NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

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ASSESSMENT OF ADVANCED PERSONAL COOLING SYSTEMS FOR USE WITH CHEMICAL PROTECTIVE OUTER GARMENTS

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Jonathan W. Kaufman, Ph.D.
Linda T. Fatkin, M.A.

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DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
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14. ABSTRACT

Persons responsible for removing extremely hazardous chemical agents or responding to chemical incidents typically wear fully encapsulating chemical protective ensembles (Level A (LA)) during field operations. LA ensembles are currently used without any ancillary cooling system, thereby greatly increasing the risk of thermal injury. The present study evaluated four candidate cooling systems intended to mitigate thermal stress experienced by LA ensemble users in hot humid conditions. Four current members (males, ages 22-24) of a military chemical response unit served as subjects in this study. Participants wore operationally configured LA ensembles with a closed circuit soda-lime based rebreather system while performing repeated rest (5 min)/work cycles (25 min: alternating treadmill walking (4.8 km hr^{-1}, 5% grade) and level walking while carrying 22.7 kg) designed to simulate tasks and workloads associated with actual missions for up to 2 hr. Air temperature was maintained at 37°C with relative humidity = 75% throughout exposures. Tested cooling systems were: 1) liquid cooled vest with hood (ice cooling source); 2) phase change vest; 3) wetted vest; and 4) liquid cooled whole body garment (super critical air cooling source). The noncooled LA configuration served as the experimental control. No significant differences were observed between control and cooling runs. Subjects were unable to complete more than two rest work cycles (mean ± standard deviation = 47.9 ±8.5 min) while experiencing changes in rectal temperature = 1.4 ±.4°C and maximum heart rates = 167 ±11 beats min^{-1}. Runs terminated either because of breathing difficulties, high heart rates, or subject exhaustion. None of the cooling systems proved effective in overcoming the severe heat stress imposed on subjects. Hot breathing gas coming off the rebreather was originally thought to be a major factor contributing to the thermal burden but this proved incorrect. Conventional cooling methods appear entirely inadequate to address the combined stressors of high ambient temperature and humidity coupled with demanding physical workload.

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EXECUTIVE SUMMARY

An assessment of the efficiency of advanced man-mounted cooling systems in minimizing thermal stress induced by a hot/humid environment combined with exercise was conducted at NAWCAD Patuxent River, Maryland, during April and May 2001. Four members of the U.S. Marine Corps Chemical Biological Incident Response Force (CBIRF) volunteered to be repeatedly exposed to air temperature = 37°C, relative humidity = 75% while wearing current CBIRF and U.S. Navy chemical protective outer garments (CPOG's) and performing a repeated rest/work cycle that produced a mean estimated time-weighted metabolic rate of 572-636 W. Cooling systems tested were as follows:

a. Liquid cooled vest (LCV) (Geomet Technologies)

b. Phase change vest (Triangle Research)

c. Hydroweave vest (AquaTex Industries)

d. SuperCritical Air Mobility Pack (SCAMP) (Aerospace Design and Development)

Principal testing consisted of wearing the CBIRF Level A (LA) CPOG ensemble with each of the cooling systems though other CPOG's were also studied (CBIRF Level B, JSLIST, USN Mk1) in an abbreviated manner. The control configuration was the LA used with the LITPAC rebreather without ancillary cooling. The LITPAC was routinely used during LA runs though comparison with the CBIRF self-contained breathing apparatus was also made.

Quantitatively, none of these cooling systems provided a significant physiological advantage under test conditions. Exposure durations, rectal temperature changes, and sweat losses did not vary significantly between cooling systems. Significant heart rate variations were principally confined to use of the USN Mk1. SCAMP and LCV generally produced lower skin temperatures. Physiological and psychological stress assessments did not distinguish between cooling systems nor did subjective comfort scores though subjects generally chose LCV as the best overall cooling system retrospectively.

Subjects routinely cited breathing problems and fatigue as causes for self-termination of runs. Elevated heart rates were the principal cause of involuntary run terminations. While fatigue and associated elevated heart rates were anticipated termination issues, breathing difficulties suggest additional work may be warranted to ferret out the nature of these problems (e.g., inadequate breathing airflow, hot breathing gas).

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Inclusion of cooling systems in this study does not imply official or unofficial endorsement of these products in any way. The opinions expressed in this document reflect only the author's viewpoint and do not constitute an official position by the U.S. Navy, USMC, Department of Defense, or other U.S. Government agencies.

INTRODUCTION

Impermeable or semipermeable garments providing protection against chemical and biological warfare (CBW) agent threats can retain large quantities of body heat. Body heat trapped within these encapsulating garments needs to be removed if the garment user is to adequately perform required tasks, especially when users are physically active. Otherwise, trapped heat leads to hyperthermia, a potentially dangerous condition that can severely degrade mission performance, cause injury, and, in extreme cases, result in death.

The U.S. Marine Corps (USMC) Chemical Biological Incident Response Force (CBIRF) routinely employs encapsulating CBW protective garments in all environmental conditions while performing a variety of demanding physical tasks. CBIRF personnel experience performance degradation and reduced endurance while wearing these garments during training and actual missions. They are currently investigating a number of advanced cooling concepts that can theoretically address this problem. The present study was intended to evaluate five advanced cooling methodologies (Advanced Personal Air Conditioning System (APACS), hydroweave (HW) suit, liquid cooled vest (LCV), phase change vest (PCV), and Super Critical Air Mobility Pack (SCAMP)) in combination with compatible chemical protective outer garments (CPOG's) ensembles.

METHODS

The purpose of this study was to identify cooling systems which maximize an individual's tolerance time in hot/humid environments by mitigating heat-related degradation of physical endurance and strength experienced while wearing CBIRF CPOG's during simulated operational tasks.

Subjects: The experimental protocol was approved by NAWCAD Patuxent River Institutional Review Board in accordance with Department of Defense and U.S. Navy requirements. Four healthy male Marines currently assigned to CBIRF volunteered to particpate after being fully informed of the details of the experiment protocol and associated risks. These four subjects routinely perform rigorous physical tasks in CPOG's under a wide variety of environmental conditions. Consequently, study conditions were judged to reflect conditions these individuals would experience during normal operations (i.e., training or actual operations). Table 1 lists the physical characteristics of the subjects. Body surface area was calculated from the height and weight of each subject (5) and percent body fat was calculated from skinfod measurements (6, 19).

Table 1: Physical Characteristics of Subjects

Subject	Age	Height (cm)	Weight (kg)	Surface Area (m^2)	Percent Body Fat
A	23	168	72.8	1.82	16.7
B	23	188	83.4	2.10	13.9
C	22	180	80.6	2.00	17.0
D	24	175	81.9	1.98	11.9
Mean ± standard deviation (SD)	23 ±.8	1.78 ±.08	79.7 ±4.7	1.98 ±.12	14.9 ±2.4

COOLING SYSTEMS

Five distinct cooling systems were employed in this study as shown in table 2. Two of these systems (SCAMP and APACS) also provided breathing air while the others (HW, LCV, and PCV) relied upon an external breathing source in this study.

Table 2: Cooling Systems Evaluated in Present Study

Item	Study Notation	Manufacturer	Cooling System	System Weight (kg)	Cooling Technology	Primary Heat Transfer Mechanism
1	LCV	Geomet Technologies	"Personal Ice Cooling System" (PICS)	6.0	Liquid cooled tube suit (water/ice)	Conduction
2	PCV	Triangle Research and Development	"Portable Environmental Control System" (PECS)	2.9	Phase change beads (hydrocarbon wax)	Conduction
3	HW	AquaTex Industries	HW vest	1.4	Water-soaked vest	Evaporation
4	SCAMP	Aerospace Design and Development	SCAMP		Liquid cooled tube suit Cooled breathing gas	Conduction Respiratory evaporation
5	APACS	System Design and Engineering	APACS	5.9	Cooled ventilatory air	Evaporation/ convection

Liquid Cooled Vest: Two systems (LCV and SCAMP) employed liquid-filled tube garments to extract heat from the body surface. The LCV tube garment consisted of a water-filled tubed shirt and hood worn directly over the skin. Conduction (and some convection) transferred heat from the skin to the circulating fluid. Water passed from the tubing through an ice filled bottle and then recirculated through the tubing via a pump directly attached to the ice bottle. A tubing pass-through enabled cooled water to enter and exit the tubing garment without compromising Level A (LA) garment integrity. Mounting the LCV cooling unit onto LA was accomplished by a hook mounted onto a reinforced point on the LA surface. A strap system mounted opposite the supporting hook was intended to transfer the ice bottle/pump weight onto the weight bearing straps from the breathing system.

Phase Change Vest: An open-weave mesh vest containing hundreds of small plastic coated wax beads comprised the PCV. Convection extracted heat from the skin and melted the wax. PCV vests were worn over a tee shirt to prevent chaffing and covered both the entire torso and upper shoulders. The open weave mesh permitted airflow through the vest during use.

Hydroweave Vest: The HW vest was prepared by soaking the lightweight porous fabric vest containing a hydrophilic inner lining in water and wringing it out. Cooling occurred when heat released from the skin evaporated the trapped water. The vest was worn over a tee shirt to prevent chaffing and covered most of the torso.

Super Critical Air Mobility Package: A full coverage (arms, legs, torso) tubing suit worn next to the skin was used to extract heat from the skin. Polyethylene glycol passing through the tubing transferred heat to a heat exchanger through which supercritical air (-193°C) passed as part of the breathing loop. The supercritical air removed heat from the circulating propylene glycol and was consequently warmed to an acceptable breathing temperature. A Dewar bottle chilled with liquid nitrogen retained the supercritical air under low pressure (750 psi) for both body cooling and as breathing gas.

Advanced Personal Air Conditioning System: This cooling system blows cooled air through the inner mesh lining the entire inner surface (arms, legs, torso) of the U.S. Navy (USN) Helicopter Aircrew Integrated Life Support System (HAILSS) garment. Ventilation air is cooled by passing through a water-filled heat exchanger kept at reduced pressure and connected to a zeolite bed. Heat extracted from the air boils water within the heat exchanger. Water vapor then diffuses into the zeolite bed, adsorbs onto the zeolite surfaces, and releases heat.Ventilation air also serves to provide breathing air and cooling/demist air to the HAILSS hood/visor essembly.

CHEMICAL PROTECTIVE OUTER GARMENTS

Level A: A single-piece, impermeable, and totally encapsulating garment completely sealing the user from the external environment. A supplemental breathing source worn inside the LA supplies oxygen to the user. LA was used with either a LITPAC rebreather (approximate fully charged weight = 18.2 kg) (LA-L) or self-contained breathing apparatus (SCBA) (approximate fully charged weight = 17.3 kg) (LA-S) in this study.

Table 3: Components of the Test Clothing Ensembles

Ensemble	Symbol	System Weight (kg)	Components
CBIRF Level A CPOG	LA	22.3	• Fully encapsulating Tyvek outer garment with plastic face shield and integral booties • Litpac II chemical protective SCBA • Cotton blend shirt and trousers, underwear, socks • Combat boots
CBIRF Level B (LB) CPOG	LB	8.0	• Tyvek single piece outer garment • Powered Air Purifying Respirator (PAPR) • Chemical protective (butyl) gloves • Cotton blend shirt and trousers, underwear, socks • Combat boots
Joint Service Lightweight Integrated Suit Technology (JSLIST)	JSLIST	11.0	• Carbon-impregnated rip-stop nylon outer garment • M-40 chemical protective mask • Rubber over boots • Chemical protective (butyl) gloves • Cotton blend shirt and trousers, underwear, socks • Combat boots
A/P 22P-14(V)	Mk1	12.4	• CWU-27/P standard flight suit • Cotton moisture-wicking undergarment • MK-1A activated carbon chemical liner • MCK-3A/P aircrew mask/hood assembly with Mk-2 manifold • CMU-33/P "Airsave" survival vest • Wicking (cotton) and chemical protective (butyl) gloves worn under standard FRP-2 flyer's gloves. • Plastic vapor impermeable chemical protective socks worn over cotton inner socks and taped to Mk1 liner, standard issue flight boots, plastic over boot
Helicopter Aircrew Integrated Life Support System	HAILSS	19.7	• Flight coverall made of a 2-ply Nomex delta T/A laminate, ventilation mesh • Booties worn inside flight boots • Latex rubber seals at the neck and wrist • APACS cooling system • Chemical/biological visor/respirator (CBVR) worn under flight helmet • Nomex long underwear, socks, and flight gloves • CMU-33/P "Airsave" survival vest

Level B: A single-piece lightweight impermeable garment encapsulating all but the face from the external environment. Either a SCBA or filterted breathing system provides clean air to the LB user. A powered filtered air system (PAPR) was used in this study.

Joint Service Lightweight Integrated Suit Technology: A two-piece CPOG intended for combat use, JSLIST uses carbon-impregnated fabric and a filtered breathing system (M-40 mask) to protect users. Drawstrings and zippers are used to seal openings (wrists, ankles, pants, and jacket) and butyl rubber overboots protect feet from exposure to noxious agents.

U.S. Navy A/P22P-9(V) Protective Assembly (Mk1): A chemical protective system intended for use by USN and USMC helicopter aircrew, this system consists of cotton underwear, a carbon-impregnated permeable liner (worn under a standard CWU-27/P flight suit), and impermeable foot and hand protection. Permeability ostensibly reduces heat stress without significantly reducing chemical protection. A forced air filtered respirator (MCK-3/P) provides breathing air to the user.

U.S. Navy Helicopter Aircrew Integrated Life Support System: A prototype multipurpose helicopter aircrew protective garment, HAILSS consists of Nomex undergarments, a nylon/polyethylene mesh liner, and an impermeable CPOG. The mesh liner provides the path for ventilation air to course over the majority of a user's body surface to cool by evaporation. An integrated CBVR provides head and neck protection against noxious agents. Filtered breathing air is provided by the APACS cooling system.

Experimental Design: The study was initially designed to expose each test subject to eight experimental trials organized into two test phases (table 4). Phase I was intended to identify the most effective of three cooling systems (HW, LCV, and PCV) by measuring work endurance in a hot/humid environment while wearing LA, the most encapsulating CPOG currently used by CBIRF. The current operational configuration (LA-L with no supplemental cooling) was used as the experimental control. Phase II was designed to use the most effective cooling system identified in Phase I to compare work endurance with two other chemical protective suits (JSLIST and LB) currently used by CBIRF. Additionally, Phase II was to evaluate the HAILSS suit using the APACS cooling system (a potential replacement for the LB) using the Mk1 (which has no supplemental cooling system) as the experimental control.

Table 4: Experimental Design to Assess Cooling Techniques

	Condition No.	CPOG	Cooling Systems
Phase I	1	LA-L	PCV
	2	LA-L	HW
	3	LA-L	LCS
	4*	LA-L	none
Phase II	1	LB	+
	2	JSL	+
	3	HAILSS	APACS
	4**	A/P22-14	N/A
* - experimental control, current USMC CBIRF configuration			
** - current USN aircrew CBW configuration			
+ - cooling system (PCV, HW, or LCV) identified as most effective in Phase I			

Delays in cooling system deliveries, exacerbated by subject and biomedical support staff unavailability, led to significant experimental design modifications. In addition, short exposure duration in the earlier runs led to adding runs to assess the effect of breathing system (self-contained rebreather (LITPAC) versus pressurized air bottles (SCBA)) on exposure tolerance. Ambiguous results in LA-L trials resulted in no single cooling system being identified as "best" for purposes of choosing a Phase II cooling system. Consequently, the clear distinction between the Phase I and Phase II studies was lost and some runs, most notably HAILSS, were omitted. In an attempt to provide some data on cooling system/CPOG interaction, Phase I cooling systems

(HW, LCV, and PCV) were tested with JSLIST and LB; one subject per configuration (CPOG/cooling system) with CPOG/no cooling serving as a control. The intended and actual daily schedules are shown in table 5.

Table 5: Daily Schedule (Planned and Actual) of Cooling System Evaluation

Note that experimental design (table 4) was lost in actual runs.

Initial experimental design used for planning purposes.

Week No.	Monday	Tuesday	Wednesday	Thursday	Friday
1	A-LA-L, PCV	B-LA-L, HW	C-LA-L, LCV D-LA-L, ctrl	A-LA-L, HW B-LA-L, LCV	C-LA-L, ctrl D-LA-L, PCV
2	A-LA-L, LCV B-LA-L, ctrl	C-LA-L, PCV D-LA-L, HW	A-LA-L, ctrl B-LA-L, PCV	C-LA-L, HW D-LA-L, LCV	A-LB, *
3	B-HAILSS	C-JSLIST, * D-Mk1	A-HAILSS B-JSLIST, *	C-Mk1 D-LB, *	A- JSLIST, * B- Mk1
4	C- LB, * A- Mk1	D- HAILSS	B- LB, *	C- HAILSS D- JSLIST, *	A-LA, SCAMP
5	B-LA, SCAMP	C-LA, SCAMP	D-LA, SCAMP		

NOTES: LA-L signifies Level A suit used with LITPAC rebreather.
ctrl – experimental control (i.e., no cooling system).
Phase I ended on Thursday of week 2.
* - "best" cooling system identified in Phase I.
SCAMP included after initial experimental design was complete.

Actual experimental design resulting from project exigencies (see text for explanation)

Week No.	Monday	Tuesday	Wednesday	Thursday	Friday
1	A-LA-L, ctrl	B-LA-L, PCV	C-LA-L, ctrl D-Mk1	A-LA-L, PCV B- Mk1	C-LA-L, LCV D-LA-L, PCV
2	A- Mk1 (aborted) B-LA-L, LCV	C- HAILSS D-LA-L, HW A- Mk1	B-LA-L, ctrl	C-LA-L, HW	
3				A-LA-L, HW D-LA-L, LCV	C-LA-L, PCV
4	A-LA-L, LCV D-LA-L, ctrl	C-LA-S, ctrl		C- LB, HW A-LA-S, PCV	B-LA-S, LCV
5	B- LB, LCV D-LA-S, PCV	A-LA, SCAMP C-LA, SCAMP	B- JSLIST, PCV D-LA, SCAMP	A- JSLIST, ctrl C- JSLIST, HW	D- JSLIST, LCV B-LA, SCAMP
6		A- LB, PCV D- LB, ctrl C- Mk1			

NOTES: LA-S signifies Level A suit used with SCBA.
Equipment and personnel unavailability along with subject illness accounted for days in which runs did not occur.

Experimental Conditions: Environmental conditions were selected to reflect some of the more extreme environments CBIRF personnel are exposed to during training and operations. Air temperature (T_{air}) = 37°C and relative humidity (RH) = 75% were chosen to reflect hot summer days in Southeastern United States. Workloads were imposed to reflect the physical tasks performed by CBIRF personnel in the field. CBIRF personnel perform many of their field tasks while wearing CPOG's including walking from vehicles to a contaminated site, carrying equipment into and about the site, and dragging injured individuals from the site. To simulate these activities, subjects attempted to complete four consecutive rest/work cycles comprised of 5 min of rest (R period) followed by 25 min of light to moderate work (figure 1). These work periods were comprised of three 5-min bouts of treadmill walking (4 – 5.6 km hr^{-1} (2.5 to 3.5 mph) at 5% grade) (T period) interspersed with two 5-min periods of carrying weights (two 11.3 kg (25 lb) barbells) repeatedly across the chamber (W period). Subjects carried weights across the chamber only on alternating walks during W periods because of excessive strain on their hands and forearms. Brisk walking to and fro across the chamber (a total distance of approximately 15 m) replaced treadmill exercise in 9 of 36 runs because of treadmill failure.

Instrumentation: Two temperature probes (model 4491E, Yellow Spring Instr., Yellow Springs, OH) inserted 10 cm anterior to the anal sphincter measured rectal temperatures (T_{re}) during exposures. Four skin surface temperature probes (model 4499E, Yellow Spring Instr., Yellow Springs, OH) measured upper left chest (T_{chest}), upper right arm (T_{arm}), anterior thigh (T_{thigh}), and lateral shin (T_{shin}) temperatures. Temperature probes were interfaced with VitalSense temperature telemetry systems (Mini Mitter Co., Sunriver, OR). In addition, inlet and outlet airstream temperatures and air temperatures just behind the visor were measured within the LITPAC and SCBA masks with 36 AWG (.05 mm dia.) type T thermocouples. Thermocouple signals were collected and processed with a thermocouple data logger (model SmartReader Plus 6, ACR Systems, Surrey, BC, Canada). The temperature measurement system was calibrated at two points with a constant temperature (29.7718°C) Gallium cell (model 17402, Yellow Springs Instruments, Yellow Springs, OH) and a zero-point (0°C) cell (model K140-4, Kaye Instruments, Bedford, MA). Heart rate was displayed on an ECG monitor (model Visa II, Datascope, Inc., Paramus, NJ) and recorded with a heart rate monitor (model Xtrainer Plus, Polar Electro, Kempele, Finland). Clothed and nude body weights were measured with an electronic scale accurate to ±50 g (model FV-150K, A&D Ltd., Tokyo, Japan).

Stress Measurements: Subject stress levels were assessed in three ways. Salivary amylase concentration has been shown to correlate with norepinephrine levels during physical (4, 21) and emotional stress (4, 17). Amylase levels were assessed in this study to provide a quantitative measure of intrinsic stress subjects underwent. Salivary samples were obtained before and immediately after thermal exposures and following a recovery period (approximately 1 hr) subsequent to chamber egress. Quantitative analysis of salivary amylase concentration was performed according to established procedures (4). Likewise, two self-assessment tests of stress perception, the Multiple Affect Adjective Check List – Revised (MAACL-R) and the National Aeronautics and Space Administration (NASA) Task Load Index (TLX), were administered during trials. MAACL-R assessments describe the subjective state of an individual across five indices and were obtained before, during, and after exposures to thermal stress. TLX tests assess the relative stress each task (cognitive or physical) imposes on the individual and were imposed during and immediately following exposures and after a recovery period of approximately 60 min. MAACL-R and TLX test results were scored and analyzed by the Army Research Laboratory. Subjects were asked to subjectively rate their comfort, sweating, fatigue, and temperature (comfort scores) on a seven point scale every 15 min. Comfort, sweating, and fatigue were reported using a scale of increasing distress (e.g., for fatigue: 1 = very rested and 7 = extremely exhausted) and temperature was reported as 1 = very cold, 4 = neutral, and 7 = very hot.

Multiple Affect Adjective Checklist-Revised. The MAACL-R General or "Trait" form (23) consists of 5 primary subscales (Anxiety, Depression, Hostility, Positive Affect, and Dysphoria or Negative Affect) derived from a 1-page list of 132 adjectives. Respondents are instructed to check all the words that describe how they "generally" feel. The "Today" form of the MAACL-R is a measure of individual stress perceptions. Its structure is identical to the trait form except that subjects are instructed to answer according to how they feel "right now" or how they felt during a specified time period or event. MAACL-R has been particularly suitable for investigations that postulate changes in specific affects in response to stressful environments because of the improved discriminant validity and the control of the checking response set. This standardized measure has demonstrated high construct validity within the stress research literature.

The National Aeronautics and Space Administration-Task Load Index. The NASA-TLX is a psychophysical technique for mental workload measurement that has sensitivity to different levels of task demand. The NASA-TLX provides an overall subjective workload score based on a weighted average of ratings on six subscales or dimensions: mental demands, physical demands, temporal demands, own performance, effort, and frustration (16). Each of six 20-point scales is believed to represent the underlying characteristics of subjective workload. At the conclusion of an event, subjects provide ratings on each of the six dimensions (see table 6 for rating scale definitions). Ratings from the scale are then weighted on the basis of data generated by the subject concerning the contributions of each dimension to the total workload associated with performance of a task. The weighted ratings are then combined to create an overall index of subjective workload (7). Although the physical demand of the task is included in the overall rating provided by the NASA-TLX, the index is not used as a measure of physical workload but instead recognizes the influence of physical activity on the perception of mental workload.

Table 6: NASA-TLX Rating Scale Definitions

Title	Endpoints	Descriptions
Mental Demand	Low/High	How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	Low/High	How much physical activity was required? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	Low/High	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	Good/Poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself?) How satisfied were you with your performance in accomplishing these goals?
Effort	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Experimental Exposures: Each subject generally reported to the laboratory at roughly the same time (early (7-9 a.m.) or late (10 a.m.–12 p.m.) morning) each day they participated. A brief physical exam and medical history was conducted when subjects entered the laboratory dressing area to begin each trial. Mean ambient air temperatures maintained inside this preparation area = 22.5° ±.2°C. An initial MAACL-R questionnaire was completed and comfort scores obtained while subjects provided saliva samples by chewing a small cellulose sponge for approximately 1 min. Saliva samples were then seperated into two vials and immediately frozen for susequent analysis. No TLX test was completed at this time because it was assumed that subjects experienced negligible stress. Seminude weight (with underwear and rectal probes) ($m_{i,nude}$) was obtained after subjects inserted their rectal probes. Four ECG electrodes attached to the upper torso were adjusted to obtain the clearest signal and skin thermocouples were taped to the subject (Transpore tape, 3-M, Minneapolis, MN). A Polar heart rate transmitter was placed on the chest after moistening the contact surface with water. The subject was then dressed in the remaining clothing items and the cooling and breathing systems mounted on the subject. Telemetry transmitters (i.e., VitalSense (temperature), Datascope (ECG)) were affixed to either the breathing apparatus (LITPAC, SCBA, and SCAMP) in LA runs or placed in a pocket for other CPOG runs. The ACR datalogger for collecting respiratory mask temperatures was mounted on the top of the LA breathing apparatus (mask temperatures were not collected during non-LA runs) at this time. The Polar wrist receiver was affixed to a chest strap just prior to sealing the CPOG. Computer data collection began roughly after the skin temperature probes were affixed to the skin but useful data collection (i.e., stable reliable data) generally began at approximately the t = -5 min mark. Clothed weight ($m_{i,clothed}$) was obtained immediately after garments were sealed and then subjects entered the chamber to begin experimental exposures.

Subjects entered the environmental chamber at t = 0 and began a series of up to four consecutive rest/work cycles. Chamber conditions for all runs were fixed at $T_{air} = 37.0 \pm 0.2°C$ and RH = 75 ± .7%. Subjects seated at a small table completed MAACL-R and TLX questionnaires and provided comfort scores (estimated metabolic rate =195 W assuming metabolic output for writing (11) given a mean clothed weight = 99.6 ± 8.2 kg) during the initial R period. At the end of 5 min, subjects began the first T period (estimated metabolic rate = 637 (13) -710 W (22)). Subjects were instructed to walk briskly across the chamber on those occasions when a treadmill was malfunctioning (estimated metabolic rate = 562-683 W at 4 mph (13, 22)). This represented a 4% decrease in workload with walking versus treadmill. Two alternating W (estimated metabolic rate = 746 W (3)) and T periods completed the first rest/work cycle. These rest/work patterns produced a mean estimated time-weighted metabolic rate of 572-636 W (assuming treadmill use) and represent a heavy (12) or continuous (13) workload while bearing 20 kg. Estimated metabolic rates for lighter garments (10kg) were approximately 10% less (11). The third R period was designated the time for replacing breathing apparatus or bottles. In practice, however, breathing system replacements often occurred prior to the third R period due to unanticipated high breathing rates. Ice bottles (LCV runs) were replaced when requested. Subjects were not provided water or food during exposures because drinking or eating are not provided for in the LA design and would require removing the CPOG. This is consistant with field conditions; drinking occurs prior to doning a LA CPOG or subsequent to its removal but not while wearing it.

Chamber exposures terminated when (a) subjects completed four rest/work cycles, (b) they requested removal, (c) T_{re} increased to 39°C, (d) a subject's sustained heart rate (HR) reached 90% of estimated maximum safe HR for age (220 - age in years), or (e) critical equipment failure occurred. Clothed weight ($m_{f,clothed}$) was obtained immediately upon exiting the chamber. A saliva sample was obtained as quickly as possible while most clothing items were removed. Subjects were then seated and rested for approximately 15 min while their T_{re} was monitored. Subjects were released to remove their rectal probes and take a shower once T_{re} dropped below 38°C. MAACL-R and TLX tests were completed at the start of the rest period and after subjects completed their shower. In addition, final seminude weight ($m_{f,\ nude}$) was measured after the shower and then subjects were medically cleared to leave the laboratory.

Physiological Indicies: Physiological temperatures were analyzed as differences (e.g., $\Delta T_{re} = T_{re,\ final} - T_{re,\ initial}$) over an exposure period because within-subject initial temperatures varied between exposures. Mean weighted skin temperatures were calculated using the method of Ramanathan (15):

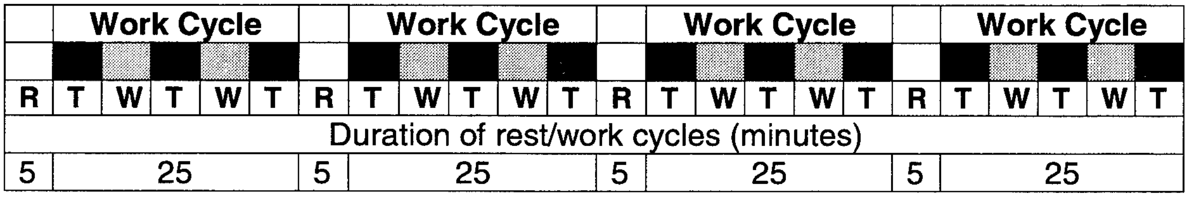
[1] $T_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{shin})$

Total sweat losses, SWL, including evaporation and dripping, was

[2] $SWL = m_{i,\ nude} - m_{f,\ nude} + \text{water consumed}$

and the amount of sweat absorbed by the clothing was calculated by

[3] $\Delta GW = (m_{f,clothed} - m_{f,\ nude}) - (m_{i,clothed} - m_{i,\ nude})$.



	Work Cycle						Work Cycle						Work Cycle						Work Cycle				
	■	▨	■	▨	■		■	▨	■	▨	■		■	▨	■	▨	■		■	▨	■	▨	■
R	T	W	T	W	T	R	T	W	T	W	T	R	T	W	T	W	T	R	T	W	T	W	T
Duration of rest/work cycles (minutes)																							
5	25					5	25					5	25					5	25				

Figure 1: Planned rest and work periods for an individual trial. Each rest or exercise period (R, W, or T) had a 5-min duration and total exposure times were intended to last up to 240 min. Subjects entered the environmental chamber at the start of rest period No. 1. Exchanging depleted breathing systems was intended to occur during rest period No. 3. R = rest periods, T = treadmill (or brisk walking), W = walking with two 25 kg weights across the chamber.

Data Analysis: The central hypothesis of this study was that at least one cooling system would generally enable users to tolerate exposures of greater than 60 min. Exposure tolerance was broadly defined as retaining the volition or physical ability to continue performing physical and mental tasks while exposed to experimental conditions. Independent variables were defined as the protective ensemble and cooling system. Dependent variables were T_{re}, skin temperatures, HR, sweat loss, salivary amylase concentration, and subjective stress assessments.

A sample size of four was chosen as a compromise between statistical power and study cost and duration. This sample size provides a statistical power, $1-\beta$, of 0.873 when using an analysis of variance to compare mean final T_{core} between four individuals exposed four times (once per clothing configuration) assuming the study detects T_{core} differences = 0.3°C with a SD = 0.1°C. Reducing the sample size to three subjects drops the statistical power of the paired-t test to $1-\beta$ = 0.745. The intent was to have a balanced experimental design for subsequent statistical analysis.

Disruption in the original experimental design limited only LA-L and Mk1 runs to an n=4. The remaining CPOG/cooling combinations (those using LB, JSLIST, Mk1, LA-S) have an n=1. Final values were tested for between-subject variability with a nonparametric Kruskal-Wallis analysis of variance (ANOVA). One goal in analyzing study data was to use each subject as their own control and eliminate between-subject variability. A nonparametric Friedman ANOVA was employed to analyze within-subject variability. When the ANOVA detected significant differences among configurations, a Newman-Keuls posthoc test was used to identify those configurations that differed significantly from the others. Linear correlation analysis was used to assess relationships between variables. Data are reported as mean value ± SD. Differences were considered significant at the $\alpha = .05$ level.

RESULTS

In general, study conditions did not identify any of the tested cooling systems as significantly more effective in mitigating the thermal stresses imposed by environmental conditions and physical workloads. Physical and mental tolerance, measured by exposure duration, and physiological responses to the thermal stresses were statistically indistinguishable by most measures with three factors causing the majority of run terminations: HR, fatigue, and breathing difficulties (appendix A). The HAILSS run was unique in terminating because of comfort related to fit. In general, however, CPOG/cooling system configuration did not significantly affect exposure durations (figure 2) as observed in both between-subject and within-subject analyses.

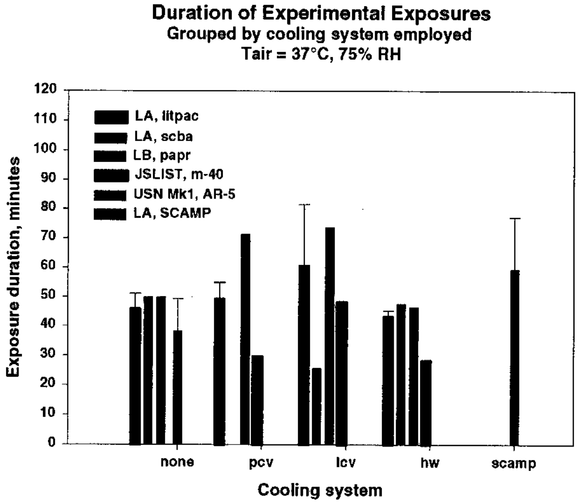


Figure 2: Exposure durations observed as a function of cooling system. Note that n=4 for LA, Mk1, and LA/SCAMP runs while n=1 for LA-S, LB, and JSLIST runs.

Though breathing gas temperatures in LA-L runs were deemed hot and many runs terminated for subjective intolerance to breathing hot air (appendix A), any breathing system effects were not determined to be statistically significant. Initially, subjects subjectively attributed short LA-L exposures to breathing heated air generated by the LITPAC rebreather. Soda lime contained in the LITPAC removes CO_2 from the exhaled airstream but the chemical reaction generates heat. This increases LITPAC temperature and the inhalation gases coming out of the unit. In contrast, SCBA consists of compressed air bottles; expanding breathing gas cools as it exits the bottles. There are no exothermic chemical reactions to generate heat in the SCBA breathing system. Comparison between LITPAC and SCBA mask inlet temperatures, however, indicated that breathing gas temperature was independent of breathing system while wearing a LA. Strong correlation of inlet mask temperature with ambient temperature (figure 3, $r^2 = 0.91$ (LITPAC), $r^2 = 0.81$ (SCBA)) demonstrated that mask inlet temperature was primarily a function of the interior LA air temperature. In addition, no significant differences in exposure duration, ΔT_{re}, total sweat loss, or sweat rate between LITPAC and SCBA runs were observed. Consequently, use of either the LITPAC or SCBA did not significantly affect exposure durations due to breathing gas temperature.

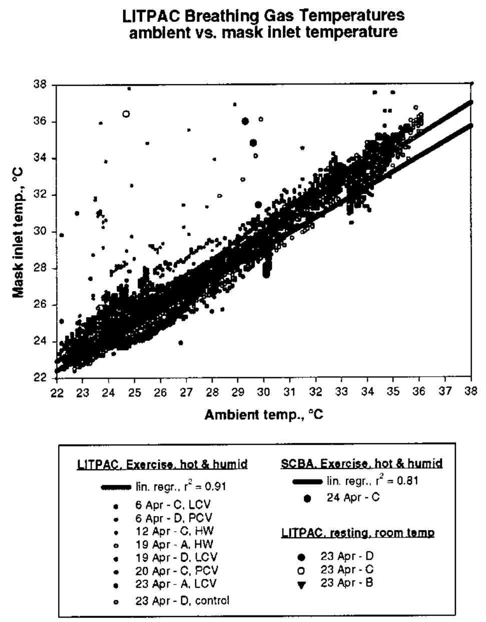


Figure 3: Relationship between breathing gas temperature and ambient temperature as a function of breathing system.

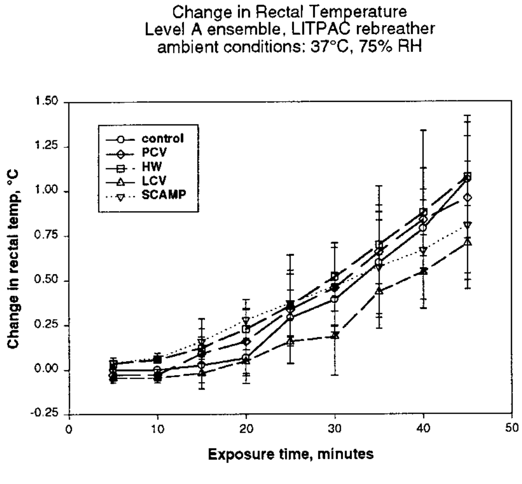


Figure 4: T_{re} changes over time as a function of cooling system. Data are given as mean ± SD.

<u>PHYSIOLOGY</u>: Overall, between-subject analysis demonstrated no significant ΔT_{re} differences between configurations (figure 4). Within-subject analysis, however, showed cooling systems effects were inconsistent with different systems producing the smallest ΔT_{re} depending on the subject. LA-L/LCV produced the smallest ΔT_{re} in subjects A (along with LA-L/PCV) and B. LA/SCAMP and LB/HW produced the smallest ΔT_{re} in subject C while LA-L/control and LA-S/HW generated the smallest ΔT_{re} in subject D.

Maximum HR did not vary significantly between configurations in between-subject or within-subject comparison. HR variation over the course of an exposure did not differ significantly overall nor within subject A and

B runs (figure 5). Mk1 produced significantly higher HR than all other CPOG/cooling system configurations during subject C runs. Likewise, subject D Mk1 runs produced higher HR than LA-L runs (except HW and SCAMP), LA-S/HW, and LB/control. Subject D LB/control also produced lower HR than LA/control, LA/SCAMP, or JSL/LCV. Not surprisingly, T_{re} correlated to heart rate ($r = .495$; $p = .003$).

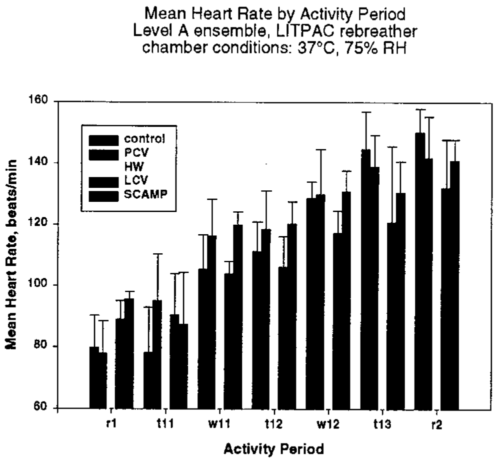


Figure 5: Mean HR's measured at the end of each activity period as a function of cooling system (LA runs only). Data given as mean ± SD.

Sweat losses did not vary significantly between CPOG/cooling system configurations when analyzed as either total sweat losses, % body weight loss, or sweat rate (table 7). Analysis of sweat loss was not able to differentiate between evaporation and liquid sweat as much of the sweat loss occurred postexposure during removal of the CPOG, especially when LA or LB were used.

Table 7: Observed Subject Tolerance and Physiological Temperature Changes during Experimental Exposures

		Duration (min)			Total Sweat Loss (kg)				Percent Weight Loss			
	n	mean	max	min	mean	max	min	SD	mean	max	min	SD
LA-L/control	4	45.8	51	39	0.87	1.1	0.58	0.21	1.1	1.3	0.7	0.3
LA-L /HW	3	43.1	45	41	4.78	0.59	2.32	2.19	2.8	5.7	0.8	2.5
LA-L /LCV	4	60.4	87	40	1.04	1.49	0.69	0.39	1.3	1.8	0.9	0.5
LA-L /PCV	4	49.2	56	45	0.56	0.99	0.71	0.12	1.1	1.2	1.0	0.1
LA /SCAMP	4	59.4	72	33	0.89	0	1.46	0.71	1.2	2.0	0	0.9

Mean skin temperatures were significantly lower during LA/LCV and SCAMP than LA-L/control across all subjects and generally lower than other configurations though these results were inconsistent among subjects. SCAMP generally maintained significantly lower ΔT_{thigh}, ΔT_{shin}, ΔT_{chest}, and ΔT_{arm} than other cooling systems (except LCV) in all subjects ($p<0.01$ in most cases). LCV also provided significantly better than other cooling systems in minimizing ΔT_{chest} and ΔT_{arm} (generally $p < 0.01$) but results for ΔT_{thigh} and ΔT_{shin} were equivocal. HW consistently produced significantly higher skin temperatures than the other runs ($P < 0.05$) while PCV results were inconclusive and more dependent on individual subject variations. Using either the LITPAC or SCBA did not significantly affect skin temperature changes. JSL runs produced significantly greater temperature increases in most runs compared to other configurations.

HAILSS produced significantly lower ΔT_{chest} and ΔT_{arm} than most other configurations but essentially equivalent ΔT_{thigh} and ΔT_{shin} in the single individual tested.

All four subjects experienced neck pain due to improper use of the support straps supplied with the LCV. Neck strain resulted from pump weight pulling the LA downward and causing subjects to walk stooped during exposures. Possible ECG abnormalities were also detected in one subject which delayed some of his exposures. A subsequent cardiac stress test indicated no underlying pathology and led to reinstating the subject to active participation.

SALIVARY AMYLASE: Moderate positive correlations were found between salivary amylase levels and T_{re} ($r = .459$; $p = .007$) and SA levels and HR ($r = .557$; $p = .001$). A within-subject analysis, however, showed that only one subject (A) produced a strong positive correlation between salivary amylase and T_{re} ($r = .833$; $p = .010$).

A strong positive linear correlation also exists between exercise duration and T_{re} ($r = .795$; $p < .001$). This relationship between duration and thermoregulatory response (i.e., physiological stress) suggests a linear correlation between a subject's salivary amylase level and exercise duration. The experimental data show that although this correlation was not significant, the pattern of responses is indeed in the expected direction ($r = .305$; $p = .085$).

No significant differences exist between nearly all the experimental conditions in terms of SA levels. Of the LA-L configurations, HW had the lowest mean SA value, but PCV produced the smallest range of SA values (suggesting individual differences may not be as important in this configuration). SA levels obtained from JSLIST/control and JSLIST/HW (Configuration Nos. 17 and 18 in figure 6) were significantly lower than the LA-L/control though both conditions were terminated after less than 25 min. Consequently, neither subject's T_{re} reached 38°C nor did they complete the first work/rest cycle. High SA levels would be unexpected in these two conditions given the other physiological measures.

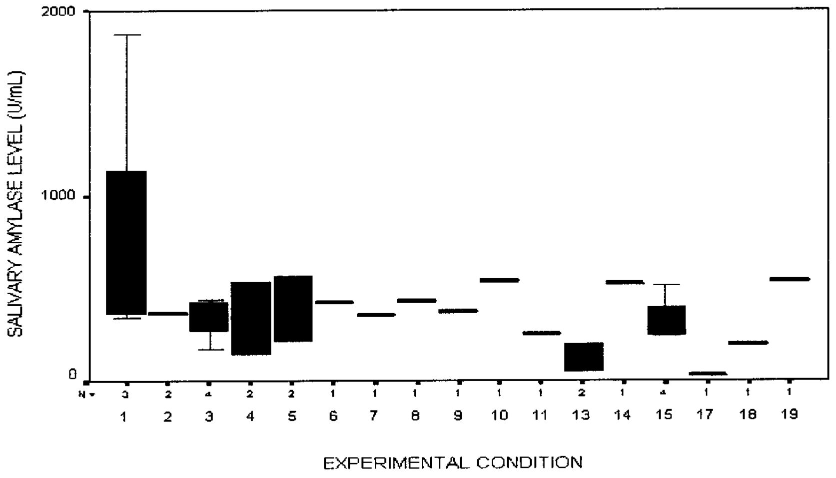


Figure 6: Observed salivary amylase concentration reported by configuration. Values are means (center bar) ± SD (box length) with minimum and maximum values indicated by bar length. Condition numbers are: 1-4 = LA-L/control, /PCV, /LCV, /HW; 5 = Mk1, 6 = HAILSS, 7-10 = LA-S/control, /PCV, /LCV, /HW; 11-14 = LB/HW, /LCV, /PCV, /control; /LCV, /HW; 15 = SCAMP; 16-19 = JSLIST/PCV, /control, /HW, /LCV.

SUBJECTIVE RESPONSES: No significant differences in comfort score sums were observed between configurations during the preexposure period or at the first rest period. A subjective ranking of cooling systems merit is given in table 8. These responses reflect retrospective subjective assessments provided by the subjects at the end of the study and are not based on any quantitative analysis.

Table 8: Subjective Cooling System Ranking and Overall Comments following Completion of Study

	Subject			
	A	B	C	D
Best	SCAMP	LCV	LCV	LCV
Worst	HW	HW	HW	HW
Subject comments	Given logistic considerations would prefer PCV	SCAMP worked best but not logistically feasible	Better training needed before using some systems	No comments

NASA-TLX: The NASA-TLX did not differentiate one configuration from the others in terms of combined workload score (CWS) (figure 7) and CWS did not significantly correlate to any physiological measure (table 9). However, CWS exhibited a moderate positive relationship with where the subject was in an exposure (i.e., NASA-TLX data were taken at each of the rest periods) (r = .415; p < .001). Spearman correlations were calculated to look at the relationships between all the TLX dimensions (mental, physical, effort, frustration, performance, and temporal) and the CWS. All NASA-TLX dimensions correlated significantly and positively with the CWS (table 10). The two dimensions showing a moderate relationship with the CWS are the physical (r = .558; p < .001) and the temporal (r = .491; p < .001) dimensions. It should be noted that the duration of the session did not relate significantly to the physical score (r = -.063; p = .736).

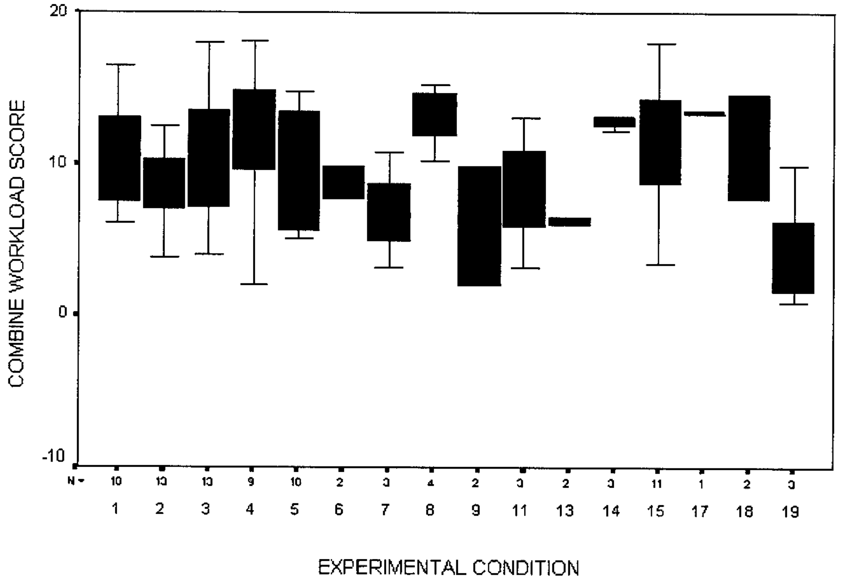


Figure 7: Reported NASA-TLX combined workload score by configuration. Values are means (center bar) ± SD (box length) with minimum and maximum values indicated by bar length. Condition numbers are those defined in figure 6.

Table 9: Correlations between CWS and Physiological Measures

	Combined Workload	
Temperature	r = .149	p = .476
Salivary Amylase	r = .004	p = .986
Heart Rate	r = -.182	p = .326
Duration	r = -.011	p = .952

Table 10: Correlations between CWS and NASA-TLX Dimensions

	Combined Workload Score	
Physical Weighted	r = .558	p < .001
Mental Weighted	r = .275	p = .008
Effort Weighted	r = .351	p < .001
Frustration Weighted	r = .358	p = .001
Temporal Weighted	r = .491	p < .001

The weighted physical dimension data (see figure 8) showed three conditions that are significantly different from the control condition. The subjects rated the LA-L/PCV configuration (No. 2) significantly lower in the physical component than the other configurations. Although not significant, the LA-L/PCV configuration is generally weighted lower in the other TLX dimensions than the control configuration. The LA-S/LCV configuration (No. 9) was also rated significantly lower for the physical dimension. This configuration only had one subject in the sample, but the subject performed the experiment for 71 min before the exposure was terminated.

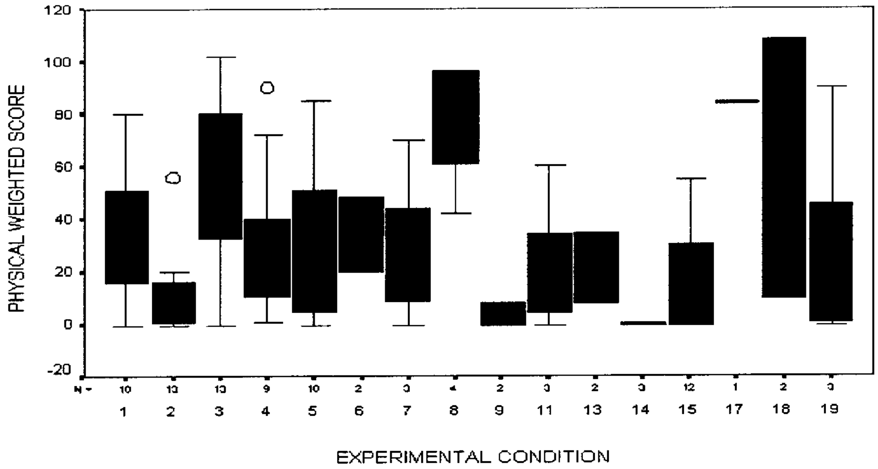


Figure 8: Physical weighted score obtained from NASA-TLX responses by configuration. Values are means (center bar) ± SD (box length) with minimum and maximum values indicated by bar length. Condition numbers are those defined in figure 6.

However, the LA-S/PCV configuration (No. 8) was rated significantly higher than the other configurations for physical workload. The higher score is limited only to the physical dimension and the other TLX dimensions do not show significant differences from the control means. One confound with the LA-S/PCV sample is that it is made up of one person, although this subject also performed the experiment for 73 min before termination. Therefore, the data from this trial may not be reflective of the targeted population.

MAACL-R: Personality Assessment: The MAACL-R Trait Form was used to provide information that could be used to screen for subjects whose personality characteristics were so extreme that they might be classified as displaying clinical abnormalities. None of the subjects were excluded by these criteria. Data from the trait measures (current subjects and established norms) are summarized in table 11.

Table 11: Mean MAACL-R Scores on Psychological Trait Measures

MAACL-R Measure	Mean score (±SEM)	NORMS
Anxiety	43.75 (.63)	51.0
Depression	45.75 (.25)	50.0
Hostility	45.5 (1.94)	50.0
Positive Affect	48.25 (5.31)	50.0
Dysphoria	43.25 (.95)	50.0

Stress Perception Assessment: The baseline stress perception measures were obtained from the subjects during a pretest time period as they were presented with administrative information about the study. Table 12 shows that Subject A scored higher than an independent control group on the Depression, Hostility, and Negative Affect subscales, and Subject C scored higher on the Anxiety and Dysphoria subscales.

Table 12: Individual Baseline Levels Based on the MAACL-R Subscales*

	Subject				Independent Control
	A	B	C	D	
Anxiety	58	45	70	58	48
Depression	71	47	47	47	50.3
Hostility	71	46	58	58	46.6
Positive Affect	49	51	42	47	49
Dysphoria	72	44	65	58	47.1

*The five primary subscales include: (a) anxiety, a measure of uncertainty; (b) depression, a measure of the individual's perceived failure to meet their expectations; (c) hostility, a measure of frustration level; (d) positive affect, a measure of perceived sense of well-being; and (e) dysphoria or negative affect, an overall distress score calculated from the anxiety, depression, and hostility subscales.

Comparative Metric for Stress Perception Levels: The assessment of the level and intensity of the individual's stress experience is accomplished by comparing results from the current study with data from other studies using identical psychological and physiological measures (see figure 9, a through d). These comparisons provide a method for estimating the relative stress experienced in a given situation and for studying the links between stress responses and performance in a variety of settings (8). For example, an independent control (INDEP CNTRL) was included as comparison data, representing a group of males investigated during normal work days when they were experiencing no unusual stress. The INDEP CNTRL group represents a relatively low stress level to a condition of no stress. Other groups represented in the following figures include (a) male soldiers representing elite units in marksmanship competition (WPN COMP); (b) noncommissioned officers participating in toxic agent training at the Chemical Defense Training Facility; (c) soldiers during field training exercises after a 48-hr period of sleep deprivation (SUSOPS); (d) military troops deployed within 24 hr to fight out-of-control fires at Yellowstone National Park (FIRE FIGHTING); and (e) Army recruiters throughout five brigades experiencing high levels of stress (RECRUITER). These data provide a metric with which to compare participants from the present study.

As shown in figure 9a, the anxiety levels of the CBIRF personnel were low, indicating that they were not experiencing any uncertainty about the performance of their tasks. The Depression subscale of the MAACL-R typically reflects the individual's perceived failure to meet personal expectations. Mean responses for subjects completing the "Work Cycle 3" period (figure 9b) indicate they were experiencing a moderate level of distress. However, the standard errors from that Work Period reflect a significant amount of variability in the responses. The findings from the Hostility subscale are similar to the Depression subscale results. As shown in figure 9c, the CBIRF personnel were experiencing moderate levels of hostility, indicating they were experiencing a fair amount of frustration during their time in the environmental chamber. Once again, the standard errors from the third Work Period reflect a significant amount of variability in the responses. The Positive Affect subscales typically reflect an individual's sense of well-being. As seen in figure 9d, the positive affect levels of the CBIRF personnel are significantly lower than those of the independent control group. It is interesting to note that, when compared with the responses from other situations, CBIRF personnel who made it through the third Work Period felt similar to the military personnel who were deployed for 29 days to fight fires.

Due to the high variability in stress appraisals seen for "Work Cycle 3," the individual data points for that Work Period are illustrated in figures 10 and 11 in order to provide some insight into the source of the variance. For both the Depression and the Hostility subscales, the responses from two of the three subjects (subjects B and D) were consistent. The variance in the mean responses for Work Cycle 3 may be due in part to the cognitive appraisals of Subject A.

EQUIPMENT: A number of equipment limitations and problems were detected during the course of the study. Most of these related to LCV and SCAMP hardware; HW and PCV were passive systems employing relatively simple technology. Both LCV and SCAMP cooling media provided for shorter exposure durations than initially anticipated. LCV ice containers typically lasted between 30-45 min before cooling became undetectable and needed replacement. In addition, one of the pump outlet hoses leaked after only 1-2 runs.

SCAMP bottles typically lasted approximately 30 min before requiring replacement, 50% less than an anticipated 60-min duration. Furthermore, there were significant problems with initially charging the SCAMP bottle; leakage in the charging unit caused excessive use of liquid nitrogen and compressed air bottles. Even when repaired, the SCAMP recharging unit required a minimum of one “K” bottle of compressed medical grade air per SCAMP bottle.

Other problems encountered during SCAMP runs included a malfunctioning SCAMP monitoring meter. This meter generally posed a problem even prior to failure because the meaning of meter output was not well defined. A SCAMP air bottle inlet coupling also failed, leading to rapid depletion of available breathing gas and requiring a rapid swapping of bottles. Poor garment fit led to crimping in the inlet tubing of the SCAMP lower extremity tube suit and diminished leg cooling during that run.

A common problem was the extreme discomfort associated with the LITPAC and SCAMP support straps. Narrow straps and the attachment points on the units caused the straps to dig into a user’s shoulders. In addition, subjects complained of the awkward position of the LITPAC weight on the back (see appendix A).

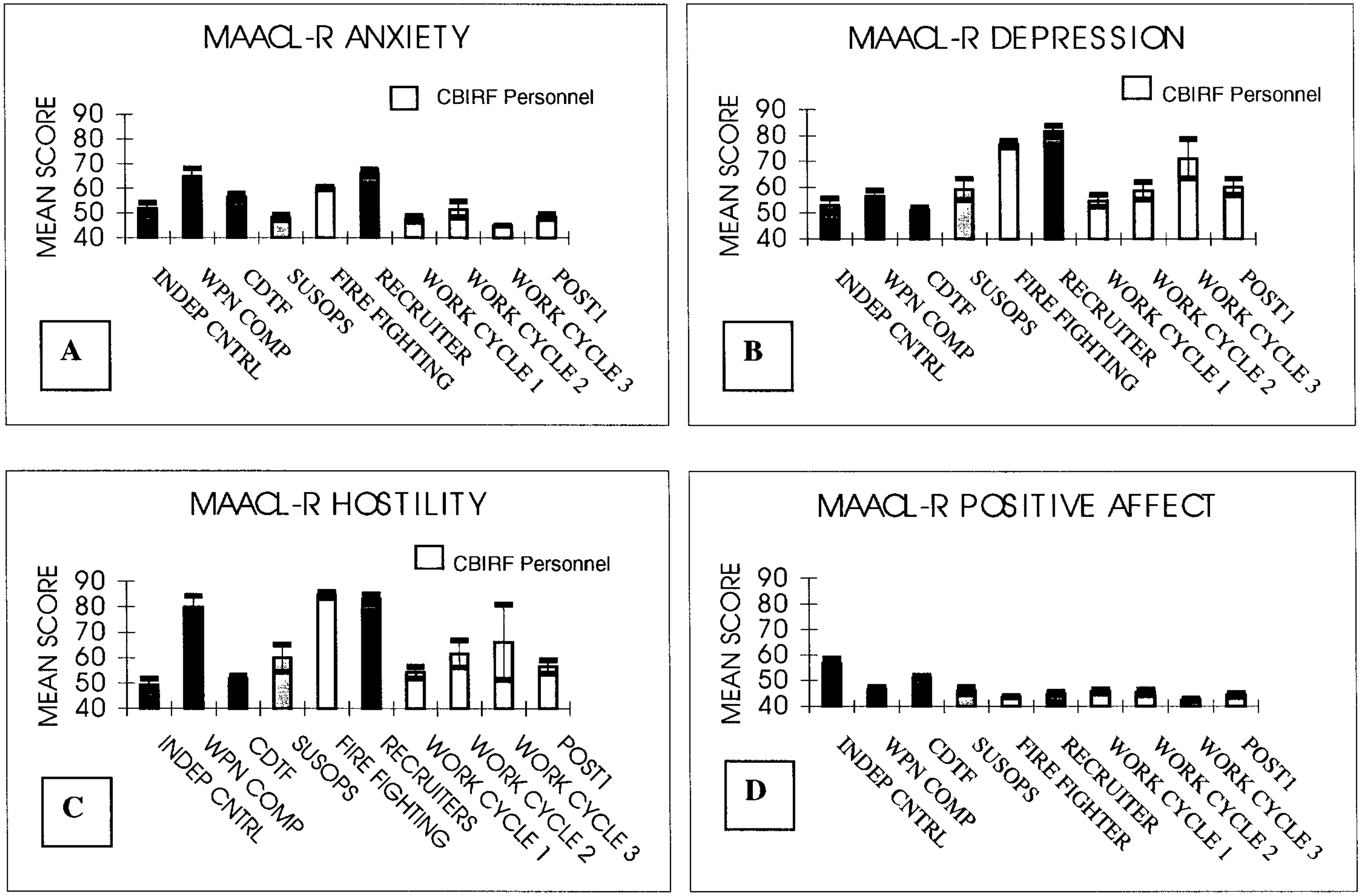


Figure 9: MAACL-R Anxiety (A), Depression (B), Hostility (C), and Positive Affect (D) levels (means and standard errors of the means (SEM's)) from the CBIRF personnel who completed three full work periods within the environmental chamber. Their responses are compared with stress perceptions of soldiers involved in elite weapon competition, chemical decon training, sustained operations, fire fighting, and recruiting stressors.

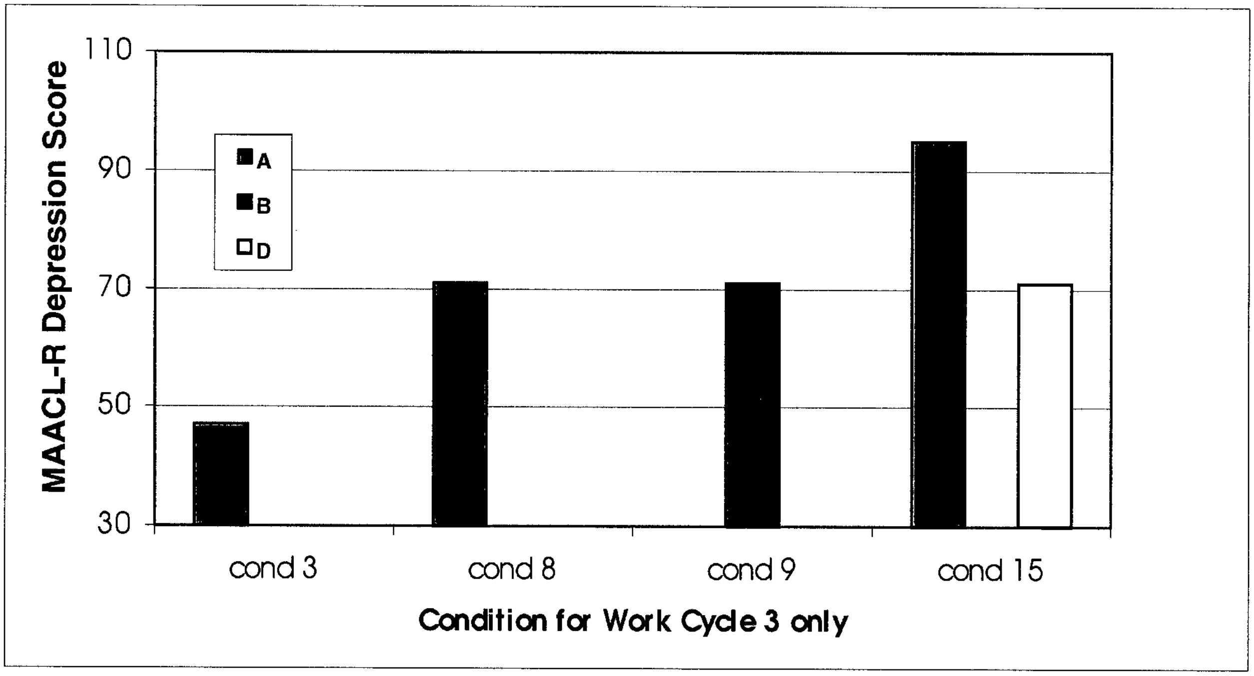


Figure 10: MAACL-R Depression levels of the subjects who remained in the environmental chamber through Work Cycle 3.

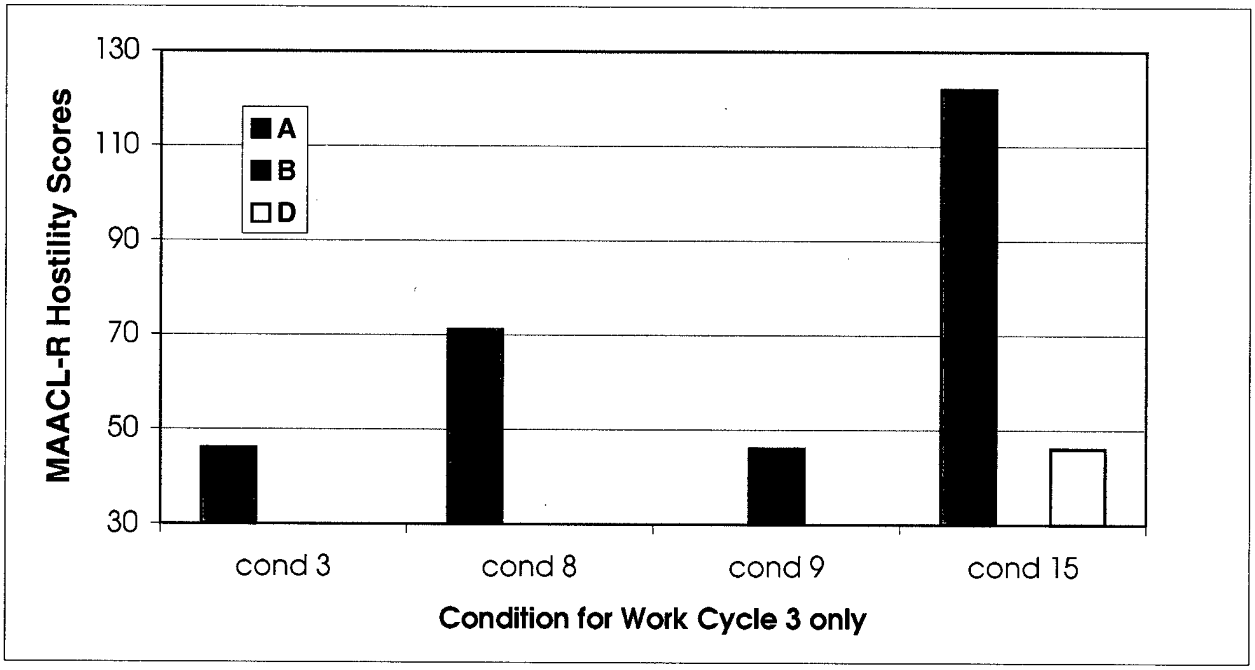


Figure 11: MAACL-R Hostility levels of the subjects who remained in the environmental chamber through Work Cycle 3.

DISCUSSION

None of the cooling systems tested in this study provided significantly greater protection in terms of extending exposure tolerance or minimizing the risk of heat injury. Physiological stress, as reflected in HR and salivary amylase data, also appeared unaffected by cooling system. Even overall comfort scores were unable to differentiate between cooling systems. HR and fatigue do reflect, however, the physical strain imposed by environmental conditions, physical tasks performed by subjects, and the burden of wearing heavy, bulky garments with additional weight imposed by cooling systems.

These equivocal results may reflect the severity of test conditions; wearing a LA in a hot/humid environment while exercising may overwhelm the cooling capacity of any of these systems. The intent of the study, however, was to identify cooling systems which might alleviate heat stress under the most dangerous environmental conditions by exposing subjects to extreme conditions. Dry bulb temperatures often exceed 37°C in much of the U.S. (e.g., approximately 5% of August days in Meridian, MS exceed 38°C (9)), so air temperatures used in the study are relatively conservative for a worst case scenario. The temperature/humidity combination used in this study is high (heat index (HI) = 144 (1)); only selected international geographic regions approach these combined high temperature/high RH on a regular, albeit uncommon, basis (e.g., Manama, Bahrain; Gwalior, India (2)). Humidity levels and consequently HI in the U.S. are typically lower but excursions approaching these levels can occur. This extreme hot/humid environment seems to reflect extreme but realistic conditions for CBIRF personnel wearing chemical protection and are the very conditions in which a cooling system becomes essential.

Humidity, however, should only affect heat exchange in vapor permeable garments (i.e., JSLIST, Mk1); thermal conditions within LA and LB should be unaffected by ambient humidity because evaporation cannot occur across the impermeable material. Consequently, HI values are meaningless in assessing potential heat stress in individuals wearing impermeable clothing. This suggests a need for a new heat stress/strain index and exposure guidelines for users of impermeable clothing in hot environments.

Predominantly testing in the LA may have also biased results. The configuration most used in the study (LA-L) represented extreme conditions for CBIRF personnel who generally use either the LB or JSLIST CPOG's. LA-L use conformed CBIRF's desire to expose subjects to a worst case scenario. However, it could be argued that this choice biased test results by creating overwhelmingly stressful conditions due to weight, bulk, or permeability. Insufficient data precludes a definative response but the limited JSLIST and LB data suggests that using these more permeable or lighter garments did not appreciably improve heat stress. A more complete evaluation of heat stress in these garments may be merited despite previous and ongoing studies (10, 14, 18, 20) because the combination of heavy exercise/high humidity has generally not been studied.

Likewise, use of LITPAC was feared to bias results because breathing gas gradually warms after repeatedly traversing the soda lime bed to extract CO_2. Using relatively cooler SCBA compressed air, however, did not mitigate T_{re} increases. It seems likely that heat transfer occurs as breathing gases travel from the gas source (LITPAC, SCBA) to the breathing mask because the gas is cooler than the surrounding atmosphere. Breathing gas warms as atmospheric heat is transferred to the tubing connecting the gas source and mask as noted in figure 3. Inhaling this warm gas limits respiratory heat exchange and diminishes a potentially significant source of body cooling. Insulating SCBA tubing might mitage this problem by allowing cooler breathing gas to reach the respirator mask and improve overall body cooling. SCAMP potentially provides cooler air to the respirator though mask temperatures were not. The large number of runs terminated due to breathing related complaints (appendix A) suggests that breathing system improvements may provide tremendous benefits in extending tolerance of hot/humid environments.

A major goal of this study was to impose workloads and conditions that mirror field conditions. Subjects noted that the study workloads (treadmill walking, weight bearing) provided a reasonable approximation of field workload demands but dragging a heavier weight (approximately 50-100 kg) rather than bearing weights upright would better reflect field conditions. In addition, subjects noted that temperature and humidity were high but not unrealistic.

Liquid cooled systems (LCV and SCAMP) appeared to reduce skin surface temperatures but did not appreciably retard rising core temperatures. The general sense of approval given to LCV and SCAMP indicated in table 8 probably reflects greater comfort due to lower skin temperatures. It was therefore surprising that comfort scores did not reflect these results and did not differentiate between configurations. These results suggest that benefits from liquid cooling are generally independent of the source of cooling. SCAMP tended to produce somewhat cooler skin temperatures than LCV, but generally their performance was similar. It is unclear whether the increased complexity of the SCAMP system is merited until a more detailed assessment of respiratory heat exchange is made. In contrast, passive cooling systems (PCV, HW) did not provide a noted improvement over the control condition of no cooling with regard to rectal or skin temperatures, HR, or comfort scores.

Sweat loss was also indistinguishable between cooling systems. Given similar thermal burdens represented by equivalent ΔT_{re}, sweat output would likely be equivalent. Cooling efficiency would improve if some of this sweat can evaporate. Unfortunately, none of the non-APACS cooling systems have any mechanism to actively extract water vapor from the microenvironment within a CPOG. Consequently, sweat loss during exposures depended entirely on diffusion which was impossible in the impermeable LA and LB, and limited in the JSLIST and Mk1 because the activated carbon acts as a sink for water. Improving evaporative cooling in these CPOG's has limited potential because LCV, PCV, SCAMP, and HW depend on conduction as their primary heat exchange mechanism. While HW employs evaporation, it is not evaporating sweat but using conductive heat exchange with the skin to evaporate water trapped in HW fibers.

The salivary amylase correlations are very similar to the predicted results. Salivary amylase release has been shown to correlate highly with body temperature. It is not surprising to see the correlation between body temperature and HR since increased body temperature induces a homeostatic response resulting in an increase in peripheral circulation. Since correlations were found between HR and temperature with session duration, a significant correlation between duration and amylase activity was expected. That was not the case. One possible explanation for this is that salivary amylase is a measure of both mental and physical stress.

In addition to correlating with the physiological indices, amylase was significantly correlated with the responses from the MAACL-R Anxiety subscale. Although physical stress would continue to rise over the duration of the session, the anxiety or levels of uncertainty of the subjects remained low. It is possible that salivary amylase levels were similar from the time the subject dressed to the time the subject undressed. The sources of that stress are different throughout the session. One possible way to confirm or deny this hypothesis is to take another baseline reading right before the subject enters the chamber (suit limitations might prevent this), and again at each rest break. However, we cannot draw strong conclusions from salivary amylase data because of confounds added by the small and different sample sizes. One other limitation in the salivary amylase data is that the premeasure was taken well in advance of the subject suiting up.

The NASA-TLX data show that not many significant differences exist between the suits configuration in terms of combined workload score. The data also suggests that the gradual CWS increase is related mostly to the weighted physical score and the weighted temporal score, given the moderate relationships that exist between those dimensions. The correlation between frustration and the physical score suggests that the subjects felt less frustration when they were exerting themselves. The subjects may have felt that if they were actually exercising in the suit configuration that everything was going well (as opposed to some of the configurations where subjects lasted less than one work/rest cycle). This finding was also supported by the significant positive correlations between positive affect and HR. The subjects' HR increased as their sense of purpose increased.

Not surprisingly, the MAACL-R also produced no results that would differentiate one suit from another. The significant results found in the within-subjects analysis are probably the results of the subject's individual likes, dislikes, and experiences (e.g., problems with the straps on the SCBA) than a result of the suit itself, and not a product of the suit itself.

When defining an experience as difficult or stressful, it is necessary to look beyond the specific conditions and recognize the mediating effects of specific characteristics and resources of the individuals involved. Although all the subjects in this study experienced low levels of anxiety throughout the exercise, there were individual differences in their baseline appraisals of two other critical components of stress, depression (sense of failure to meet expectations or demands) and hostility (sense of frustration). Some of the subjects' baseline scores were higher than their scores for testing the different configurations. It appears that for this particular sample, the effect of individual differences in stress perception was a more dominant contributor to distress than the effect of system configuration.

One positive aspect of impermeable material was the insulation it apparently provided for roughly the first 20 min of exposure. Subjects had relatively low HR and ΔT_{re} at the first rest period during LA-L/control runs, probably reflecting relatively cool air trapped within the LA during dressing. This contrasts with the immediate discomfort felt in the permeable Mk1, semipermeable JSLIST, and ventilated HAILSS upon entering the hot/humid atmosphere. This may suggest development of a variably permeable CPOG that can trap relatively cool air and passively extend exposure times.

CONCLUSIONS

None of the cooling systems provided a distinct advantage in the hot/humid environment with an imposed exercise regime. Consequently, individuals wearing impermeable garments in high heat/humidity conditions appear vulnerable to heat injury even when using one of the tested cooling systems. Defining heat exposure limits, therefore, appears necessary to provide some degree of protection against heat exhaustion and heat stroke for personnel wearing impermeable garments.

Passive cooling systems provide no apparent benefit over no cooling when used with an impermeable garment in extremely hot/humid environments. Liquid cooled systems may provide some benefit over no cooling but equivocal results suggest further study. SA and NASA-TLX results suggest LCV or PCV may have advantages over control and HW.

Breathing plays a major role in determine tolerance to hot/humid exposures. Choice of LA breathing system (LITPAC and SCBA), however, did not appear to affect outcome though the SCBA sample was very small.

Clear instructions and adequate training are required to avoid improper use of cooling systems. Inadequate quality control can hamper cooling system effectiveness.

Stress results conform with the physiological data in that it does not clearly identify one configuration as superior to the others. Consequently, no cooling configuration recommendation can be made from this data. This study should be treated as a pilot study, and a repeat experiment conducted with a larger sample size, as well as using the same sample size for each configuration. A new study could eliminate many confounds introduced in this experiment that prevented us from drawing strong conclusions from the data.

Although all the subjects in this study experienced low levels of anxiety throughout the exercise, there were individual differences in their baseline appraisals of two other critical components of stress, depression and hostility. Some baseline levels were higher than the levels obtained during testing the different configurations. It appears that, for this particular sample, the effect of individual differences in stress perception was a more dominant contributor to distress than the effect of system configuration.

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APPENDIX A
SUBJECT POSTEXPOSURE COMMENTS

(Note: comments in order subject gave them)

Subject	Date	Configuration				Subject Comments
		CPOG	Cooling	Breathing	Exercise	
A	2 Apr 01	LA	none	LITPAC	Treadmill	<u>Cause of run termination: fatigue</u> No recorded comments
B	11 Apr 01	LA	none	LITPAC	Treadmill	<u>Cause of run termination: hot</u> "head was pounding", pressure was building in head
C	4 Apr 01	LA	none	LITPAC	Treadmill	<u>Cause of run termination: breathing</u> a. "couldn't get enough air" b. "winded" , felt couldn't keep up with treadmill c. "air warm", "at least a 7" on a 1-10 scale
D	23 Apr 01	LA	none	LITPAC	Treadmill	<u>Cause of run termination: dizziness</u> No recorded comments
A	19 Apr 01	LA	HW	LITPAC	Walk	<u>Cause of run termination: fatigue</u> a. subject exhausted b. LITPAC uncomfortable c. Irritable d. Dislikes HW, felt like it failed to cool shortly after starting run
B		LA	HW	LITPAC	Treadmill	Not run
C	12 Apr 01	LA	HW	LITPAC	Walk	<u>Cause of run termination: fatigue</u> Subject exhausted
D	10 Apr 01	LA	HW	LITPAC	Treadmill	<u>Cause of run termination: hot</u> a. "just too hot – had trouble breathing that hot air" b. "vest felt like it stopped cooling during the second treadmill"
A	23 Apr 01	LA	LCV	LITPAC	Walk	<u>Cause of run termination: rectal temperature</u> Neck hurt
B	9 Apr 01	LA	LCV	LITPAC	Treadmill	<u>Cause of run termination: fatigue</u> a. suit felt cool but weight made it burdensome the whole time b. kept bumping switch and accidently turning off pump c. no head cooling, felt like head "was burning up"
C	6 Apr 01	LA	LCV	LITPAC	Treadmill	<u>Cause of run termination: hot</u> "cooling still working but kept getting hotter"
D	19 Apr 01	LA	LCV	LITPAC	Walk	<u>Cause of run termination: heart rate</u> a. pulled suit down on neck from weight of cooling unit b. webbing did nothing to alleviate weight from suit c. sensation of cooling ceased after second rest period d. felt good on head
A	5 Apr 01	LA	PCV	LITPAC	Treadmill	<u>Cause of run termination: heart rate</u> a. Felt good immediately prior to run termination b. "feels great" at minute 23 into exposure
B	3 Apr 01	LA	PCV	LITPAC	Treadmill	<u>Cause of run termination: breathing</u> a. breathing gas too hot, "felt like burning my lungs" b. "face, arms, legs extremely hot but torso cool"

Subject	Date	Configuration				Subject Comments
		CPOG	Cooling	Breathing	Exercise	
C	20 Apr 01	LA	PCV	LITPAC	Walk	Cause of run termination: breathing a. subject exhausted b. didn't feel had enough O2 per breath c. warning bell was irritating d. vest worked for a while e. didn't feel cooling f. didn't think much of it g. torso felt cool, arms and legs extremely hot
D	6 Apr 01	LA	PCV	LITPAC	Treadmill	Cause of run termination: heart rate a. feet are hot, nothing else really hot b. much better than other runs c. vest felt really good
A	1 May 01	LA	SCAMP	SCAMP	Treadmill	Cause of run termination: empty gas bottle a. works like LCV b. no cooling in legs c. no pressure in breathing air, like breathing through M-40 mask, can't catch breath d. hood does not seem to provide added cooling e. no air supply when bottles swapped f. gauges complicated, made no sense g. concerned about quality control, leg cooling didn't work h. suit fit somewhat loosely, straps cinched underwear down significantly i. no circulation in leg tubing j. feels good physically k. "I feel a little better than other runs" l. straps dug into shoulders
B	4 May 01	LA	SCAMP	SCAMP	Treadmill	Cause of run termination: fatigue Felt drained, exhausted
C	1 May 01	LA	SCAMP	SCAMP	Treadmill	Cause of run termination: empty gas bottle a. exhausted b. couldn't breath c. hot d. no saliva e. "shoulders killing me" f. felt dazed at end of run g. there was air but gasping for breath h. completely dried out mouth i. "didn't feel cool" j. felt cold patches periodically k. didn't like SCAMP l. better than others except LCV – except for breathing m. felt like at end of exercising – when you just can't get enough air
D	2 May 01	LA	SCAMP	SCAMP	Treadmill	Cause of run termination: breathing a. suit freezing with open bypass, especially head b. couldn't get enough air to breath, just toward end of run c. pack was uncomfortable, poor fitting d. felt like breathing CO_2, hyperventilating e. didn't feel cooling until bypass opened f. felt cooling all over body g. leg tubing didn't have good contact

Subject	Date	Configuration				Subject Comments
		CPOG	Cooling	Breathing	Exercise	
A	26 Apr 01	LA	PCV	SCBA	Walk	Cause of run termination: fatigue a. "today felt hotter" b. "worked my ass off" c. "burning inside" d. has to keep mouth open with SCBA e. torso felt cool, arms and legs felt like burning f. "hell of a lot better than LITPAC" g. always liked vest h. SCBA much more comfortable, easier to do things while wearing it
B	27 Apr 01	LA	LCV	SCBA	Walk	Cause of run termination: equipment problems a. Feels good b. Shoulders are sore
C	24 Apr 01	LA	none	SCBA	Walk	Cause of run termination: heart rate a. felt cooler than LITPAC b. bled air to cool suit c. felt lighter d. "felt a lot better"
D	30 Apr 01	LA	HW	SCBA	Treadmill	Cause of run termination: heart rate a. felt pretty good b. "hotter than usual", "sweating more than usual"
A	10 Apr 01	Mk1	none	MCK-3/P	Treadmill	Cause of run termination: heart rate "can't breathe worth a damn"
B	5 Apr 01	Mk1	none	MCK-3/P	Treadmill	Cause of run termination: mask fit "when breathing, whole mask would collapse on head, nose cup would collapse on mouth so I couldn't breathe"
C	8 May 01	Mk1	none	MCK-3/P	Treadmill	Cause of run termination: breathing a. felt he couldn't exhale out of mask b. couldn't breathe in fresh air c. felt he was inhaling expired air [exhalation valve was checked during run and was open] d. mask didn't fit face e. feels angry
D	4 Apr 01	Mk1	none	MCK-3/P	Treadmill	Cause of run termination: heart rate a. felt relatively comfortable, no particularly uncomfortable part of test b. liner itchy, "feels like wool" c. mask didn't fit right d. tape sites [skin temperature] burned at first
A	8 May 01	LB	PCV	PAPR	Treadmill	Cause of run termination: instrumentation problems No recorded comments
B	30 Apr 01	LB	LCV	PAPR	Treadmill	Cause of run termination: breathing, hot a. subject can't breath, visibly distressed b. felt nausea leaving chamber c. was "too hot at first rest period" d. "felt hot to breathe" e. "too hot to get oxygen" f. worst of all runs g. air initially cool "but it felt hot after 2 min into first rest period"
C	26 Apr 01	LB	HW	PAPR	Walk	Cause of run termination: fatigue a. subject exhausted b. felt dizzy, headache c. "feel tired, winded" d. couldn't hold up head e. mask on too tight f. telemetry packs in way of swinging right arm

Subject	Date	Configuration				Subject Comments
		CPOG	Cooling	Breathing	Exercise	
D	8 May 01	LB	None	PAPR	Treadmill	Cause of run termination: heart rate Just hot
A	3 May 01	JSLIST	none	M-40	Treadmill	Cause of run termination: breathing a. had trouble breathing, "air so thick in there" b. much harder to breath through M-40 mask than any other breathing system c. "not tired, just could not breathe"
B	2 May 01	JSLIST	PCV	M-40	Treadmill	Cause of run termination: breathing a. too hard to breathe b. "felt no cooling whatsoever" c. felt vest when first going in, nothing after that d. felt fine just couldn't breathe e. felt a sudden change for worse when starting third treadmill f. upper torso felt "wet" heading into second treadmill
C	3 May 01	JSLIST	HW	M-40	Treadmill	Cause of run termination: breathing a. "couldn't breathe, too hot" b. mask seemed to slip down c. vest did not feel cool d. "a few minutes after entering the chamber, I couldn't feel it [vest]"
D	4 May 01	JSLIST	LCV	M-40	Treadmill	Cause of run termination: heart rate a. feels pretty good b. Second bottle didn't feel as good or effective as first bottle c. No cooling to arms except when bent, cooling at elbow only [observer felt pump pulse in one hose but not the other] d. did not have trouble breathing e. easy to walk with harness f. arms were only problem
C	10 Apr 01	HAILSS	APACS	APACS	Treadmill	Cause of run termination: discomfort, fit a. subject exhausted b. rectal probes pulling while walking on treadmill c. couldn't breathe through nose, mask not properly fitted d. felt cool before entering chamber to about the waist level, felt hot shortly after entering chamber, felt cool again after exiting chamber

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