ILC system). Sweat rate was lower with the STEELE ice vest than with the American vest. The STEELE ice vest coolant lasted an average of 117 min whereas the coolant in the American system lasted an average of 85 min. Six of eight subjects preferred the STEELE ice vest over the other systems

Heaney et al. (1991) studied the effect of an ice vest on cardiovascular drift (HR rise) in 11 subjects during a simulated 4-hr engine room watch (~120 W energy expenditure). HR rise was essentially eliminated when the vest was worn, perhaps because peripheral blood pooling was reduced.

The effectiveness of the STEELE ice vest in extending work tolerance time was evaluated in six subjects during heavy exercise (700 W metabolic rate) in the heat while wearing chemical

protective clothing (Bain, 1991). Although stay times tended to be slightly longer with the vest (44.3 min vs. 39.6 min without the vest), the difference was not statistically significant. It was concluded that the STEELE ice vest was ineffective in prolonging stay time during moderate to heavy exercise in the heat.

### **Manikin Study**

Fonseca (1982) measured torso cooling, provided individually by two ice-packet vests, on an electrically heated sectional manikin wearing a complete chemical protective suit in the heat. The number of ice packets attached to a vest ranged from 43 to 91. He reported that for a given quantity of ice, heat exchange between the torso and the ice is maximized by using a complete "formfitting" ice layer over the torso.

### **DRY ICE COOLING**

Dry ice cooling, which utilizes both conduction and sweat evaporation, was first reported almost three decades ago (Petit et al., 1966). Dry ice cooling has been more recently investigated by Konz et al. (1974) who found that a dry ice vest provided about 79 kcal/hr (92 W) of cooling in one subject seated in a 43.3°C, 45% to 55% RH environment. It was concluded that dry ice does not have the precise cooling control that is possible with liquid or air cooling, but an advantage is in its cost efficiency.

### **COMBINED (AIR-LIQUID) COOLING**

Combined air-liquid cooling systems could be used by combat vehicle crewmen needing both air and liquid cooling for mounted and dismounted activities. Cadarette et al. (1988) tested the effectiveness of a prototype "hybrid" air-liquid cooling system by comparing it with the cooling provided by currently available air and liquid cooling systems in five subjects who were treadmill walking at a metabolic rate of 332 W for 2 hr in a 37.7°C db environment while wearing a chemical protective overgarment. Four cooling configurations were examined: an air-cooled vest, the hybrid vest in the air-cooled mode, a liquid-cooled vest, and the hybrid vest in the liquid-cooled mode. Neither endurance time nor subjective measurements (perceived exertion and thermal sensation) differed between cooling configurations. However, thermal strain was greater with the hybrid vest in the liquid-cooled mode relative to the air-cooled vest.

### **OTHER COOLING METHODOLOGIES**

Although the torso has been the principal cooling site focused upon thus far in this review, it is pertinent to note that other cooling methods have been employed that target other body regions. Several of the studies reported below did not involve chemical protective overgarments. Nonetheless, the reader may find these brief summaries helpful.

Gordon et al. (1990) employed neck cooling during a strenuous 45-min exercise bout and discovered that  $T_{re}$  and sweat rate were reduced over the control condition. Greenleaf et al. (1980) measured plasma volume during 60 min of rest, 60 min of ergometer exercise, and 30 min of recovery in men wearing liquid-cooled neoprene headgear. They found that cooling increased plasma volume by 3% during rest and this increase was maintained throughout exercise and recovery. Livingstone et al. (1989) found that immersing the hands up to the wrists in cold water resulted in a heat loss of between 31 and 124 W given the water temperature and metabolic heat production. They suggest that hand immersion may be used to decrease resting time during work in the heat.

Antuñano (1987) used a refreezable head cooler on subjects exercising at an external work rate of 60 W on a cycle ergometer for 60 min while wearing a protective overgarment and found that head cooling attenuated the rise in HR,  $T_{re}$ , and  $T_{sk}$ . Shvartz (1970) found that cooling the head alone resulted in oral and forehead temperatures that were closer to those found during both head and body (torso, upper arms, thighs) cooling than were found without cooling. Nunneley et al. (1971) found that head cooling with a water-cooled cap removed about 30% of resting metabolic heat and 19% of available work-engendered heat. Katsuura et al. (1989) cooled the head by circulating water through Tygon tubing placed on the head and found that head cooling significantly inhibited sweating during rest. During exercise, sweat rate over the chest was reduced significantly.

Gonzalez et al. (1986) investigated the usefulness of a wettable cover over a chemical protective garment and found that skin heat loss was 40 W at 35°C and 200 W at 50°C. This method of cooling could be useful in an environment in which personnel could be periodically sprayed with water in that the requirement for additional supplemental cooling could be reduced.

Riggs et al. (1981) investigated the effect of face cooling on HR during a short, increasingly intense exercise bout and found that HR was significantly reduced when a cold wind was directed at the subjects' faces. In a later study (Riggs et al., 1983) they determined the effects of face cooling during 60 min of cycle ergometry exercise and found that oxygen uptake ( $\dot{V}O_2$ ), lactate concentration, and estimated myocardial  $\dot{V}O_2$  were higher with face cooling. These results suggest that the effectiveness of face cooling on exercise stress is difficult to interpret.

Furthermore, face cooling may have limited value in the chemical, biological, radiological environment.

## SUMMARY

Alleviation of thermal stress in high heat environments, especially for military personnel wearing chemical protective overgarments, has been approached via cooling the microenvironment; i.e., cooling the environment immediately surrounding the individual vs cooling the macroenvironment (work area). Approaches to reducing heat stress by microclimate cooling have primarily involved use of air-cooled vests, liquid-cooled garments, and (passive) ice vests. Air-cooled systems rely on evaporative cooling, the efficiency of which can be increased by maximizing the proportion of air that diffuses over the body surface while minimizing the proportion that exits directly through the clothing (Speckman et al., 1988a). Advantages of air-cooled systems include their relatively low weight, maintenance of drier clothing for the individual, and the unlikelihood of overcooling because sweat evaporation is the mechanism for body cooling.

The mechanism of heat transfer in liquid-cooled systems is conduction. As inlet water temperature decreases, more heat is removed (Fonseca, 1981), and the rate of cooling is proportional to the difference in temperatures between skin and inlet water (Goldman & Winsmann, 1976). The benefit of regional cooling with liquid-cooled garments is evident. However, overcooling can occur, resulting in local cutaneous vasoconstriction and thermal discomfort (Nunneley, 1970). Disadvantages of liquid-cooled systems include weight, battery life, and possible compression of tubes resulting in interruption of flow of the cooling medium (Speckman et al., 1988a).

Ice-cooled systems possess the advantage of allowing the wearer to move about untethered and without having to carry the cooling unit as is necessary with air- and liquid-cooled systems. However, ice-cooled systems are generally not as effective as either air- or liquid-cooled systems for various reasons: (1) because the shape of the ice changes as it melts, heat will not be removed at a constant rate (Speckman et al., 1988a); (2) when the ice melts completely to water, the water temperature will increase in an attempt to equilibrate with the body surface in which it is in contact; (3) because the cooling provided by ice vests is time dependent i.e., cooling rate is high at first, then decreases as the ice melts; and (4) because heat storage is not prevented, ice-cooled systems are probably suitable only for short-term work (2- to 4-hr duration) (Speckman et al., 1988a) unless the ice packs can be replaced.

The "ideal" microclimate cooling system has not yet been developed. It is unlikely that any one particular system design will prove optimal for all military personnel requiring cooling, because duties, modes and levels of exertion, and environments will vary. Perhaps the most potentially successful approach will be to design cooling systems specific to the conditions under

which they will be utilized. Consideration should be given not only to the ambient environment but also to the exercise mode and perhaps even to the gender of the personnel utilizing the systems.

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|--|--|---|---|---------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.  |  |   |   |                                 |
| 1. AGENCY USE ONLY (Leave blank)   |  | 2. REPORT DATE<br>9-22-93                               |   | 3. REPORT TYPE AND DATE COVERED |
| 4. TITLE AND SUBTITLE<br><br>A Review of Microclimate Cooling Systems in the Chemical, Biological, Radiological Environment  |  |   | 5. FUNDING NUMBERS<br>Program Element: 62233N<br>Work Unit Number:<br>M33P30.005-6207 |                                 |
| 6. AUTHOR(S)<br>T. Derion, R.S. Pozos  |  |   |   |                                 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Naval Health Research Center<br>P. O. Box 85122<br>San Diego, CA 92186-5122  |  |   | 8. PERFORMING ORGANIZATION<br>Report No. 93-23  |                                 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>Naval Medical Research and Development Command<br>National Naval Medical Center<br>Building 1, Tower 2<br>Bethesda, MD 20889-5044   |  |   | 10. SPONSORING/MONITORING<br>AGENCY REPORT NUMBER                                     |                                 |
| 11. SUPPLEMENTARY NOTES  |  |   |   |                                 |
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT<br><br>Approved for public release; distribution is unlimited.  |  |   | 12b. DISTRIBUTION CODE  |                                 |
| 13. ABSTRACT (Maximum 200 words)<br>Soldiers may work in hot environments and under conditions posing a biological, chemical, or nuclear threat. Chemical protective overgarments are worn to prevent contact with toxins; however, they prevent dissipation of body heat. This review addresses the effectiveness of microclimate cooling systems in alleviating thermal strain in personnel encapsulated in protective overgarments during exertion in the heat. Air, liquid, and passive ice cooling systems are primarily reviewed, but other methodologies are also discussed. Air cooling can increase tolerance time fourfold, but high ambient temperature air cooling may be dangerous. Liquid cooling is effective in reducing heat strain at light to moderate work loads and is beneficial when applied to the thighs during lower-body exercise. Overcooling and discomfort can occur with a liquid-cooled system due to cutaneous vasoconstriction. Liquid-cooled systems are heavy, require excessive maintenance, and tube compression can result in interrupted coolant flow. Air cooling is inefficient compared to liquid cooling because of air's lower specific heat. Ice cooling may only be suitable for short-term work and is generally less effective than either air or liquid cooling although the wearer can move about untethered. The best cooling system design approach may be indicated by consideration of the unique cooling needs of personnel performing specific tasks in various environments. |  |   |   |                                 |
| 14. SUBJECT TERMS<br>Microclimate cooling CBR Environment  |  |   | 15. NUMBER OF PAGES<br>27   |                                 |
|  |  |   | 16. PRICE CODE  |                                 |
| 17. SECURITY CLASSIFICATION OF REPORT<br>Unclassified  | 18. SECURITY CLASSIFICATION OF THIS PAGE<br>Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT<br>Unclassified | 20. LIMITATION OF ABSTRACT<br>Unlimited   |                                 |