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THERMAL STRESS IN SEVEN TYPES OF CHEMICAL DEFENSE ENSEMBLES DURING MODERATE EXERCISE IN HOT ENVIRONMENTS

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NOTICES

The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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United States Air Force (USAF) personnel must perform their duties in many operational environments, including those with the potential for contamination with toxic chemical warfare (CW) agents. This study evaluated the physiological response to thermal stress in subjects performing moderate work in current and prototype chemical protective garments including the Battle Dress Overgarment (BDO)+BDU, BDO without BDU, United Kingdom (UK) undercoverall+BDU, Gore-Tex rainsuit+PJ-7 undercoverall, Marine Light Fighter Suit (MLFS), CWU-77P, PJ-7 alone, and the BDU alone. Experimental conditions were dry bulb temperature of 40°C (104°F), a wet bulb temperature of 27°C (80.6°F), and a black globe temperature of 45°C (113°F). Eleven subjects walked on a treadmill at 3 mph with a 5% grade incline until rectal temperature (T_{re}) rose 1.5°C (2.7°F) above the starting value. Heart rate, rectal and mean skin temperature, and body heat storage were monitored continuously. Sweat evaporation and production were determined from the differences between pre- and postexperiment clothed and nude weights. Significantly longer work times, lower heart rates, lower T_{msk}, and lower heat storage, were seen in the group comprised of the BDU, MLFS, CWU-77P, and PJ-7 compared to the Gore-Tex with PJ-7, UK plus BDU, BDO+BDU, and BDO no BDU ensembles. Suits which resulted in shorter tolerance times also caused higher rates of sweat production and lower % sweat evaporation than the less physiologically burdensome suits.

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INTRODUCTION

United States Air Force (USAF) personnel must perform their duties in many operational environments, including those with the potential for contamination with toxic chemical warfare (CW) agents. These agents can appear in liquid, vapor, or aerosol states with incapacitating or lethal effects and remain in the environment from minutes to weeks. Protective clothing is a necessity for isolating personnel from contact with these chemical agents. Most chemical defense ensembles (CDEs) used today address the need for preventing skin contact with chemical agents by creating either toxic barriers or sumps through repellent fabric coatings that resist noxious liquids and impregnated activated charcoal granules that adsorb toxic vapors.

In addition to providing exposure protection, protective clothing should ideally provide minimal interference with task performance and comfort; this goal has yet to be achieved. The single greatest physiological problem imposed by these ensembles is thermal stress, followed by problems of deterioration in visual and mechanical performance (1,2). The major factor limiting sustained performance in hot or warm environments is the increase in body temperature and the resultant fatigue. Physical and mental performance quickly deteriorate once critical body temperatures are reached (3).

Mathematical models have been used to predict the expected degrees of heat stress. In a 1988 review article, Parsons (4) summarized the current theoretical modeling approaches to clothing effects on physiological heat balance. Most models predict heat storage to be the sum of metabolic heat minus effective work, evaporative, and dry heat transfer mechanisms. Clothing is modeled as a factor that reduces heat transfer over the percentage of the body surface covered. This reduction is through added insulation which decreases dry heat transfer and by diminished water vapor permeability and poorer evaporative heat loss. Both vapor pressure and thermal gradients are necessary for estimating the effects that clothing imposes on thermal regulatory efficiency. Although especially useful as a theoretical tool, modeling has not been able to fully account for factors such as individual garment fit, fabric drape, air movement within the suit, etc., which come into play operationally. Thus, the need for *in vivo* garment testing is an essential part of any clothing system evaluation protocol.

Heat dissipation in humans is normally achieved through a combination of convective, radiative, and evaporative mechanisms. This dissipation is necessary to offset the metabolic heat generated, especially that produced by physical activity. CDEs reduce the efficiency of all three avenues of heat balance. Wearing chemical defense garments in hot environments, such as those encountered in Operation Desert Storm, only exaggerates difficulties in transferring heat from body to environment. Past studies of exercise in the heat conducted in this and other laboratories have established normal times that various metabolic rates may be maintained before critical core temperatures are reached (5). Enhancing the capability to transfer heat away from the body would result in longer performance times. However, attempts at improving heat transfer by reducing suit thickness and increasing vapor permeability risk a decrease in chemical protection. Therefore, an inherent paradox exists between optimizing CDEs for maximal protection against chemical agents while minimizing thermal stress.

The CDE configuration now used by the USAF is a two-piece (coat and trouser) garment made of a coated outer nylon cotton shell layer for repelling liquid and an inner charcoal impregnated foam filter for vapor adsorption. Although protective, this configuration seriously impedes heat dissipation. Several new clothing designs have recently been developed that use alternative outer shell materials and different charcoal technologies. Thinner and more moisture and air permeable fabrics based on these technologies show promise for improving sweat vapor passage and dry heat transfer while continuing to maintain adequate protection.

Static laboratory tests of fabric swatches are useful for establishing the "engineering" properties of protective fabric. However, they do not substitute for *in vivo* testing. Bench level tests can determine properties such as resistance to heat flux, porosity, or vapor adsorbency. These types of data are a necessary differentiation when incorporated into mathematical models. However, actual field performance of the system depends upon complex interaction between many variables including clothing design and fit, body shape and size, heat generation, activity level, environment, etc. Any realistic evaluation of thermal stress imposed by the combination of fabric and clothing design is best determined by dynamic system testing. Again, this is especially true since physiological and clothing characteristics interact and may alter considerably over periods of sustained activity. Furthermore, it is important to evaluate the physiological response under environmental conditions that provide a realistic simulation of the thermal stress likely to be encountered in future scenarios such as Operation Desert Storm.

The purpose of this study was to evaluate the acute physiological response to thermal stress in subjects performing moderate work in current and prototype CDE configurations. Both one- and two-piece CDE suit designs using newer fabrics were examined for possible reductions in thermal stress. Specifically, eight garments were evaluated including the CDE used by the U.S. Army and Air Force and the Battle Dress Uniform (BDU) alone which is worn in uncontaminated scenarios.

MATERIALS AND METHODS

Subjects

Eleven USAF volunteer subjects were used in this study. Subjects were informed of potential risks and signed consent forms in accordance with AFR 169-3 before participating in any experiments. This group is considered representative of USAF personnel now serving on active duty status. Table 1 summarizes physical characteristics of the subject pool. The same 11 subjects participated in tests of the Battle Dress Overgarment (BDO)+BDU, BDO no BDU, United Kingdom (UK)+BDU, Gore-Tex+PJ-7, Marine Light Fighter Suit (MLFS), CWU-77P, and PJ-7 alone. The BDU or control trial was conducted on only 10 of the subjects.

Table 1. Summary of Subject Characteristics

N = 11 (1 Female, 10 Males)		
Age (years)	34.6	± 5.0
Weight (kg)	79.6	± 8.5
Height (cm)	178.0	± 3.8

Experimental Design

These experiments were designed to determine the average time that normal individuals could safely maintain moderate activity in a hot dry environment while wearing various chemical defense suits, and to assess the physiological accommodation to thermal stress made by subjects during these work periods. The environmental conditions and work load should be constant so that differences in performance and physiological function could be directly attributed to variations in the CDE being worn.

The environmental conditions selected for these tests were representative of average daily midday temperature and humidity in Dahran, Saudi Arabia, as determined by the U.S. Army during Operation Desert Shield. Experimental conditions were dry bulb temperature (T_{db}) of 40°C (104°F), a wet bulb temperature (T_{wb}) of 27°C (80.6°F), and a black globe temperature (T_{bg}) of 45°C (113°F). These conditions equated to a relative humidity of 20%.

Subjects walked on a treadmill at 3 mph with a 5% incline. For purposes of USAF application, the selected activity level corresponds to moderate exercise performed by active flight line ground crews during integrated combat turns (6). Metabolic heat produced by this effort was approximately 450 kcal/h. Activity was continuous until rectal temperature (T_{re}) rose 1.5°C (2.7°F) above the starting value. No trial was conducted if the beginning core temperature was above 37.5°C. Trial length was considered to be the median time for the subject pool to reach target temperature in a specific suit. This exposure tolerance also became a measure of the suit's thermal stress on the wearer.

The criterion independent variable in these thermal experiments was the chemical defense suit worn during the trial. Certain parts of clothing were the same for all experiments. These constants included a butyl rubber hood, the MCU/2P face mask with filter, rubber gloves with cotton liners, and athletic shoes. The only exception was the MLFS which was worn with its integral fabric hood instead of the butyl rubber hood. A previous study indicated little difference in physiologic tolerance when a permeable fabric hood was worn instead of an impermeable hood (7). Athletic shoes rather than standard overboots were worn as a concession to subject safety and subject comfort while walking on the treadmill. Eight suits were tested in these trials:

Battle Dress Uniform (BDU): A summer weight BDU was included for purposes of comparing thermal effects of a normal duty uniform worn under desert conditions to those of the various CDEs. This ensemble has no chemical defense technology applied in design or manufacture.

Battle Dress Overgarment (BDO)+BDU: A two-piece, trouser and jacket, standard issue CDE using charcoal-foam sandwiched within cloth layers. The outer fabric layer was treated to repel liquids. This CDE is now used by the USAF and is normally worn over the BDU in cooler climates.

BDO no BDU: The standard issue CDE just mentioned worn without the BDU in hot climates.

UK Mark I Undercoverall (UK)+BDU: A one-piece coverall worn under flight suits or BDU. Charcoal adsorbent is latex bonded to liquid repellent viscose nylon and requires long underwear when worn.

Gore-Tex+PJ-7: A two-piece, trouser and jacket, liquid and aerosol repellent shell of Gore-Tex™ worn with a PJ-7 as an undergarment as the vapor agent adsorbent layer using Bluecher carbon sphere technology.

PJ-7: A one-piece, vapor adsorbent garment without liquid repellent cloth treatment. As mentioned earlier, this garment uses Bluecher carbon spheres as the vapor adsorbent material. This garment was designed to be used as an undergarment but could be used alone in hot climates.

Marine Light Fighter Suit (MLFS): A two-piece, trouser and jacket, overgarment that may be worn alone in hot climates. Jacket design has an integral hood as part of the design. Vapor adsorbent layer uses Bluecher carbon spheres.

CWU-77P: A one-piece coverall worn over underwear with the outer fabric treated to repel liquid agents. Vapor adsorbent layer uses Bluecher carbon sphere technology.

Physiological Measures

Electrocardiogram (ECG) and body temperatures were monitored continuously throughout the experiments. The ECGs were continuously displayed and monitored via Transkinetics ECG transmitters to ensure subject safety. These signals were processed to determine heart rate (HR) on a beat-to-beat basis. Temperatures were measured from thermistors placed at specific body and clothing sites including rectal (T_{re}) (10 cm insertion depth), forearm (T_{fa}), chest (T_{ch}), thigh (T_{th}), and calf (T_{ca}). Clothing temperatures were recorded from sites immediately external to the placement of skin thermistors. Clothing thermistors measured forearm clothing (T_{clfa}), chest clothing (T_{clch}), thigh clothing (T_{clth}), and calf clothing (T_{clca}) temperatures. From skin or clothing temperatures, we were able to calculate mean temperature of skin (T_{msk}) and clothing (T_{mcl}). Mean skin temperature was calculated from weighted averages of leg, torso, and arm temperatures (8). Total body heat storage was calculated from body weight, rectal and mean skin temperatures (9). Temperatures, HR, and related calculations were recorded every 30 s by a Macintosh II computer data acquisition system.

Since sweat is an important biophysical mechanism for coping with thermally stressful conditions, it was important that data be gathered on sweat production, sweat rate, evaporation, and percent evaporation. These data were determined from the differences between clothed weight and between nude weight of subjects before and after each experiment. Sweat production was the difference in pre- and postexperiment nude weights; sweat evaporation was the difference in pre- and postexperiment clothed weights obtained on a scale accurate to ± .05 kg. Percent evaporation was calculated by dividing sweat evaporation by sweat production and sweat rate was calculated by dividing sweat production by trial length.

Subjective Measures

Subjective evaluations of rated perceived exertion (RPE) (10) and thermal comfort (TC) (11) were taken every 5 min and manually entered into the computer data acquisition system.

Statistical Analysis of Data

Values for physiologic measures used in the data analysis were median values calculated from the period occurring 30 s before, at, and 30 s after each 5-min interval. This procedure was considered to yield the most representative value of that parameter at that sample time. Analysis of parameter change over time was by three-way repeated measures analysis of variance (ANOVA) (Suit x Subject x Time). Separate analyses of conditions at selected times (beginning, 30 min, and final) were conducted by two-way ANOVA (Suit x Subject) per variable. Variables analyzed included trial length, HR, T_{re}, T_{msk}, heat storage, TC ratings, RPE scores, sweat production, sweat evaporation, percent evaporation, and sweat rate. Differences were considered significant if $p \leq 0.05$.

RESULTS

The primary goals of this investigation were: (1) to determine the length of time that subjects wearing CDEs could be expected to perform moderate work in a desert environment; and (2) to document biological accommodations of personnel working in these conditions. A trial's length was determined by how long it took an individual's T_{re} to rise 1.5°C (2.7°F) above the starting value. Physiological responses to this temperature change were used to establish patterns that characterized an ensemble's thermal stress. The selected temperature increase allowed for a realistic sampling of responses over a thermally stressful range without unduly forcing subjects to medically critical temperature extremes. Given constant work loads and environmental conditions, physiological measures would be expected to continue change at a consistent rate. Therefore, responses when core temperature is moderately above those of the experimental range may be predictable from data obtained over a lower, and safer, temperature range.

Ensemble Performance

Mean times for each ensemble's performance are shown in Table 2. Analysis of these data indicate that there are two distinct groups of garments based on exposure tolerance time. A two-way ANOVA (Suit x Subject) confirmed that significant differences ($p < 0.001$) existed between data means. Duncan's multiple range test established two groups, each significantly different ($p < 0.05$) from the other, but without significant variation within each group. Longer work times were seen in the group comprised of the BDU, MLFS, CWU-77P, and PJ-7. Shorter work times characterized the second group that included the Gore-Tex with PJ-7, UK plus BDU, BDO+BDU, and BDO no BDU ensembles.

Table 2. Trial Length

Ensemble	Mean Time (min)	Percent of BDU Time
BDU	55.9	100
PJ-7	53.4	96
MLFS	53.2	95
CWU-77P	52.8	94
UK+BDU	38.9	70
BDO no BDU	37.1	66
G-Tex + PJ-7	36.2	65
BDO + BDU	32.2	58

All suits within the first group performed within 94% of the BDU time. All three CDEs had surprisingly similar thermal performance compared both to each other and to the standard issue BDU. Subjects wearing only the BDU lasted an average of 55.9 min while the PJ-7 alone lasted 53.4 min, the MLFS 53.2 min, and the CWU-77P 52.8 min. Thus, the mean times of the three chemically protective suits differed by a total of only 36 s.

All suits in the second, shorter performing, group had trials lasting an average of 70% or less of the standard BDU. The ensemble with the shortest average time in this study was the BDO+BDU at 32.2 min. However, the other ensembles in this group did not vary significantly from the BDO+BDU. This grouping included the UK+BDU (38.9 min) and the Gore-Tex+PJ-7 (36.2 min) as well as the BDO worn without BDU (37.1 min).

Sweat Production and Sweat Evaporation

Cooling through sweat evaporation is one of the most important mechanisms for avoiding thermal stress in a hot environment. Sweat produced and evaporated through a suit significantly alters the thermal stress imposed by the garment and both are strongly affected by garment designs and materials. Table 3 displays the data means for trial length, sweat rate, percent sweat evaporated, total sweat produced, and total sweat evaporated by suit. Total sweat produced ranged from a high of 1,900 g for the CWU-77P test to a low of 1,423.6 g for the BDO+BDU. These results are related to the length of a trial period. The longer sweating continued, the greater the total sweat produced. Sweat rate, unlike total sweat, is independent of time and useful in comparing thermal stress of the various garments. Mean sweat rate ranged from a low of 25.8 g/min for the BDU alone to a high of 31.0 g/min for the BDO+BDU.

Table 3. Sweat Production and Evaporation

Suit	Time	Sweat Total	Percent Evap.	Evaporation Total	Sweat Rate
BDO+BDU	32.2	1,423.6	31.4	433.2	31.0
G-Tex + PJ-7	36.2	1,480.0	32.2	461.4	29.2
UK + BDU	38.9	1,588.2	37.1	546.4	30.0
BDU no BDU	37.1	1,476.5	36.5	551.0	28.9
MLFS	53.2	1,736.5	45.7	786.1	26.1
CWU-77P	52.8	1,900.9	47.0	867.3	28.6
PJ-7	53.4	1,876.8	48.0	892.3	27.6
BDU	55.9	1,801.0	53.2	945.0	25.8

The ability of sweat vapors to pass through clothing is important in the transfer of heat away from body surfaces. Thus, it is valuable to know the evaporation properties of a garment. Total evaporated sweat ranged from a high of 945 g for the BDU alone to a low of 433.2 g for the BDO+BDU. Total sweat evaporation, like total sweat production, is affected by the length of a trial. The longer a trial continues, the greater the amount of sweat that can evaporate. Percent evaporation is the ratio of total sweat evaporated to total sweat produced and is independent of time. Thus, percent evaporation is a rough measure of the evaporative properties of a garment. Values ranged from a maximum of 53.2% evaporated for the BDU to a minimum of 31.4% evaporated for the BDO+BDU. A relationship between evaporation percent and the tolerance time in that suit is seen in Figure 1 which is a graph of percent evaporation by suit with suits listed in chronological order by trial length.

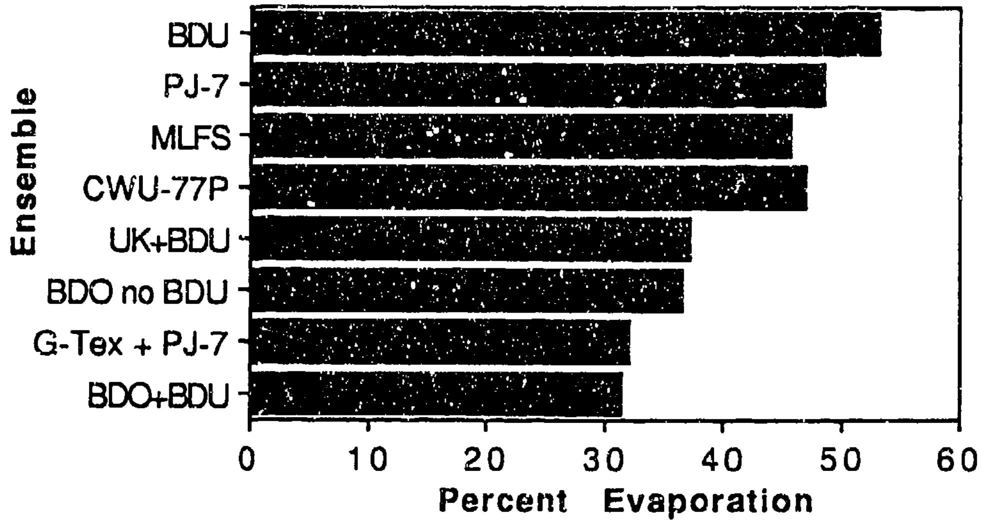

Figure 1. Percentage of Sweat Evaporated by Suit.

Physiological State at the Beginning of Experiments

This study was conducted over an 8-month period. When responses to different ensembles are compared over time, it is important that the subject pool be physiologically similar in all trials. Any differences observed would then be attributable to the garments themselves rather than to subject adaptation. Data from the first 5 min of experiments were analyzed for variation. Heart rate in the Gore-Tex+PJ-7 (98.0 beat $\min^{-1}$) was the only variable identified as being significantly different from the other values. Within 5 min this difference in HR was no longer present. The similarity of overall physiological state may be seen in the data for the beginning of experiments shown in Table 4.

Table 4. Initial Physiological Measurements

Suit	HR (Beats/min)	Tre (°C)	Tmsk (°C)
BDU	109.2	37.1	36.5
PJ-7	113.7	37.0	36.5
CWU-77P	108.3	37.1	36.5
MLFS	111.5	37.1	36.5
UK+BDU	106.6	37.1	36.6
BDOnoBDU	111.5	37.1	36.6
GTEX+PJ-7	98.2*	37.1	36.7
BDO+BDU	120.1	37.2	36.6

*Significant difference $P < 0.05$

Physiological State After Thirty Minutes

A two-way ANOVA (Suit x Subject) was also performed on data sampled from the 30-min interval of experiments. The 30-min point represented the last 5-min interval for which nearly complete data were available for all ensembles and for which sufficient time had passed to develop differences in response to thermal stress of each suit. Table 5 shows the mean physiological and psychological measures after 30 min. As expected, physiological responses generally paralleled performance times. The MLFS, CWU-77P, PJ-7, and BDU all had lower mean HR, lower T_{re}, lower T_{msk}, lower heat storage, somewhat lower RPE values, and lower TC values than the BDO+BDU, BDO no BDU, Gore-Tex+PJ-7, and UK+BDU. The first group of four suits with the lower physiological rates or measures also had the longer performance times. At the 30-min point, the first group also had somewhat lower subjective ratings for RPE and TC.

After 30 min, mean heat storage was significantly lower ($p < 0.0001$) for subjects wearing the MLFS, the CWU-77P, PJ-7, and BDU. Heat storage in the long performance group ranged from 35.7 kcal kg^{-1} for the BDU only to 52.7 kcal kg^{-1} for the PJ-7. The short performance group means varied from a high of 88.9 kcal kg^{-1} in the BDO+BDU to a low of 74.5 kcal kg^{-1} in the BDO without BDU.

By definition, differences in heat storage between the two groups should parallel changes in rectal and/or skin temperatures. Rectal temperatures at 30 min in the long-exposure group (range = 37.8-37.9°C; group mean = 37.8°C) were lower than T_{re} responses of subjects wearing suits only permitting short performance times (range = 38.2-38.4°C; group mean = 38.3). Mean skin temperatures were also significantly lower in the long-exposure group (T_{msk} range = 36.4-37.0°C; group mean = 36.8) in contrast with the higher T_{msk} of the short-trial grouping (37.3-37.9°C; group mean = 37.7). The ensemble grouping with long-exposure times showed lower HRs.

Table 5. Mean Physiological Responses After 30 Minutes

Suit	HR (Beats/min)	Tre (°C)	Tmsk (°C)	HtStr (kcal/kg)	RPE	TC
BDU only	147.6	37.8	36.4	35.7	12.5	5.6
PJ-7	143.6	37.8	37.0	52.7	12.6	5.5
MLFS	148.3	37.9	36.8	47.1	12.8	5.8
CWU-77P	145.0	37.8	36.8	45.5	13.1	5.9
UK+BDU	156.6	38.2	37.3	81.8	14.0	6.2
BDO no BDU	159.3	38.2	37.5	74.5	14.2	6.3
GTex + PJ-7	163.2	38.2	37.9	80.1	13.7	6.7
BDO+BDU	169.3	38.4	37.9	88.9	13.9	6.2

Physiological State at the End of Experiments

Mean responses of subjects at the end of experiments are shown in Table 6. A two-way ANOVA (Suit x Subject) performed on these results identified significant differences in T_{msk} and heat storage. Application of Duncan's multiple range test to these two parameters showed subjects had lower T_{msk} and lower heat storage when wearing the CWU-77P, MLFS, PJ-7, or BDU than when wearing the BDO+BDU, BDO no BDU, UK+BDU, or Gore-Tex+PJ-7.

Table 6. Physiological Values at Experiment End

Suit	Time (min)	Heart Rate (beats/min)	Tre (°C)	Tmsk (°C)	HtStr (kcal/kg)	RPE	TC
BDU	55.9	160.9	38.5	36.7	80.1	14.4	6.1
P1-7	53.4	164.1	38.4	37.0	86.0	15.3	6.6
MLFS	53.2	160.5	38.5	37.0	83.0	11.3	6.3
CWU-77P	52.8	156.8	38.5	37.1	84.4	14.4	6.4
UK+BDU	38.9	162.0	38.5	37.6	91.3	14.9	6.5
BDOnoBDU	37.1	164.5	38.5	37.6	88.3	13.9	6.7
GTex + PJ-7	36.2	164.1	38.4	38.1	96.2	11.2	6.5
BDO+BDU	32.2	170.4	38.5	38.0	103.2	13.9	6.2

Changes Over Time

When the data for most variables are viewed over the time course of the experiments, the obvious groupings and the changes to the long- and short-duration groups are easily seen. Figure 2 shows the changes in T_{msk} over time. Garments from the short-duration group show T_{msk}s that increase rapidly and remain at a higher value than for subjects wearing suits with longer tolerance times. Rectal temperatures increase more slowly in the four suits of the long-exposure group but eventually reach the same point as seen in Figure 3. Heat storage is a function of body size, T_{re}, and T_{msk}. Since the subject pool was constant, and skin and rectal temperatures rose more slowly in the long-exposure grouping, then heat storage rose more slowly in these suits. Heat storage is graphed over time in Figure 4 and demonstrates the lower final heat storage of the long-exposure group. Heart rate rose more slowly in the long-tolerance group, but final rates were not significantly different between long- and short-exposure groups as discussed in the previous section of this report (Fig. 5).

Psychological Perceptions

Subjective measures are important in estimating performance, can give some indication of physiological status, and certainly can indicate factors affecting motivation in thermally stressful circumstances. Two subjective indicators, rated perceived exertion and thermal comfort, were monitored every 5 min throughout these experiments. The RPE, a score of how hard the subjects feel they are working during an activity, may correlate with HR (10). Thermal comfort is believed to be a relative indicator of T_{msk} (11). Significant differences in TC ratings were seen only at 30 min of work between the PJ-7+ Gortex and the PJ-7 alone or the BDU alone. Other than that, the differences between values for RPE and TC were not significant.

DISCUSSION

The purpose of this study was to compare various CD ensemble configurations relative to measures of physiological stress. Choices of a 40°C (104°F) ambient temperature, a radiant overhead heat load, and a 20% relative humidity place a premium on evaporation as the prime biophysical mechanism for dissipating metabolic heat. Using a constant walking speed and incline throughout the trials resulted in consistent rates of metabolic heat production. Additionally, the same subjects participated in all CDE trials in a repeated measures design. Thus, consistent external and internal thermal stresses in combination with subject pool containing the same individuals in all experiments minimized differences between experimental trials except for suit effects.

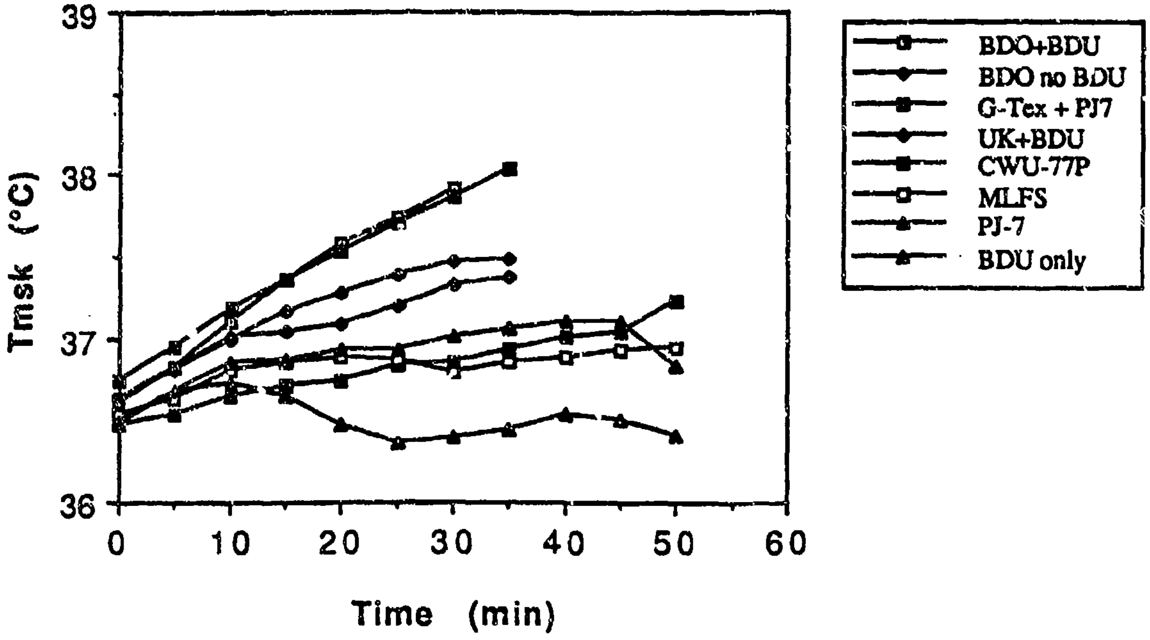

Figure 2. Mean Skin Temperature Across Time.

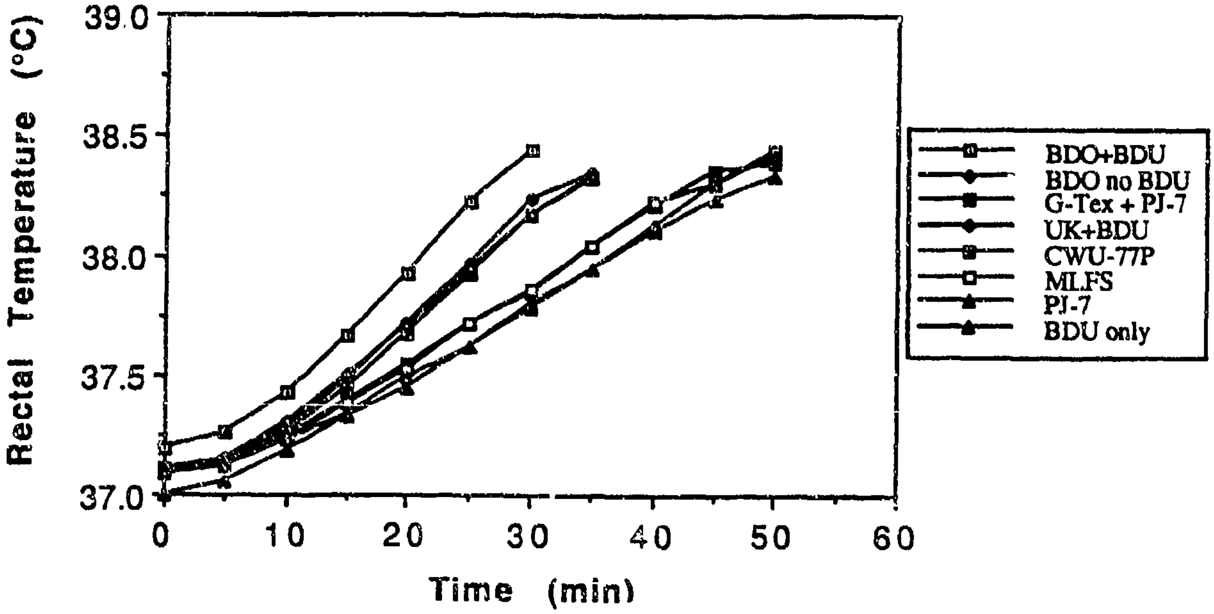

Figure 3. Mean Rectal Temperature Across Time.

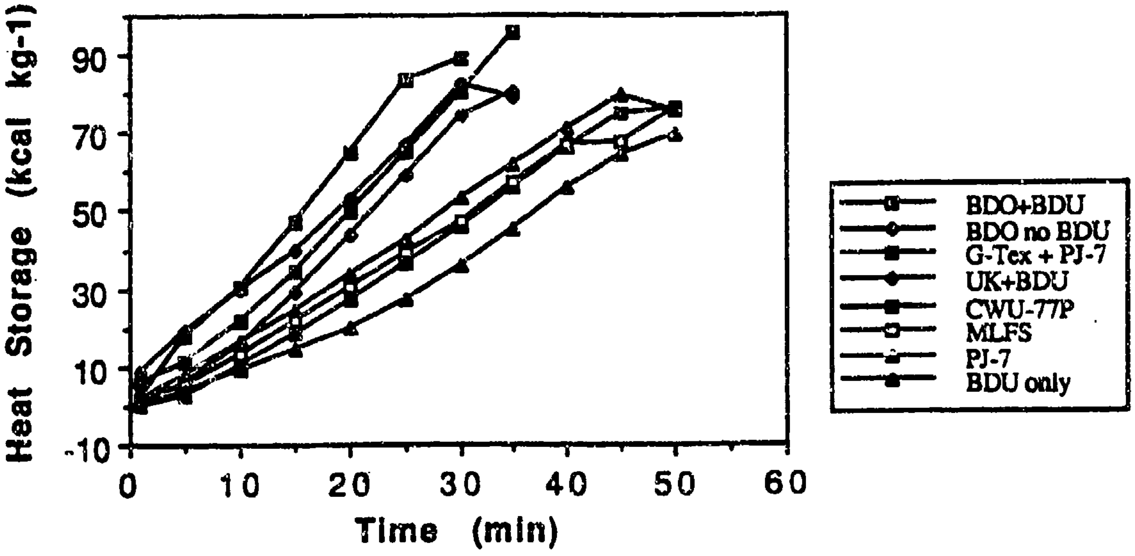

Figure 4. Mean Heat Storage Across Time.

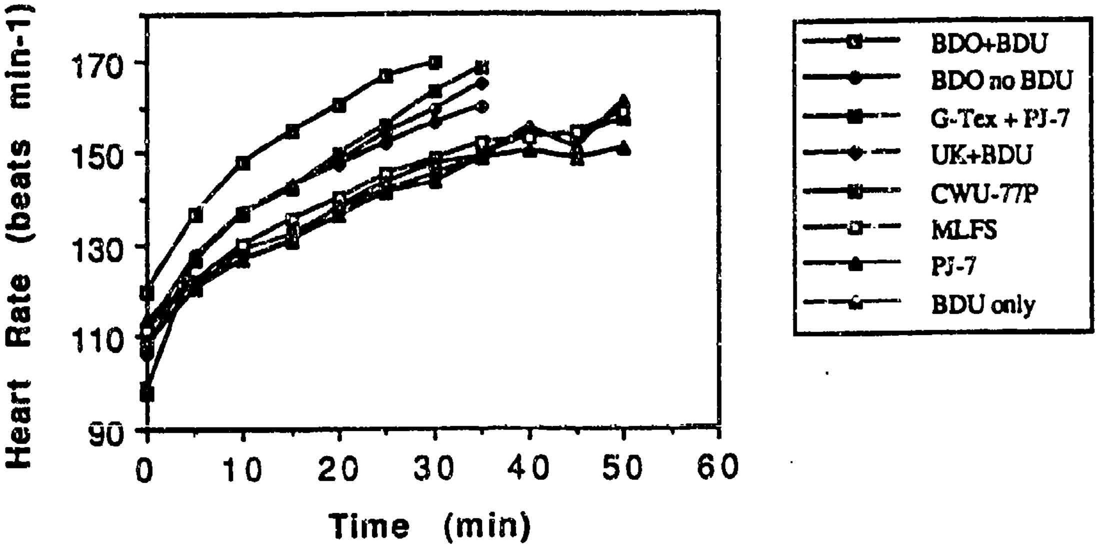

Figure 5. Mean Heart Rate Across Time.

Fabric manufacturers and garment designers often strive to minimize thermal stress on the basis of theoretical calculations and prior experience. Simple mathematical-empirical models have identified a number of different clothing factors that interact to affect thermal stress (4, 12). Prominent variables include the body area covered by a garment, the insulative garment properties, and the evaporative garment capacity (4). Continuing research has resulted in the development of barrier fabrics with reduced insulative properties and increased evaporative capacities. These fabrics have been incorporated into protective clothing in an attempt to resolve the inherent conflict between protection and thermal stress. Such designs require both laboratory and field testing since the interactions of fabric, design, fit, and numerous other factors are too complex to be accurately modeled from fabric test data alone. Moreover, experimental data aids and contributes to the evolution of theoretical models of thermal effects of clothing thereby improving future clothing design.

Two of the garments in the present test configurations are not normally used as chemical warfare ensembles. These garments are the BDU and the PJ-7. The BDU was evaluated by itself in these experiments to answer two questions. First, how long can an individual wearing a normal duty uniform (worn in a CD ensemble configuration) be expected to perform moderate work in desert conditions before reaching a criterion body temperature? Secondly, what physiological accommodations are made to desert conditions while performing work in this environment? These findings should help to establish an operational standard to which chemical defense ensembles may be realistically compared. It should be recalled the rest of the ensemble (respirator mask, hood, and gloves with liners) was donned as in the standard MOPP IV posture in this trial. Use of the PJ-7 as a separate trial also warrants discussion. This suit was designed as an undergarment to be used under repellent or impermeable outer shells although it could be worn in a hot environment. In these experiments, the PJ-7 was the vapor adsorbing layer for a Gore-Tex shell. Therefore, it was necessary to test the thermal properties of the PJ-7 alone to distinguish Gore-Tex effects from those of the PJ-7.

In contrast to the single clothing layer/Bluecher Sphere technology characteristic of the long-exposure group, the short-exposure time suits had designs using both single and multiple clothing layers (three of four garment designs) and fabrics with poor vapor permeability. Multiple layers impede heat transfer more than single layers, although this may not always be a detriment in a hot environment. For example, the foam-charcoal overgarment (BDO) is worn over the BDU, the Gore-Tex+PJ-7 is two layers, and the UK+BDU uses long underwear, a BDU, and the undercoverall itself. The only garment in this group worn as a single layer ensemble was the BDO worn without BDU. Since multiple layers are expected to increase insulation beyond that provided by single layers due to air gaps, work time is expected to decrease; this is, in fact, what happens.

In the Results section, it was established that data tended to fall into two groups by exposure tolerance time, each group having little intragroup variability, but still differing significantly from one another. An examination of similarities and differences in suit design may serve to explain the data clusters observed.

Suits in the long-exposure group included the BDU, the PJ-7, the MLFS, and the CWU-77P. The last three CDEs have distinctly different designs: the PJ-7 is a close fitting one-piece garment; the MLFS is a loose fitting, two-piece trouser and jacket with integral hood; and the CWU-77P is a one-piece coverall usually worn over underwear. Despite obvious differences in appearance, all three suits have several construction features in common. These features include a fabric with a relatively porous weave, the use of Bluecher process carbon spheres, and a design that allows them to be worn as a single clothing layer (2). Separate tests have established that all three suits can provide adequate levels of chemical protection as single clothing layer garments. These CDEs proved so surprisingly similar to the BDU's thermal performance that further improvement in heat dissipation for CD garment materials might only bring about modest payoffs in work tolerance using standard configuration.

"Short" trial suits also had relatively poor water vapor transfer characteristics. Short-duration garments consistently had lower percent evaporation making heat transfer more difficult. This evaporation is a property of the cloth and design used in the manufacture of these garments. In contrast, all three ensembles with long trial times use Bluecher carbon spheres laminated between two plies of relatively porous cloth.

Data presented earlier in Table 3 support a relationship between evaporation and performance. When suit types are sorted by percent sweat evaporated, the resultant order is similar to the order achieved when sorted by performance time. Figure 1 shows percent evaporation by suit from data in Table 3. The data are presented in descending order of mean trial length. The MLFS, CWU-77P, and PJ-7 show percent evaporation values similar to that of the BDU under simulated desert conditions. In contrast, ensembles with poor performance times showed low percent evaporation. That is, the four shortest trial times also had the four lowest percent evaporation values, thus suggesting a correlation exists between average trial time and average percent evaporation.

A relationship also appears to exist between average sweat rate and average trial length (Table 3). In general, higher sweat rates were associated with briefer work periods. High rates of sweat production are a probable response to high heat storage rates or to higher mean skin temperatures occurring in these suits (13). Both measures exhibit significant differences between ensembles throughout the entire trial (Figs. 2 and 4).

As ambient temperature increases, the physiological significance of evaporative cooling also increases. It is a basic assumption that increased evaporation through a suit translates to increased cooling of skin surfaces (14). The data support this assumption in that T_{msk}s are consistently lower in suits with higher evaporation percentages and longer trial times. Figure 4 shows T_{msk} over time for each suit. Skin temperatures are lower in suits with long-exposure times. These differences exist throughout most of the trials and proved to be significant at the 30 min and final data points. Effective evaporation should lower T_{msk} and the data are in agreement with this expectation. Thus, increased suit evaporative heat transfer can more effectively cool the skin. In this study, garments constructed from single clothing layers made from porous weave cloth, that used Bluecher carbon spheres as an adsorbant, showed consistently cooler T_{msk}s and longer work times.

Rectal temperatures increased at distinctly different rates for long- and short-exposure suits as shown in Figure 3. Short-duration suits had more rapid T_{re} increases than long-duration suits. These increases are similar to the rates at which T_{msk} rose in the two groups with T_{msk} increasing more quickly in the short-trial suits. Differences in the rates at which T_{re} rose between long- and short-exposure groups can only occur if heat transfer mechanisms are more effective in one group than the other. Since T_{re} rose at a much slower rate in suits with higher evaporative rates, it is concluded that thermal stress is more effectively compensated for in suits with higher evaporative percentages than in those with lower percentages. Again, evaporation properties of a suit directly affect core temperature increases.

Heat storage is calculated from data for body weight, T_{re}, and T_{msk}. Since body weight was essentially a constant and both T_{re} and T_{msk} consistently maintained lower experimental values in the long-exposure group, it follows that heat storage patterns would parallel those of temperature changes. Heat storage over time is shown for all suits in Figure 4. As expected, long-exposure suits had heat storage rates lower than those of short-exposure suits. Significant differences were present after 30 min and these differences persisted to the end. Differences in heat storage rates between groups reflect differences in thermal stress imposed by various suits and the degree to which these suits help or hinder physiological compensation mechanisms.

Heart rate was another important physiological measurement in these experiments. Increased body temperatures result in cardiac adjustments beyond those necessary to support physical efforts (15). The slower rates of rise in body temperature of the long-exposure group were generally paralleled by a lower rate of rise in HR (Fig. 5). Since work load was constant, changes in HR appear to be related to changes in thermal stresses. Subjects wearing suits with better evaporative percentages tend to demonstrate slower increases in HR. The present data indicates that subjects wearing the BDU, PJ-7, MLFS, or CWU-77P took significantly longer times for HR to increase to the values seen in the short-duration garments. It appears, therefore, that the associated cardiac work is reduced when wearing suits with lower measured thermal stress.

Mean RPE is moderately correlated with mean HR data sampled after 30 min of activity. Data for mean RPE as a function of mean thermal comfort reveal a better relationship than that of RPE and HR. RPE may also be influenced by perceptions of TC. Thermally uncomfortable subjects may rate a work load as being more difficult than if conditions were less thermally stressful. Mean Thermal Comfort scale ratings correlate reasonably well ($R^2 = 0.84$) with mean T_{msk} measurements after 30 min of activity. Since evaporation affects T_{msk}, and since T_{msk} affects thermal comfort, it was predicted that TC would show a relationship to the evaporative properties of a suit. When mean TC is compared with mean percent evaporation, the relationship is stronger ($R^2 = 0.89$) than the one between TC and T_{msk}. In general, the higher the evaporation rate, the better (lower) the TC rating. This relationship implies that evaporation in an ensemble may be one of the more important qualities affecting garment comfort.

CONCLUSION

Data were analyzed at the beginning, after 30 min, and at the end of each experiment. Analysis has indicated that subjects were reasonably uniform at the beginning of experiments. As noted earlier in this report, some initial variation in HR for subjects in the Gore-Tex+PJ-7 ensemble disappeared quickly. From fairly uniform initial values, variables diverged due to adjustments to the differing thermal stresses of the garments. This divergence resulted in two groupings each with internal similarities seen repeatedly throughout this report. These differences were well developed and were analyzed after 30 min because subjects in poorer performing garments reached the terminal rectal temperatures of the protocol soon after this time and their data were no longer available. This 30-min sampling provided an excellent means of contrasting physiological effects. These differences have been discussed at appropriate points in this report and will not be repeated here. However, it was also important to follow the entire experiment to define differences, if any, that persisted to the end. We expected that no differences would be present at the conclusion of experiments since core temperatures increase the same 1.5°C (2.7°F) for all subjects and environmental and work stresses were the same for every trial. However, analysis demonstrated that significantly lower T_{msk}s and heat storage were present in subjects with longer performance time. Lower heat storage should result in more rapid recovery from thermal stress, an important consideration in personnel engaged in continuing field operations. The lower T_{msk}s associated with the better performing suits are significant in that the first step in recovering is normally cooling the skin.

The already lower T_{msk} of individuals in Bluecher-type suits should help in this cooling and recovery process. Although thermal stresses cannot be completely eliminated from chemical defense garments, these garments can be designed to maximize compensation through normal thermoregulatory mechanisms.

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