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PHYSIOLOGICAL EFFECTS OF WEARING THE FIRE PROXIMITY SUIT ON CRASH TRUCK ALERT STATUS TO HOT-DRY AND HOT-HUMID ENVIRONMENTS

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13. ABSTRACT

Tests were conducted in the All Weather Test Facility to determine the physiologic penalty of wearing the fire fighter's proximity suit for a 2-hour alert cycle in the crash truck. Hot-dry and hot-humid environments were produced in the chamber which duplicated the most severe thermal conditions anticipated at hot weather bases. Three subjects wearing the proximity suit (except for gloves and helmet) were exposed (twice each) to either the hot-dry or hot-wet environments for 2 hours. In half of the tests, the proximity suit coat was also eliminated from the clothing assembly. For the given hyperthermic conditions, the 2-hour exposure periods do not elicit physiologic responses or symptoms indicative of incipient heat exhaustion although significant physiological decrements were observed. For operational relevancy, where a rescue procedure could be called for toward the conclusion of the thermal stress period, the suggestion is made to continue this effort with a series of tests in which an exercise regimen is superimposed on the thermal stress exposure.

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FOR THE COMMANDER

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PREFACE

This research was conducted in the Laboratory by personnel of the Environmental Physiology Branch, Environmental Medicine Division, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio.

The authors are indebted to Capt Grant Callin, Sgt Dan Bresnahan, Aerospace Medical Research Laboratory, and Capt Gerald Shumaker, Air Force Flight Dynamics Laboratory, who acted as subjects for these experiments. We also wish to thank Mr. Dave Smedley and Ms. Darlene Bach, System Research Laboratories, 2800 Indian Ripple Road, Dayton, Ohio, for their help in data reduction and Sgt Richard Chin and Mr. Walter Summers, Aerospace Medical Research Laboratory, for their help in running the statistical analyses.

INTRODUCTION

Crash truck crews wearing the fire fighter's proximity suit perform 2-hour duty tours on standby status. These assignments, occurring at hot weather bases combining the factors of high ambient temperature and heavy impermeable clothing assemblies, involve exposure to a potentially debilitating environment. In August 1971, in response to a request from the Aircraft Fire Suppression and Rescue SPO (SMF), field tests were conducted at Davis Monthan AFB, Arizona, and Edwards AFB, California, to evaluate the effects of wearing the proximity suit for a 2-hour alert cycle in the crash truck. Unsatisfactory weather conditions, time constraints, and test subject problems hampered the conduct of these tests. An in-house program was initiated to provide quantitative information concerning the physiologic penalties associated with wearing the proximity suit under moderate to severe hyperthermic conditions.

MATERIALS, FACILITIES, AND METHODS

Temperature, humidity, and wind velocities representative of both hot-dry and hot-humid climates were simulated in the Environmental Physiology Branch's All Weather Room. Values for these parameters in the United States, Southeast Asia, and the Middle East were obtained from Aeronautical Systems Division Staff Meteorology Office. On the basis of data supplied, temperatures of 36 C DB/33 C WB with approximately 7 mph wind were selected as representative of hot-humid conditions. Temperatures of 43 C DB/27 C WB with approximately 10 mph wind were selected as representative of hot-dry conditions.

Table 1

Physical Characteristics of Subjects

Subject	Age Yr.	Occupation	Height (Cm)	Weight (Kg)	Surface Area (m^2)
SC	30	Project Officer	173	76	1.93
BR	22	Airman	178	72.5	1.99
CA	31	Project Officer	171.5	76	1.90

Three volunteer subjects, whose physical characteristics are given in Table 1, were exposed twice to each thermal environment under two separate clothing assembly conditions. One assembly consisted of one-piece cotton underwear, cotton socks, fatigues, and proximity suit boots, trousers, and coat. The other assembly was the same except for the exclusion of the proximity suit coat. Gloves and helmet were deleted completely. The experiment design matrix is shown in Table 2.

The exposures were 2 hours in duration and were conducted in random order with respect to the environmental condition and clothing assembly worn. Smoking and consumption of beverage (cold water) were permitted on an ad lib basis during the exposure period. The amount of liquid ingested was monitored and used to adjust to postexperiment weight readings. The activity level of the subjects was not rigidly controlled but was encouraged to be maintained at a rate comparable to that of alert crews in and around the standby crash trucks.

Table 2

Experimental Design Matrix

	Hot, Humid 36 C, DB/33 C, WB	Hot, Dry 43 C, DB/27 C, WB
Fatigues—Proximity Suit Trousers and Boots	3 Subjects 2 Exposures Each 6 Experiments	3 Subjects 2 Exposures Each 6 Experiments
Same as Above Plus Proximity Suit Coat	3 Subjects 2 Exposures Each 6 Experiments	3 Subjects 2 Exposures Each 6 Experiments

Physiologic measurements included 17 skin temperatures (providing a calculated mean skin temperature); rectal temperature (used in combination with the mean skin temperature to provide the weighted mean body temperature); heart rate obtained by chest electrodes; and pre- and postexperiment weighings (both nude and clothed) providing the total sweat production and total sweat evaporated, respectively.

Body heat storage (Qs) is derived from the formula

$$Qs = (WC/A) \cdot \Delta Tb$$

where W = nude body weight (kg); C = specific heat of body mass (0.83 Kcal/KgC); Δ Tb = change in mean body temperature for a given unit of time; and A = body surface area (m^2). Qs is a quantitative expression of heat which the body is incapable of dissipating to the ambient environment. The principal avenue of heat dissipation is evaporative in hot environments. Failure of this compensatory mechanism under extended hyperthermic conditions leads to excessive body heat storage and the onset of heat pyrexia

Three subjects were tested simultaneously. After obtaining baseline control data, the subjects entered the chamber, were seated in office type padded straight back chairs with arm rests, and reconnected to the recording instruments. A preweighed container of cooled water for each subject, placed in a thermally insulated box, was placed in the chamber. Heart rate was monitored continuously but recorded at 15 min intervals as were the mean skin and rectal temperatures.

The data were analyzed by analysis of variance using the BMD 02V program. Levels of the experimental conditions were compared using individual degree of freedom contrasts.

RESULTS AND DISCUSSION

MAJOR EFFECTS

Mean skin temperatures of the subjects were remarkably similar under all experimental conditions and rose about 5 C during the 2 hour heat exposures (Fig. 1). Core temperatures (Fig. 2) rose significantly less ($p < .005$) when the subjects were in a hot-dry environment wearing no coat as opposed to the other three conditions (Table 3). Thus, the presence of a coat or a humid environment accelerated the rise in core temperature during the final hour of exposure. This effect was reflected in the calculated mean body temperature (Fig. 3) and body heat storage (Fig. 4) due to the effect on core temperature coupled with homogeneous mean skin temperatures. Heart rate (Fig. 5) likewise was significantly ($p < .005$) elevated for these subjects in the humid environment or when the subjects wore the coat (Table 4). This amounted to an average 12 beats/min penalty during the last hour of exposure. Thus, thermal and cardiovascular strain was increased by wearing a coat or a humid environment.

Careful examination of the sweat production and evaporation data help explain the above effects (Fig. 6). Sweat production was significantly increased ($p < .01$) by the presence of the coat over the no coat conditions, while sweat evaporation was significantly greater ($p < .005$) under the dry conditions than under the humid conditions. The best combination for the subject would be that condition showing the greatest evaporation with the least sweat production—the no coat dry condition. This is evidenced by the significantly greater ($p < .005$) sweat evaporation/sweat production ratio of this condition versus the other three (Table 5).

Table 3

Analysis of Variance of Rectal Temperature Data

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
1. Experimental Conditions	3	2.13948	0.71316
a. C_1 = no coat wet + coat wet + coat dry vs 3 no coat dry	1	1.45925	1.45925
b. C_2 = no coat wet vs coat wet	1	0.13019	0.13019
c. C_3 = no coat wet + coat wet vs 2 coat dry	[illegible]	0.55009	0.55009
		2.13953	
2. Subjects	2	0.59312	0.29656
3. Time	3	2.65615	0.88538
12 Interaction	6	0.50771	0.08462
13 Interaction	9	0.35260	0.03918
23 Interaction	6	0.00604	0.00101
123 Interaction	18	0.10646	0.00591
Within Replicates	48	1.00500	0.02094
Total	95	7.36656	

Table 4

Analysis of Variance of Heart Rate Data

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares
Experimental Conditions	3	2755.45833	918.48611
a C_1 = no coat wet + coat wet + coat dry vs 3 no coat dry	1	2725.681	2725.681
b. C_2 = no coat wet vs coat wet	1	27.000	27.000
c. C_3 = no coat wet + coat wet vs 2 coat dry	1	2.777	2.777
		2755 458	
2 Subjects	2	7825.33333	3912.66667
3. Time	3	931.45833	310.48611
12 Interaction	6	1546.66667	257.77778
13 Interaction	9	620.37500	68.93056
23 Interaction	6	703.66667	117.27778
123 Interaction	18	455.00000	25.27778
Within Replicates	48	3806.00000	79.29167
Total	95	18643.95833	

Table 5

Analysis of Variance of Sweat Evaporation/Sweat Production

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square
1. Experimental Conditions	3	0 55668	0.18556
a. C_1 = no coat wet + coat wet + coat dry vs 3 no coat dry	1	0.521302	0.521302
b. C_2 = no coat wet vs coat wet	1	0.003996	0.003996
c. C_3 = no coat wet + coat wet vs 2 coat dry	1	0.031381	0.031381
		0.556679	
2. Subjects	2	0.0691996	0.0345998
12 Interaction	6	0.178986	0.0298309
Within Replicates	12	0.276258	0.0230215
Total	23	1.08112	

Both the dry or humid thermal exposures where the coat is worn, as well as the humid exposures without the coat present essentially the same climatic environment to the surface of the body, a hot humid microclimate. Only in the dry exposures where no coat is worn does a favorable vapor pressure gradient exist for sweat evaporation and thus provide a dramatic amelioration of physiological strain.

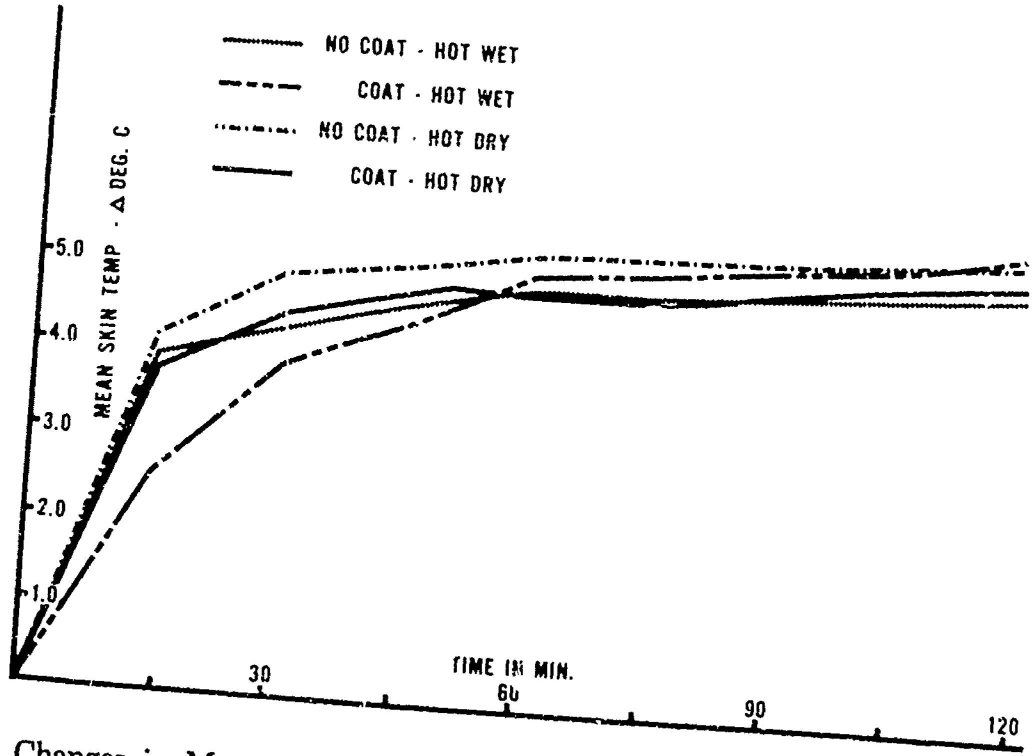

Figure 1. Changes in Mean Skin Temperature for the 2-Hour Exposure to the Various Room Temperature and Clothing Assembly Conditions

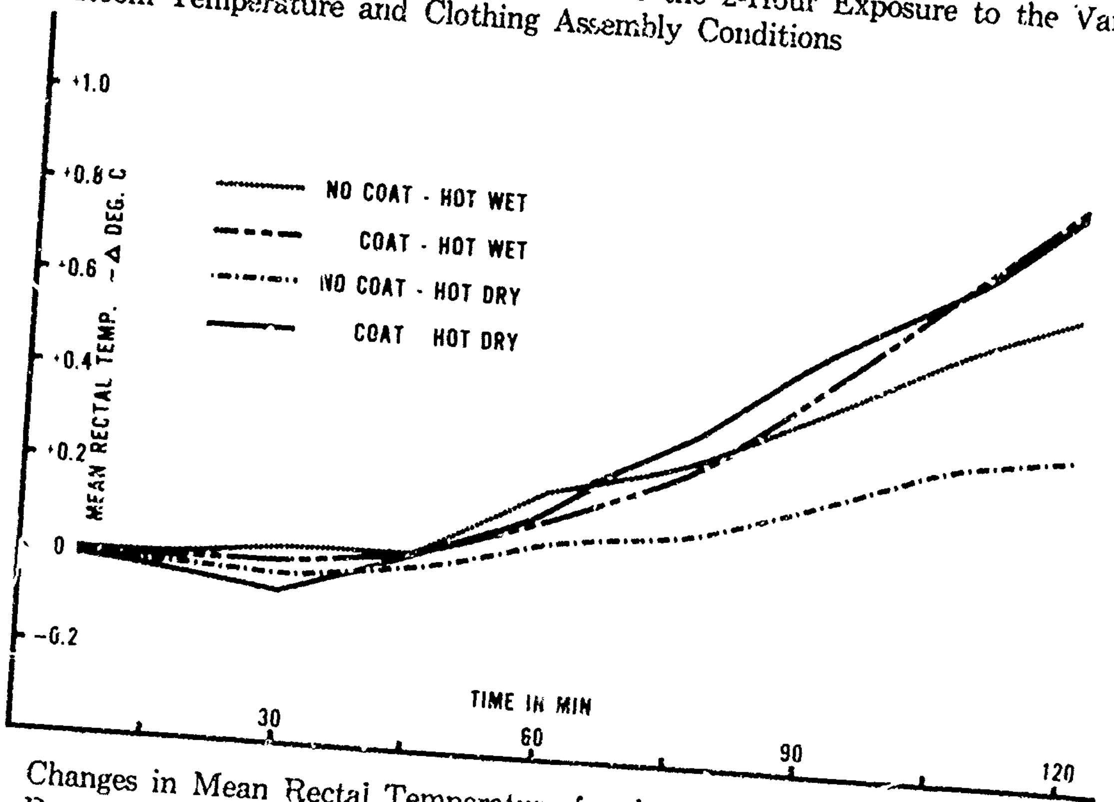

Figure 2. Changes in Mean Rectal Temperature for the 2-Hour Exposure to the Various Room Temperature and Clothing Assembly Conditions

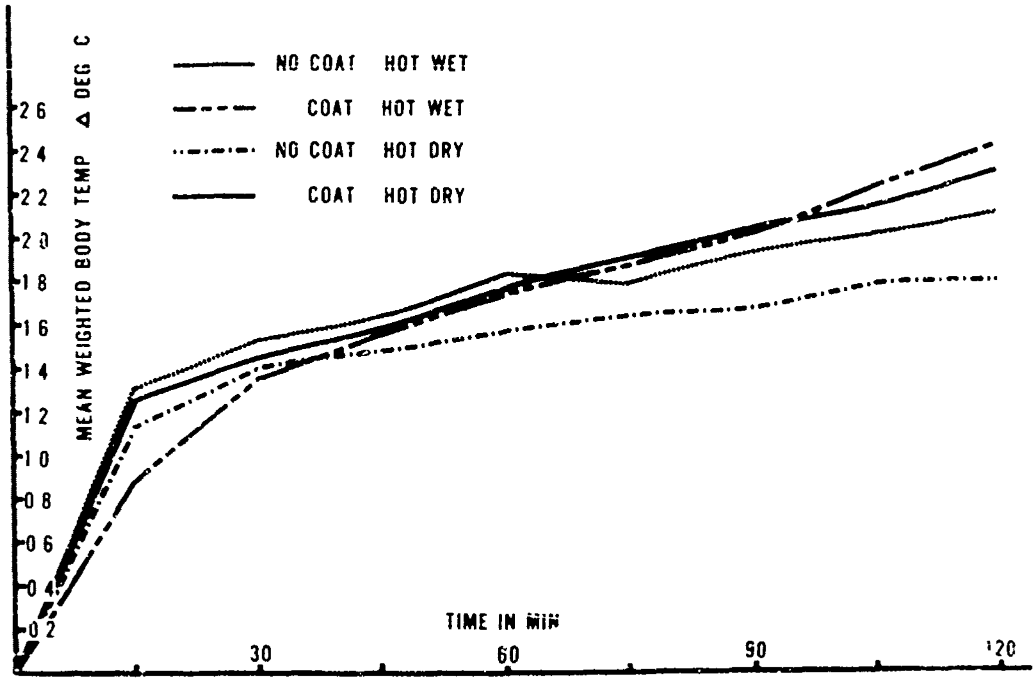

Figure 3. Changes in Mean Body Temperature for the 2-Hour Exposure to the Various Room Temperature and Clothing Assembly Conditions

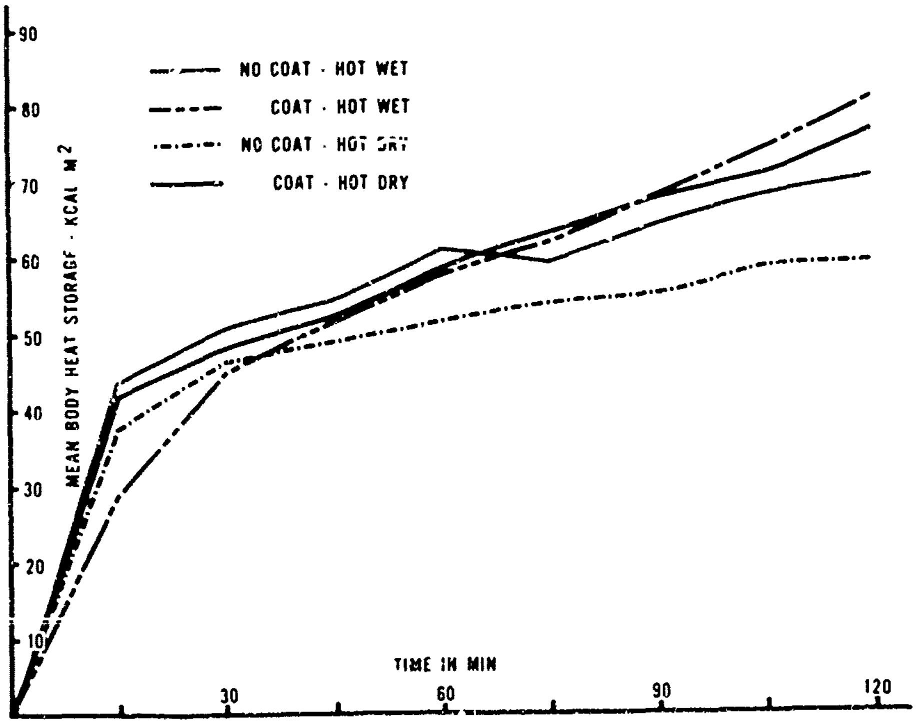

Figure 4. Changes in Mean Body Heat Storage for the 2-Hour Exposure to the Various Room Temperature and Clothing Assembly Conditions

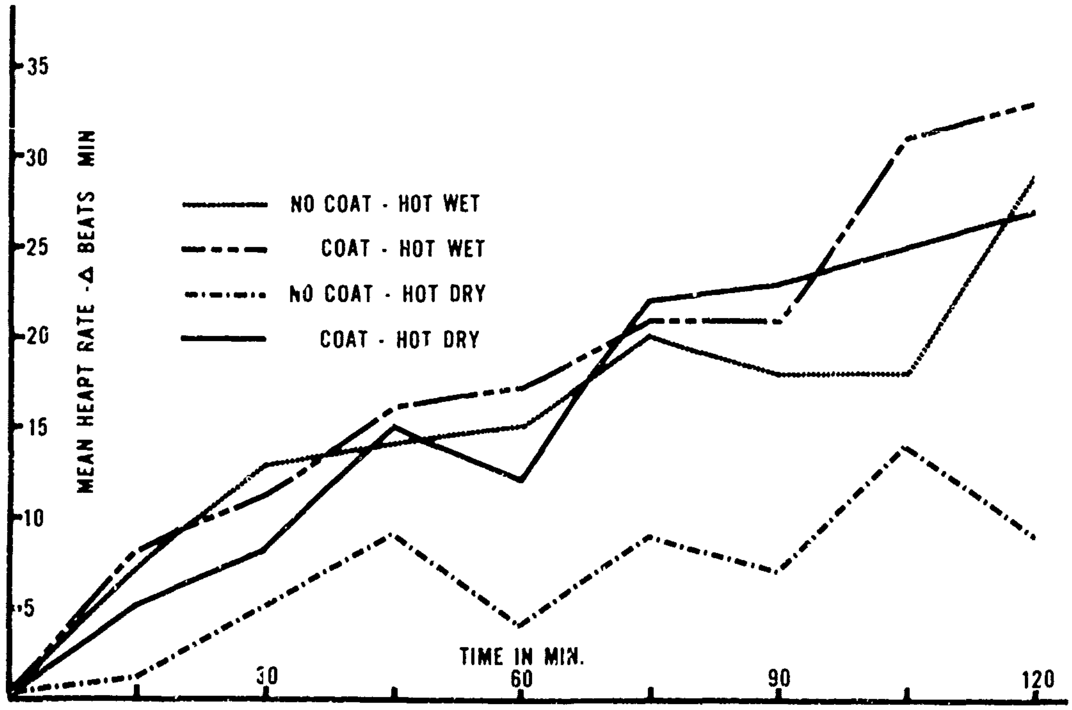

Figure 5. Changes in Mean Heart Rate for the 2-Hour Exposure to the Various Room Temperature and Clothing Assembly Conditions

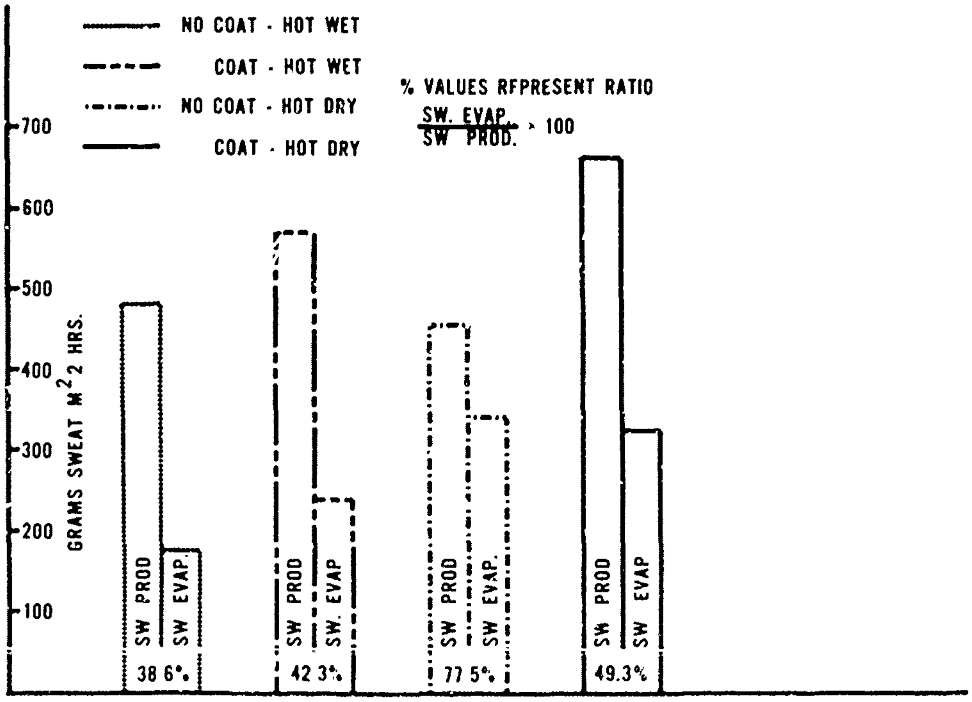

Figure 6. Total Sweat Production, Sweat Evaporation, and Sweat-Evaporation Ratio for the 2-Hour Exposure to the Various Room Temperature and Clothing Assembly Conditions

EFFECT OF WEARING THE COAT

The presence of the coat itself imposed significant penalties on the subjects regardless of the humidity. Sweat production (Fig. 6) was significantly greater with the coat than without, irrespective of humidity ($p < .01$), and this is related to the reduced convective and radiative heat loss while wearing the coat in a humid environment where the temperature is below mean skin temperature as compared to no coat in the same environment. In dry environments, the vapor barrier to evaporative cooling imposed by the coat predominates. Thus, the presence of the coat leads to a more rapid onset of dehydration, greater water and salt requirements, and a decreased effective work cycle. Rectal temperatures during the final hour of heat exposures were significantly higher ($p < .005$) wearing the coat no matter what the humidity (Fig. 2). This is especially evident during the final 30 minutes of exposure. The increased sweat production associated with wearing the coat was not able to fully compensate for the decrease in heat exchange to the environment. Wearing the coat would lead to a quicker onset of hyperpyrexia. There was a significant tendency ($p < .005$) for cardiovascular strain (as evidenced by heart rate) to be greater in these men while wearing the coat than not wearing it, when averaged over both humidity conditions.

OPERATIONAL IMPACT

None of the experimental combinations of heat, humidity, and coat or no coat conditions produce a level of physiologic strain that could be described as "tolerance." Even under environmental conditions that could be considered more stressful, the mean skin temperature rise is limited to slightly more than 5 C; terminal rectal temperature is less than 1 C above baseline values, and maximum elevation of heart rate above baseline is less than 35 beats/min. Wearing the coat under hot-dry conditions does place the subject in double jeopardy in terms of water loss. The higher dry bulb temperature stimulates increased sweat production, which is augmented by the hot humid environment under the impermeable coat preventing effective evaporation. Body heat storage (Fig. 4) of 70 Kcal/m^2 does constitute a severe thermal stress and was achieved in both the hot-dry and hot-humid environments where the coat is worn. Maintenance of this storage level (70–80 Kcal/m^2) for less than 30 minutes places the subject just short of the threshold of tolerance. While the terminal level of physiologic strain is admittedly below the point of compensatory failure, the question of operational relevancy arises. When one considers the possibility of a true emergency developing toward the conclusion of such an exposure, an emergency which would very likely call for an expenditure of maximum effort, the question of performance capability assumes critical importance since our subjects were approaching heat storage limits wearing the coat. Exercise, because of its increased heat production and cardiovascular strain, may well push the heat loaded subject beyond tolerance. There is no way, on the basis of the data generated in the present study, to assess the impact of these sequential stresses. An additional series of tests is planned that will superimpose, on an identical thermal exposure, an exercise regimen simulating the activity level associated with a rescue operation.

CONCLUSIONS

Wearing the fire fighter's proximity suit (with the exception of gloves and helmet) under the given hyperthermic conditions for a period of 2 hours does not elicit physiologic responses or symptoms indicative of incipient heat exhaustion.

The proximity suit is an impermeable garment which, under the conditions of thermal exposures described here, produces a hot, humid microclimate around the subject. It follows that where an appropriate vapor pressure gradient exists, removal of the coat precludes the development of the microclimate, permits evaporative cooling, and significantly ameliorates the impact of the thermal stress.

Data generated in the present study do not indicate the extent of performance decrement (if any) associated with rescue operations immediately after the hyperthermic exposure period.

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