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HEAT STRESS EVALUATION OF ANTI-EXPOSURE FLIGHT GEAR

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Constant-wear anti-exposure suit ensembles, employing the CWU-62/P polytetrafluoroethylene (PTFE) coverall, were evaluated for their impact on aircrew performance under heat stress. Conditions were designed to simulate stresses experienced during aircraft operations over cold water; therefore, chamber temperatures were maintained at dry bulb temperature = 34.0±1.5°C and wet bulb temperature = 23.9±4.5°C. Six males, aged 21-39, were studied twice in each of five configurations for maximum 180 minute exposures. The five configurations consisted of a standard flight suit (control), and four combinations of the PTFE coverall with different liners. Mean test duration for the control was 177 minutes, while for the other configurations, mean test durations were < 130 minutes. No significant differences were observed between the PTFE-based configurations. Total sweat rate (SRT), heat storage rate (ΔQ), final heart rate (HR), and mean weighted skin temperatures ($\bar{T}_{sk}$) indicated similar trends among the configurations. The results indicate that the liner has only a limited impact on the test results; therefore, the PTFE coverall appears to limit heat tolerance under those conditions. Aircrew wearing the CWU-62/P coverall cannot be expected to complete three hours of aircraft operations if a moderate workload is imposed under heat stress.

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INTRODUCTION

The nature of Naval operations and the range of current aircraft present to aircrews the problem of operating under widely varying thermal conditions during the course of a single mission. Since the use of anti-exposure garments is advised when operating over water at temperatures of <15.6°C (60°F), aircrew may find themselves wearing anti-exposure protection while exposed to high internal cabin temperatures(1), especially during preflight(2).

In an attempt to alleviate this problem, a new dry-type anti-exposure suit system, based on the CWU-62/P polytetrafluoroethylene (PTFE) coverall, has been introduced. It is claimed that the PTFE membrane will permit evaporative heat loss under normal conditions, while precluding the passage of water into the suit during immersion. To increase the insulation provided by the suit ensemble for added protection during cold water immersion, the CWU-72/P olefin liner has been proposed as an addition to the anti-exposure suit system.

The purpose of the evaluation reported herein was to determine the physiological effects of the CWU-62/P (with liner) suit system when worn in a hot environment. The evaluation consisted of exposing subjects to heat stress while performing a psychomotor tracking task, a physical work task, and with interspersed rest periods. The tasks were intended to simulate the general types of tasks performed by aircrew in both fixed-wing and rotary-wing aircraft. Test duration, which was a maximum of three hours, was based on average mission length for aircraft in which aircrew wear constant-wear anti-exposure suits(1).

MATERIALS AND METHODS

Six healthy males (Table 1) volunteered to participate as subjects after being fully informed of the details of the experimental protocol and associated risks.

SUBJECTS

Weight was recorded prior to each test run and the mean calculated. Body surface area (BSA) was calculated(3) from the mean weight and height of each subject. Percent body fat was determined from estimates of body density(4), which were computed from skinfold measurements(5,6) obtained with Lange Skinfold Calipers (Cambridge Scientific Ind., Cambridge, MD). Anatomical sites for the skinfold measures were the biceps, triceps, scapular margin, and suprailiac region.

Aerobic fitness was calculated in terms of the submaximal oxygen uptake test of Astrand and Rhyming(7,8), employing a bicycle ergometer. Subjects were lightly clothed and had not engaged in physical activity at least 1 hour prior to testing. After adjusting the seat and handlebars for the subject, the subject pedalled the bicycle ergometer at no load at 50 rpm for 5 minutes. The workload was then increased to a level sufficient to produce a sustained heart rate of 130-170 bpm, while maintaining a pedalling rate of 50 rpm. Heart rates were recorded after the 5th, 6th, and 7th minute following application of the increased work load, after which the test was completed. Predicted maximum VO_2 was obtained from the Astrand monogram(8), based on the steady state heart rate attained during the test, weight, age, and sex of the subject.

METHODS AND PROCEDURES

All tests were performed in the morning to minimize the effects of temperature changes due to circadian rhythms. Each test simultaneously exposed two subjects to the experimental conditions, with the subject pairings and clothing configuration worn by each subject randomized. Minimum frequency of exposure to test conditions for a given subject was two days, so that acclimation effects could be minimized.

Subjects reported to the laboratory on the morning of a test and were given physical examinations by the attending flight surgeon. After voiding, a urinanalysis was performed, and each subject's baseline weight was obtained on a scale accurate to ± 10g (Scale-Tronix, Wheaton, IL, model 6006SP). Thermocouples (type T) were then attached to the following body sites: (A) forehead; (B) upper chest; (C) scapular apex; (D) lateral upper arm; (E) dorsum of hand; (F) pad of index finger; (G) medial surface of thigh; (H) lateral surface of leg; (J) pad of great toe; (K) dorsum of foot; and (L) lower back. A rectal thermistor (YSI model 401) was inserted 8-10 cm anterior to the anal sphincter. ECG electrodes and a blood pressure cuff were placed on each subject. Baseline values of temperature, heart rate, and blood pressure were obtained at this time. Subjects were then dressed in the appropriate clothing configuration for that run (Table 2).

Upon completion of dressing, both subjects proceeded to the chamber. Testing was performed in chamber conditions of dry bulb temperature (T_{db}) = 34.0 ± 1.5°C and wet bulb temperature (T_{wb}) = 23.9 ± 4.5°C. The 20-minute test cycle consisted of a subject pedaling on a bicycle ergometer (work load = 30 W) for 5 minutes, which represents a moderate work load (9), performing a tracking task (Combat-Jet Fighter™, Atari, Inc.) for 7 minutes (i.e., 3 game cycles), and resting for 7 minutes. This cycle was repeated 6 times during a test, for a total of 180 minutes, unless the test was terminated early due to rectal temperature (T_{re}) exceeding 39.0°C, heart rate exceeding 180 bpm, or the subject expressing the desire to terminate the particular test run (1).

At the beginning of each change of activity during the test run, subjects rated their sensation of comfort (scale 1-4), temperature (scale 1-7), and sweating (scale 1-4). Subject responses were recorded by the inside observer, as were ambient dry bulb and wet bulb temperatures. These results are reported as time to sweat sensation =4 (tSS=4) and time to temperature sensation =7 (tTS=7), the comfort responses not being reported due to their highly inconsistent nature.

Mean weighted skin temperature (T_{sk}) was calculated using the equation:

$$T_{sk} = 0.7\,(A) + 0.35\,[(B+C+L)/3] + 0.14\,(D) + 0.05\,[(E+F)/2] + 0.19\,(G) + 0.13\,(H) + 0.07\,[(J+K)/2] \qquad (^\circ C) \tag{1}$$

where the variables A – L are the measured skin temperatures (10). Mean weighted body temperature (T_b) was calculated using the equation.

$$T_b = 0.33\,T_{sk} + 0.67\,T_{re} \qquad (^\circ C) \tag{2}$$

where T_{sk} is the mean weighted skin temperature and T_{re} is the rectal temperature (10). Reported changes in temperatures (ΔT_{re}, ΔT_{sk}, ΔT_b) and heart rate (ΔHR) represent the difference between final and baseline values.

The rate of heat storage (ΔQ) was calculated for each exposure using the equation:

$$\Delta Q = (\Delta T_{re}/\Delta t)\,(60 \times 0.97\,M_b)/BSA \qquad (W/m^2) \tag{3}$$

where ΔT_{re} is the change in rectal temperature (°C), Δt is the test run duration (minutes), 0.97 represents the specific heat of body tissue (W·hr/kg·°C), 60 converts hours to minutes, M_b is the

Table 1. Test Subject Profiles

Subject ~	Age (yr)	Height (m)	Weight (Kg)	% Body Fat ~	Surface Area (m^2)	VO_{2max} (ℓ/min)
1	32	1.73	95.4	26.5	2.07	1.9
2	39	1.81	78.0	23.8	1.98	2.3
3	32	1.82	91.0	21.8	2.07	2.2
4	23	1.71	90.8	29.3	1.97	2.6
5	26	1.78	96.5	26.7	2.15	4.0
6	28	1.71	100.7	25.5	2.10	3.0

Table 2. Flightgear Worn, All Configurations

- CWU-43/P, -44/P underwear
- CWU-27/P Flight coverall
- Wool socks (2 pairs), Flyer's boots
- HG-33 or SPH-3 helmet
- Torso harness
- Anti-G Suit

Configurations	
1	as above
2	CWU-62/P anti-exposure suit CWU-23/P mesh liner
3	CWU-62/P CWU-72/P short-sleeved olefin liner
4	CWU-62/P long-sleeved olefin liner
5	CWU-62/P

lean body mass (kg,)and BSA in the body surface area (m^2)(11). Total sweat rate (SRT) was determined by the difference in weight calculated from the post-test value, corrected for fluid intake, and the baseline value. The reported SRT values are normalized by dividing the change in weight by BSA.

STATISTICAL ANALYSIS

Linear correlation coefficients were calculated for all reported variables in order to identify interactions(12). Calculation of linear correlation coefficients for ΔT_{re}, ΔT_{sk}, and ΔT_b vs. time was also performed(12). A two-way analysis of variance (ANOVA) was performed on all data, comparing clothing configuration and subject effects(13). A Duncan Multiple Range test was employed to identify significant differences between means when overall significant differences were indicated by previous analysis(14). Analysis of covariance (ANCOVA), using a 6x5 factorial design, was used to analyze the covariant effects of initial T_{re}, T_{sk}, T_b, HR, and urine specific gravity on the criterion test duration, ΔQ, SRT, tSS=4, tTS=7, and final values of T_{re}, T_{sk}, T_b, and HR(15). Tests of the homogeneity of variance using Bartlett's method(12) and of the hypothesis H: (regression coefficient = 0) in the analysis of covariance(13) were used to affirm the validity of the statistical methods employed.

RESULTS

The results of the heat stress testing indicate that none of the configurations employing the CWU 62/P coverall produced mean test durations of greater than 127.9 minutes (Figure 1). This was significantly different ($p<0.01$) from the mean test duration of the control (configuration 1), which was 176.6 minutes. A two-way ANOVA showed this to be the result of configuration, and not subject effects.

Among the four PTFE-based configurations, no significant differences in test duration was observed. Linear correlation was observed between test duration and TSS=4 ($r=0.799$), and tTS=7 ($r=0.865$). The introduction of baseline values as covariants in an ANCOVA was inconclusive, since interaction, as defined by the statistical model(13), could not be shown.

The rate of heat storage (Table 3) was observed to be a function of both the configuration worn ($p<0.05$), and to a greater extent, to the particular subject ($p<0.01$). While an overall significant difference in ΔQ was detected among configurations, no individual configuration could be shown to be significantly different. Mean values demonstrate a trend, however, with configurations 3 and 4 (olefin liners) producing higher rates of heat storage (Figure 2). Linear correlation between ΔQ and T_b was observed ($r=0.678$), while no linear correlation was detected among ΔQ and the other variables.

Total sweat rate (see Table 3) was strongly influenced by both configuration ($p<0.01$) and subject effects ($p<0.01$). No individual configuration was observed to be significantly different in SRT, despite the overall significant differences. An inspection of the means (Figure 3), however, indicates that the control (configuration 1) had produced a considerably lower SRT than the other configurations.

Initial urine specific gravity, when included in an ANCOVA of SRT as a covariant, reduced the configuration effects ($p<0.05$), while increasing the subject effect F-statistic. This appears to indicate that initial hydration of the subject influenced SRT, and that configuration effects are a less important factor.

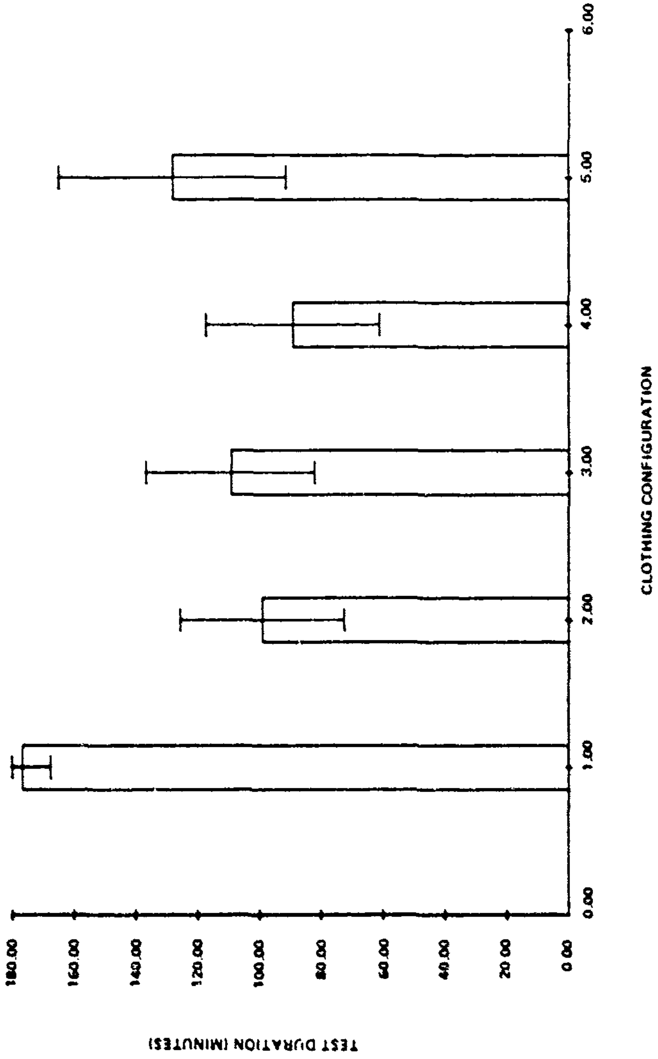

Figure 1. Configuration vs. Duration

Table 3. Test Results of Heat Stress Study.

		SUIT 1	SUIT 2	SUIT 3	SUIT 4	SUIT 5
$T_{R,F}$ (°C)	$\bar{X}$	37.5	37.5	37.5	37.5	37.4
	S	0.4	0.42	0.46	0.31	0.35
ΔT_R (°C)	$\bar{X}$	0.59	0.52	0.71	0.57	0.56
	S	0.37	0.40	0.34	0.43	0.33
ΔQ (W/m^2)	$\bar{X}$	6.50	8.70	12.90	11.60	8.63
	S	4.09	7.94	7.09	7.76	5.23
$T_{B,F}$ (°C)	$\bar{X}$	3.73	37.5	37.4	37.5	37.5
	S	0.27	0.46	0.43	0.29	0.27
ΔT_B (°C)	$\bar{X}$	1.67	1.88	2.04	1.78	1.47
	S	0.68	0.82	0.35	0.58	0.38
T_{sk} (°C)	$\bar{X}$	36.9	37.5	37.1	37.4	37.5
	S	0.47	0.84	0.62	0.51	0.20
T_{sk} (°C)	$\bar{X}$	3.84	4.60	4.71	4.21	3.30
	S	1.95	1.91	1.27	1.15	0.70
SRT (g/mn.m^2)	$\bar{X}$	3.59	5.53	5.55	6.44	5.43
	S	0.83	3.27	2.96	2.43	1.59
HR_F (bpm)	$\bar{X}$	113	128	135	140	128
	S	25.7	19.3	25.2	26.4	22.0
Duration (min)	$\bar{X}$	176.6	99.0	109.3	89.0	127.9
	S	9.15	26.6	27.3	28.1	36.6
Index of Strain*						
	$\bar{X}$	1.72	2.17	2.58	2.55	2.17
	S	0.57	0.31	0.71	0.48	0.33

* $Is = \frac{HR}{100} + \frac{\Delta T_{re}}{\Delta t} + \frac{\Delta Wt}{\Delta t}$

where Is = Index of Strain
HR = final Heart Rate (bpm)
ΔT_{re} = change of rectal temperative (°C)
ΔWt = change of body weight (Kg)
Δt = test duration (minutes)

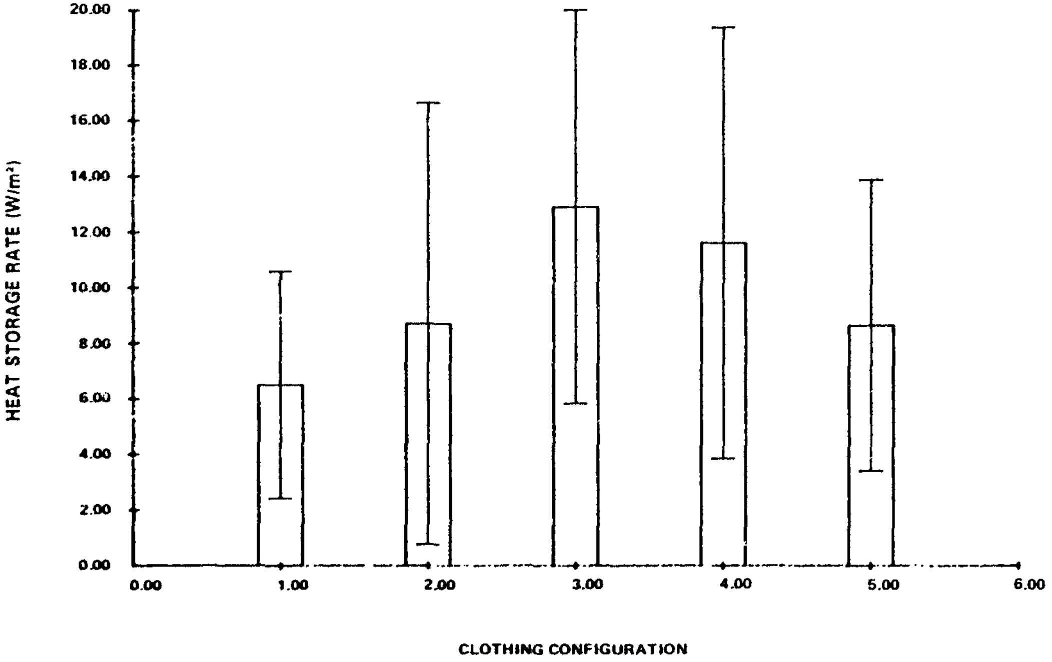

Figure 2. Configuration vs. Heat Storage

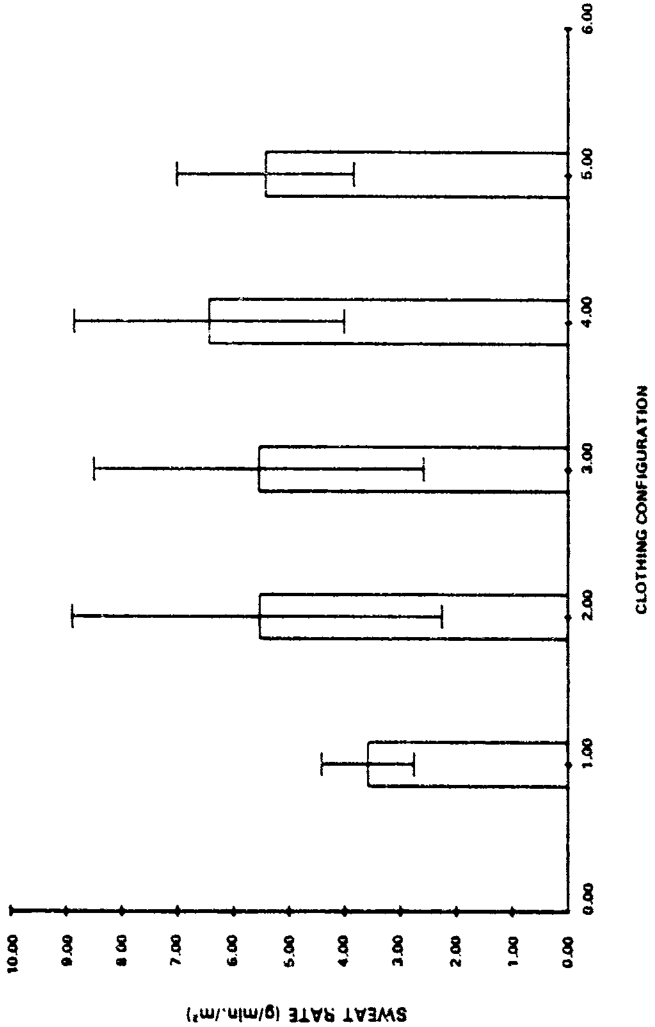

Figure 3. Configuration vs. Sweat Rate

Final rectal temperature (Table 3) appears to be primarily influenced by subject effects ($p<0.01$), as configuration effects were not significant in an ANOVA. Initial T_{re}, when used as a covariant, demonstrated the effect of initial subject state on final values of T_{re}, as the F-statistic for subject effect on T_{re} increased in an ANCOVA.

Clothing configuration produced significant differences among final T_{sk} ($p<0.05$), while subject effects were not significant in an ANOVA. The control (configuration 1) resulted in a significantly lower T_{sk} than the CWU-62/P- based configurations ($p<0.05$). No significant difference was detected among those configurations.

Since a majority of the tests involving configurations 2,3,4, and 5 were terminated prior to the three hour limit without reaching the physiological safety thresholds, extrapolation of the data was required to predict T_{re} and T_{sk} for three hour exposures. Linear regression analysis of T_{re} vs. time indicated that final T_{re} of <39.0°C could be expected for all of the experimental configurations (Figure 4). A similar analysis of T_{sk} vs. time indicated that for configurations 2,3, and 5, T_{sk} would remain below T_{re} after a three hour exposure (Figure 5). Configuration 4 would produce a T_{sk} higher than T_{re} at three hours, on the basis of the linear regression lines (Figures 4 and 5). This is a situation in which heat illness is extremely likely to occur(16).

A linear regression analysis was also performed on T_b vs. time, to obtain an approximation for the overall temperature state at the end of three hour exposures. The results of this analysis (Figure 6) indicated that long-sleeved liners (configurations 2 and 4) would produce a higher T_b at three hours. This appears to result from the greater body surface coverage of these liners, which produced a greater rate of change of T_b when compared to the other configurations (Figure 6).

Final heart rates (Table 3) have been determined by an ANOVA to be governed principally by subject effects ($p<0.05$) under the experimental conditions. However, when initial HR is considered in an ANCOVA, configuration effects become significant ($p<0.05$), while subject effects increase in significance ($p<0.01$). The observed differences in mean final HR between the control and experimental configurations was significant ($p<0.05$), while the other differences among configurations were not significant.

Results of the psychomotor task indicated the dominant factor in the results was training due to constant playing, therefore that data is not reported. Difficulty with instrumentation resulted in unreliable blood pressure data, thus their omission from this report. Aerobic fitness is reported as obtained prior to the start of the ensemble testing, with no change in aerobic fitness being detected over the ensemble testing period.

DISCUSSION

The intent of this study was to determine the physiological effects of the CWU-62/P PTFE constant-wear anti-exposure coverall, when worn with various liners, on subjects performing physical and mental tasks under heat stress conditions. The CWU-72/P olefin liner was one of the attendant liners, as it was considered likely to be included in the operational anti-exposure ensemble.

A diminution of tolerance to heat was observed in the tests with the PTFE-based configurations, as would be expected from the increase in clothing insulation and decrease in ventilation caused by the garments. This reduced tolerance is reflected in the results obtained for test duration, which clearly show the effects of wearing the CWU-62/P coverall. The significant difference in test duration between the control and the PTFE-based configurations implies that the CWU-62/P coverall is a limiting factor in heat tolerance.

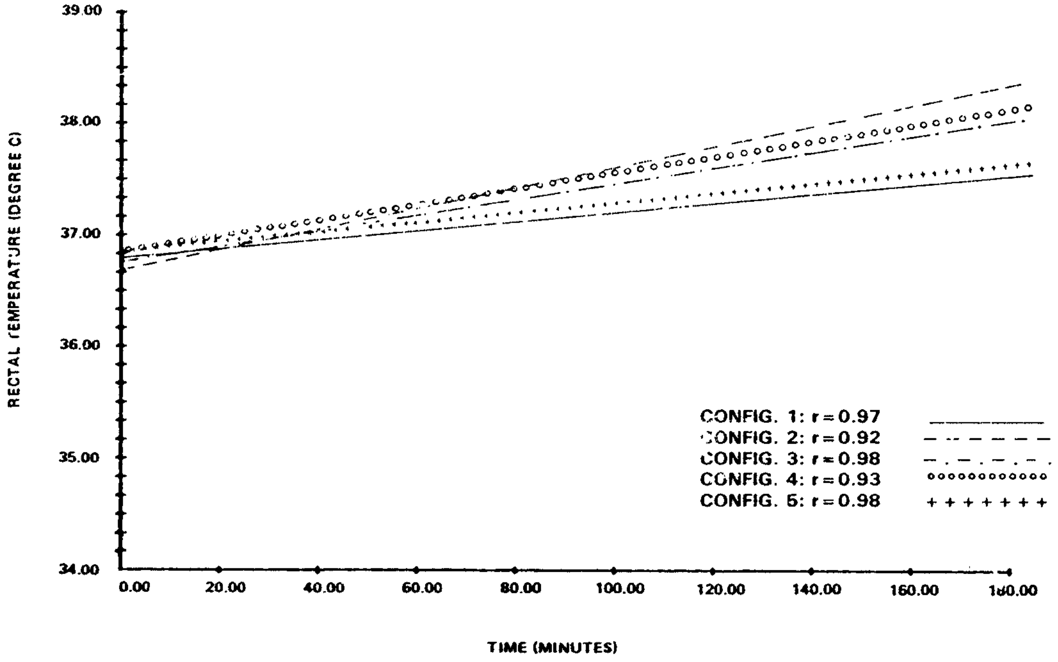

Figure 4. Regression : T_{re} vs. Time

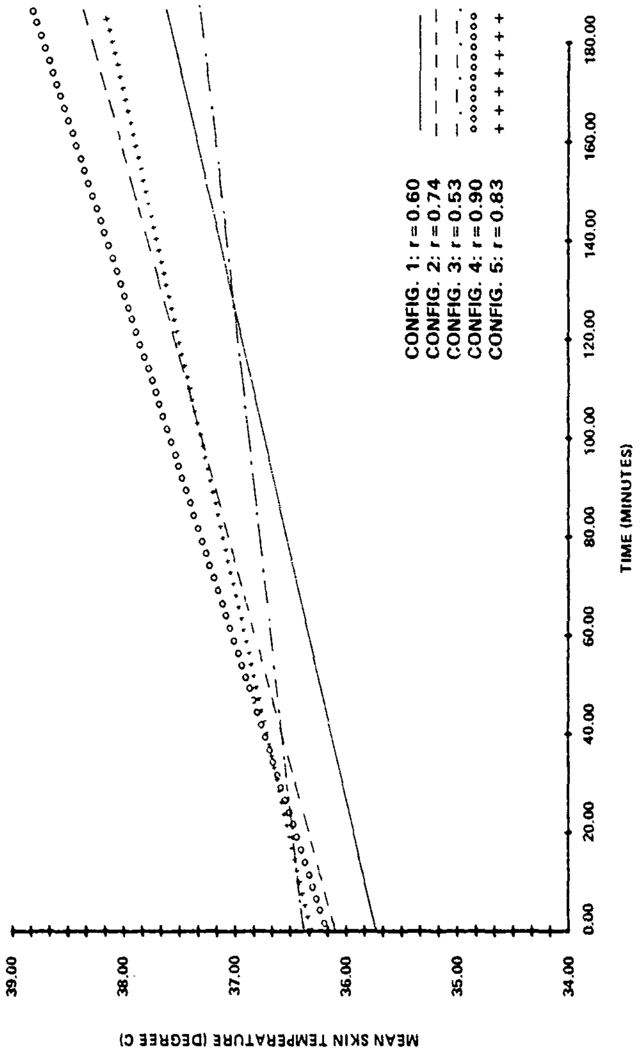

Figure 5. Regression: Mean T_{sk} vs. Time

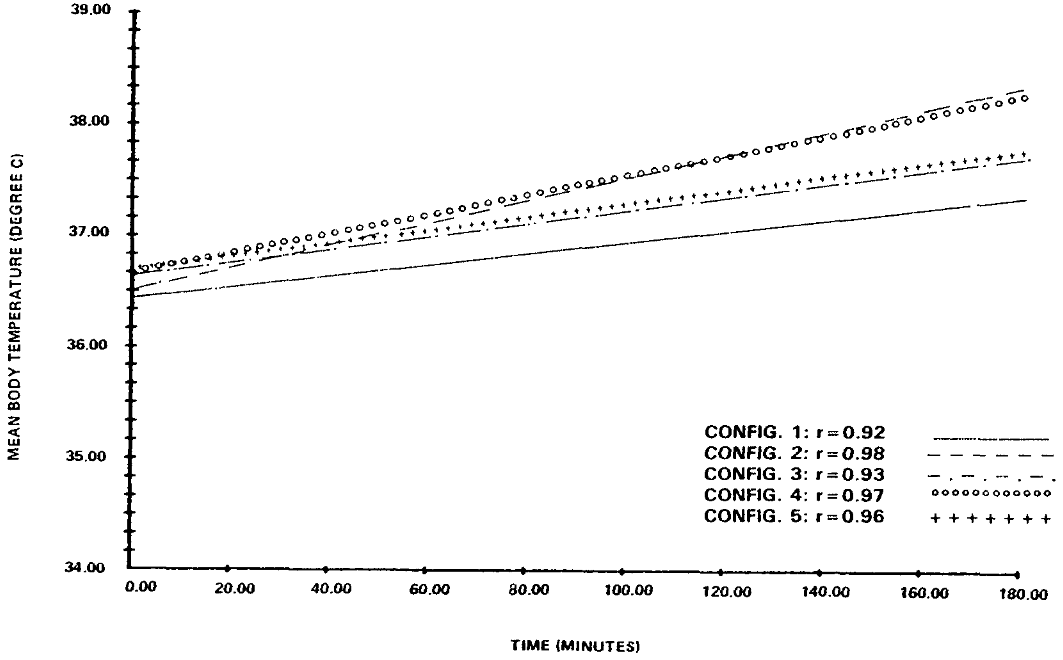

Figure 6. Regression: T_b vs. Time

The physiological basis for the test terminations is unclear, though it would seem likely that dehydration played a major role(17,18,19,20). While the correlation coefficient between test duration and SRT is not high (r = 0.461), the influence of other factors may tend to obscure this relationship(18). One study(20) has shown that in chemical defense suits with neck, wrist, and ankle seals, thermal strain is produced by significant dehydration. In addition, it has been previously observed(19) that excessive skin wetting during rising humidity depresses whole body sweating, thereby limiting effective body cooling.

Durations of less than three hours in this study might be explained by similar effects. Due to the presence of thermal underwear, which could absorb perspiration, as well as the passage of water vapor through the PTFE membrane, considerable sweating could occur before wetting of the skin surface began to depress sweating. Throughout the period in which unimpaired sweating occurred, an increase in T_{re} would be moderated by evaporative cooling(18, 19, 21). Ultimately, however, depression of whole body sweating(19) would reduce evaporative cooling, with a concomitant rise in T_{re}. Dehydration would be occurring simultaneously(20), which would exacerbate the thermal strain, while decreasing the physical work capability of the subject(22,23).

While all the aforementioned interactions were likely to be occurring, muscular fatigue was also probably occurring, due to the physical work performed by the subject. Complaints of fatigue were common at the termination of runs throughout the testing period. This fatigue was probably the result of both muscular fatigue and heat strain, and is reflected in the final HR(19).

Subjective indices of thermal sensation suggested that the presence of a liner significantly increased the perceived thermal strain. Thermal sensation may play a major role in task performance(24 15), which is an important consideration for constant-wear garments. Therefore, use of a liner in conjunction with the CWU-62/P coverall may adversely affect flight performance. It clearly affected the test durations in this evalution, based on the correlation analysis.

While none of the PTFE-based configurations allow for three hours of use under the test conditions, it should be recognized that a significant physical workload was placed on the test subjects. Thus, while extrapolating the results for a reduced workload is difficult, it is logical to assume increased durations would occur for more sedentary aircrew(20), (e.g. pilots). Flight operations up to three hours might be possible for these aircrewmen during normal operation when wearing configuration 5. However, for helicopter crewmen, the achieved test durations are likely to be representative of operational performance, due to the physical demands placed upon them(20).

Increased workloads, as during a national emergency, would greatly increase the stress experienced by all aircrew members(20). Because of the quick turnaround times, short rest periods and lack of time to permit the body to cool would be expected(20). Under these conditions, performance while wearing any of the tested configurations would be greatly reduced. The test durations obtained in this evaluation probably represent maximum performance under these conditions.

These test results do not lend themselves to direct comparison with evaluations of other anti-exposure suits under heat stress(1). While an attempt was made to produce similar environmental stresses in this evaluation as were previously used(1), a comparison of the index of strain(26) (Table 3) for both experiments indicates that the present evaluation presented subjects with greater stress(1). It would seem that this may be related to both workload and ambient relative humidity differences, though relative humidity was not reported in the previous evaluation(1).

CONCLUSIONS

1) The CWU-62/P coverall limits a wearer to less than three hours of operational duration, regardless of liner, under moderate workoads and simulated hot cabin conditions. This time could be expected to increase with less physical exertion, such that wearing the CWU-62/P coverall, with no liner, might permit three hours of operation for more sedentary aircrew (e.g. pilots).

2) Thermal sensation has a direct effect on heat toleration in these tests. Use of the CWU-62/P coverall without a liner reduced perceived thermal strain; this would be a preferred configuration.

3) Dehydration represents a potential hazard with the CWU-62/P under heat stress conditions. Adequate water supplies must be made available to aircrew wearing this garment to compensate for fluid losses.

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