THE EFFECT OF CLOTHING ON THE ABILITY OF MEN TO WORK IN INTENSE HEAT

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Although many observations have been made on the upper limits of heat tolerated by working men (1 to 6), little work has been published on the specific effects of clothing on man's performance in these limiting hot environments. Gagge, Winslow, and Herrington's calorimetric studies (7) on the effect of clothing were done on resting men in environments with operative temperatures below 101° F. However, Robinson, Turrell, and Gerking (8) have studied this problem by comparing the most severe environments in which both nude and clothed men could maintain thermal equilibrium after the second hour of a six hour work period. They showed experimentally that men wearing a single layer of light clothing (windbreak poplin) could maintain thermal equilibrium only when the environments were less severe than those tolerated by nude men. The clothing had the same effect as lowering the limiting wet bulb temperature of the environment 2° to 6° F., depending on the work rate and environment.

A previous report from this laboratory (6) described the upper limits of heat that could be tolerated by highly acclimatized nude men working for four hours at approximately 250 Cal. per hour. The present investigation was undertaken to extend these data and to study the rôle of clothing by determining certain of the most severe environments in which highly acclimatized clothed men could work at this rate.

PROCEDURE

All experiments were conducted during January, February and March 1945 in a laboratory hot room (35′ × 22′ × 14′). A Carrier 15–T6 air processing unit permitted control to within + or − 1° F. of the desired dry or wet bulb air temperature. For each set of conditions the air temperature was maintained for four to five days before any tests were conducted so that walls and air were in equilibrium. Throughout the tests, the dry and wet bulb temperatures were measured every fifteen minutes, by means of motor driven psychrometers carried around the track at a level of four feet. Air temperatures showed a gradient of about 4 degrees from the floor to the six foot level. Wall temperatures were approximately 2° to 5° cooler than the air, floor temperatures 10° cooler at a dry bulb temperature of 95° F. and up to 20° cooler at 120° F. The air movement was turbulent and was essentially that produced by the movement of the men marching at 3 mph.

In the zone of hot environments in which the dry bulb temperature (D.B.) ranges from 90° to 120° F. man's performance is limited by the wet bulb temperature (W.B.) (6). Accordingly, it was felt that the upper limits of working men's tolerance to heat could be determined by studying man's ability to march for four hours under varying wet bulb temperatures at two levels of dry bulb temperature. After preliminary study the following test environments were chosen because they represent critical wet bulb temperatures.

D.B. (°F)	W.B. (°F)	R.H. (per cent)
95	94	97
93	92	97
120	92	35
120	90	31
120	88	25

Ten healthy male soldiers (Table I) were the subjects. After a two-week physical conditioning program in the cool, the men were acclimatized to the heat by graded

TABLE I

Physical characteristics of subjects

Name	Age	Weight	Height	Surface area
	yrs.	*lbs.*	*in.*	M^2
Di	21	140	68	1.75
Hi	24	150	67	1.78
Ka	24	171	71	1.97
Kn	20	168	72	1.99
Li	20	169	72	1.99
Lo	20	141	64	1.69
Ma	20	153	70	1.86
Mi	20	145	69	1.80
Sc	21	178	71	2.02
Sz	23	144	69	1.80
Mean	21	156	69	1.87

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activity at D.B. 120°—W.B. 88° F. for 21 days before the test began. They were fully acclimatized to four hours of marching with pack in this environment before any of the test environments were studied. In addition to this preliminary acclimatization, the men marched for 3 days in each new environment, before the testing was done. This added acclimatization to each specific environment was necessary to insure peak performance at these limiting environments which did impose a greater thermal load than D.B. 120°—W.B. 88° F. At each environment the nude and clothed state were compared in each man on two consecutive test days. The standard work consisted of marching with 20 lb. packs, at 3 mph. for four hours continuously around a 77 foot track in the hot room. This work rate was previously determined on other subjects to be approximately 250 Cal. per hour. The four work periods each morning were followed by a three hour rest in the nude, in the afternoon. At night the men lived in barracks maintained at about 70° F.

Each man was studied (*1*) in the nude, wearing only shoes and socks, (*2*) clothed in a standard two piece single layer herringbone twill (8 oz.) army fatigue uniform, and (*3*) clothed in a special impregnated herringbone twill uniform. This latter garment was treated with an impregnating mixture containing paraffin, which increased the weight of the uniform by 40 per cent, increased its water repellency and reduced its permeability to air, water, and water vapor. The uniforms were dry at the start of each day. The clothing was always worn with cotton shorts, socks and shoes. The trouser legs were tucked inside the socks, the jacket of shirt inside the trousers, and the clothing always completely buttoned.

The subjects entered the hot room to be weighed nude and to dress. After an initial 8 minutes the skin temperatures, pulse rate (standing erect) and rectal temperature were taken. The start of the march immediately followed. Pace discipline was enforced. The heart rate (marking time) and rectal temperature were taken again at the end of each hour, during a three minute break. At the end of the four hour march, or at the time of falling out, skin temperatures, pulse rate and rectal temperature were again taken, as well as a final nude weight. Water consumption (0.1 per cent saline, 95° F.) and urine output were recorded. Clothing was weighed before and immediately after each wearing. Skin temperatures of the cheek, chest, palm, forearm, and calf were determined radiometrically on the erect subject, the clothing being pushed away just sufficiently to permit placing the radiometer. The temperatures were integrated into an average skin temperature by the following weighting formula based on that of Hardy and Dubois (9) : cheek 0.10, chest 0.44, forearm 0.14, calf 0.23, palm 0.09. Only the average weighted skin temperature is reported. Rectal temperatures were measured with calibrated clinical thermometers, pulse rates by palpation. Records were kept of the symptoms, complaints, general appearance, vigor and alertness of the men. Men were removed from test only when objective or subjective signs indicated it to be necessary.

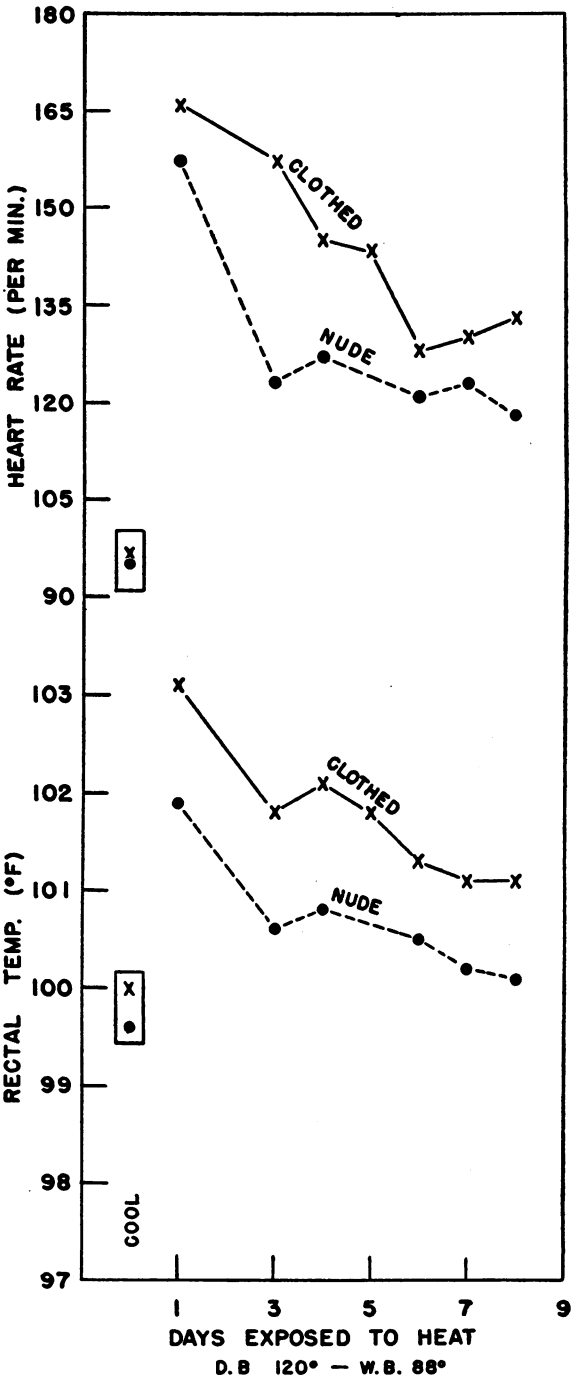

FIG. 1. EFFECT OF WEARING HERRINGBONE TWILL UNIFORM ON THE RATE OF ACCLIMATIZATION

Data presented were obtained at the end of 1 hour march at D.B. 120°—W.B. 88° F. except that the data in blocks were taken on men working at D.B. 77°—W.B. 62° F.

TABLE II

Physiologic effects of wearing standard herringbone twill clothing on acclimatized men working in the heat
D.B. 120° F—W.B. 90° F

Name	Clothing	Rectal temperature °F					Pulse rate per min.					Skin temp. (Avg. wtd.) °F		Weight loss* (Sweat)
		hours 0	1	2	3	4	hours 0	1	2	3	4	hours 0	4	grams per hour
Hi	Nude	98.7	99.7	100.0	99.9	99.9	108	123	111	111	117	96.5	96.4	1477
	Clothed	99.3	100.6	101.0	100.1	100.0	102	117	126	123	117	97.1	97.3	1859
Ka	Nude	98.6	99.7	99.8	99.7	99.8	102	123	123	120	114	96.3	97.2	1421
	Clothed	98.4	100.4	100.7	100.3	100.0	111	135	129	123	132	97.3	97.2	1711
Lo	Nude	98.4	99.6	100.2	99.9	100.2	96	114	120	120	117	96.5	97.8	1645
	Clothed	98.4	100.7	101.2	100.9	100.8	96	120	129	132	135	97.3	97.9	1543
Mi	Nude	98.5	100.0	100.5	100.4	100.3	117	126	129	123	123	97.6	96.8	1901
	Clothed	98.3	100.7	101.2	101.0	101.0	102	120	153	138	138	97.3	97.3	2123
Sc	Nude	99.0	100.4	100.3	99.9	100.1	111	129	126	123	123	97.7	96.9	2239
	Clothed	98.7	100.8	100.6	100.3	100.2	105	123	135	126	120	98.2	97.1	2693
Mean	Nude	98.6	99.9	100.2	100.0	100.1	107	123	122	119	119	96.9	97.0	1737
	Clothed	98.6	100.6	100.9	100.5	100.4	103	123	134	128	128	97.4	97.4	1986

* The term weight loss is used to indicate gross sweat loss only. It does not represent an actual change in body weight since throughout all tests the men maintained body weights constant to within ± 0.5 kgm. by water replacement.

RESULTS

During the initial period of the three weeks' acclimatization to D.B. 120°—W.B. 88° F., the ten men were divided into two groups to study the effect of clothing on acclimatization. One group wore herringbone twill uniforms each day and the other worked nude. During the first eight days the work load which started with one hour was increased by an hour every third day until the standard work period of four hours was reached. Only the man's rectal temperatures and pulse rates at the end of the first hour were stud-

TABLE III

Physiologic effects of wearing standard herringbone twill clothing on acclimatized men working in the heat
D.B. 120° F—W.B. 92° F

Name	Clothing	Rectal temperature °F					Pulse rate per min.					Skin temp. (Avg. wtd.) °F		Weight loss (Sweat)
		hours 0	1	2	3	4	hours 0	1	2	3	4	hours 0	4	grams per hour
Hi	Nude	98.4	100.4	100.4	100.4	100.6	87	111	102	117	111	97.2	98.7	1562
	Clothed	98.2	100.8	101.7	101.7	102.0	102	129	111	147	123	97.9	99.4	1688
Ka	Nude	98.6	100.0	100.0	100.2	100.7	96	120	120	132	123	97.1	98.5	1684
	Clothed	98.7	101.2	102.0	102.0	101.8	105	150	147	141	150	97.2	99.3	1774
Lo	Nude	98.6	100.1	101.4	101.7	102.1	102	144	129	120	132	98.1	99.4	1396
	Clothed	98.9	102.0	103.1	*		105	144	144	*		98.0	*	*
Mi	Nude	98.8	100.3	100.4	100.5	101.0	105	126	150	123	126	97.8	98.7	2071
	Clothed	98.8	101.3	101.8	†		129	147	141	†		98.3	†	†
Sc	Nude	99.3	101.4	101.2	101.2	101.5	111	156	123	120	126	97.8	98.2	2543
	Clothed	99.0	102.0	102.3	102.4	102.5	114	147	132	132	126	98.1	99.2	2477
Mean	Nude	98.7	100.4	100.7	100.8	101.2	100	131	125	122	124	97.6	98.7	1851
	Clothed	98.7	101.5	102.2			111	143	135			97.9		

* Unable to continue after 2.4 hours—final data: 103.2, 150, 100.4 and 1589.
† Unable to continue after 2.7 hours—final data: 102.4, 156, 99.6 and 2063.

TABLE IV

Physiologic effects of wearing standard herringbone twill clothing on acclimatized men working in the heat
D.B. 93° F—W.B. 92° F

Name	Clothing	Rectal temperature °F					Pulse rate per min.					Skin temp. (Avg. wtd.) °F		Weight loss (Sweat)
		hours 0	1	2	3	4	hours 0	1	2	3	4	hours 0	4	grams per hour
Di	Nude	98.8	100.0	100.4	100.6	100.6	93	129	114	123	117	95.3	96.4	1706
	Clothed	98.5	101.0	101.1	101.3	101.4	93	135	135	123	132	95.6	97.8	1760
Kn	Nude	98.4	99.8	100.1	100.4	100.3	90	114	117	117	120	94.8	97.0	1848
	Clothed	98.5	100.9	101.2	101.0	101.0	108	120	129	129	123	95.8	98.2	1824
Li	Nude	99.7	100.7	100.6	100.7	100.6	93	117	108	117	126	96.4	96.5	1908
	Clothed	99.4	101.7	102.3	102.0	102.1	105	135	126	144	144	96.6	98.1	2353
Ma	Nude	98.4	100.3	100.7	100.8	100.6	120	150	153	141	138	95.3	96.7	1791
	Clothed	98.1	100.9	101.6	101.3	101.6	102	141	144	150	156	95.9	97.6	2244
Sz	Nude	98.0	99.4	99.5	99.8	99.8	87	108	120	123	123	95.2	96.8	1705
	Clothed	98.7	100.6	101.5	101.0	100.7	105	129	141	132	123	95.9	97.9	1760
Mean	Nude	98.7	100.0	100.3	100.5	100.4	97	124	122	124	125	95.4	96.7	1792
	Clothed	98.6	101.0	101.5	101.3	101.4	103	132	135	136	136	96.0	97.9	1988

ied. The first hour was chosen for presentation since it was the only work load accomplished by the entire group on all days. The difference in pulse rate and rectal temperature remained constant between the two groups in response to this constant work stimulus (Figure 1). The relative effect of the clothing appeared to be no greater in the unacclimatized individual than in the acclimatized.

UPPER LIMIT STUDIES

Data on the upper limits for the subjects working both nude and clothed in ordinary herringbone twill are presented in Tables II to V, and Figures

TABLE V

Physiologic effects of wearing standard herringbone twill clothing on acclimatized men working in the heat
D.B. 95° F—W.B. 94° F

Name	Clothing	Rectal temperature °F					Pulse rate per min.					Skin temp. (Avg. wtd.) °F		Weight loss (Sweat)
		hours 0	1	2	3	4	hours 0	1	2	3	4	hours 0	4	grams per hour
Hi	Nude	98.7	100.4	101.3	101.1	101.1	96	114	132	132	123	95.4	96.8	1806
	Clothed	99.0	101.7	102.8	*		114	144	135	*		96.6	*	*
Ka	Nude	98.4	100.0	100.8	100.7	101.0	114	141	147	135	156	95.6	97.2	1600
	Clothed	98.6	101.3	102.7	†		114	159	171	†		96.1	†	†
Lo	Nude	99.1	100.8	101.6	102.2	102.6	108	132	135	138	141	96.4	98.1	1771
	Clothed	99.1	102.2	103.5	‡		114	156	156	‡		96.7	‡	‡
Mi	Nude	100.0	100.1	101.0	101.0	101.4	102	129	132	138	144	95.5	97.4	2500
	Clothed	98.6	101.6	§			120	162	§			96.4	§	§
Sc	Nude	99.1	100.4	101.1	101.7	101.5	105	138	144	138	132	94.7	97.2	3087
	Clothed	98.8	101.7	102.6	103.0	102.9	108	150	153	150	156	95.9	99.2	2586
Mean	Nude	99.1	100.3	101.2	101.3	101.5	105	131	138	136	139	95.5	97.3	2153
	Clothed	98.8	101.7				114	154				96.3		

* Unable to continue after 2.2 hours—final data: 102.7, 150, 98.4 and 1804.
† Unable to continue after 2.0 hours—final data: 102.7, 171, 98.3 and 2243.
‡ Unable to continue after 2.8 hours—final data: 103.4, 150, 99.1 and 1626.
§ Unable to continue after 1.8 hours—final data: 102.9, 144, 98.3 and 2356.

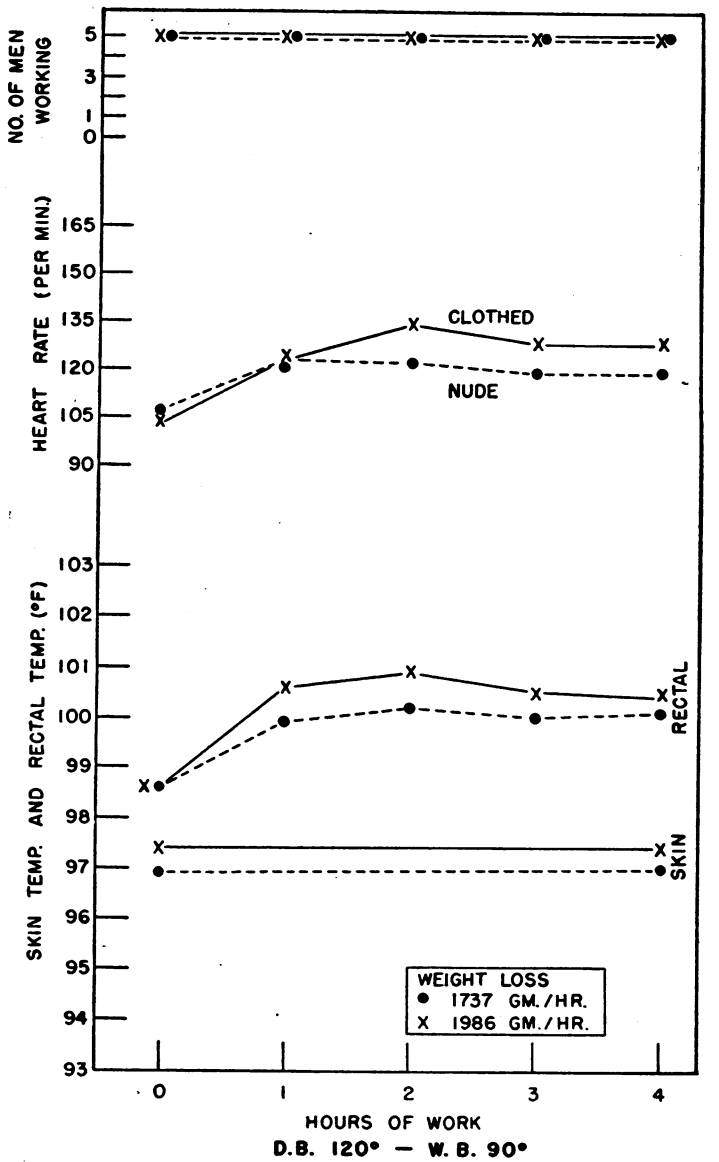

FIG. 2. AVERAGE PHYSIOLOGIC EFFECTS OF WEARING STANDARD HERRINGBONE TWILL UNIFORMS ON ACCLIMATIZED MEN MARCHING 3 MPH. AT D.B. 120°—W.B. 90° F.

This is one of the upper limiting environments for four hours of work in the clothed man. Key, •---• nude; x——x clothed.

2 to 6. In view of the impossibility of elaborately characterizing the special impregnated garments at this time, data on the men wearing these have been omitted but all the pertinent conclusions will be presented in the text.

Environments with D.B. 120° F

When nude, subjects were able to complete the required 4 hours of marching in environments with wet bulb temperatures up to and including 92° F. However, when clothed in herringbone twill, they were able to complete, as a group, 4 hours of marching at a W.B. of 90° F. but not 92° F. At W.B. 92° F., although three of the men could finish 4 hours two were unable to complete even 3 hours of work. When clothed in the special impregnated herringbone twill the men could not complete, as a group, four hours of marching at

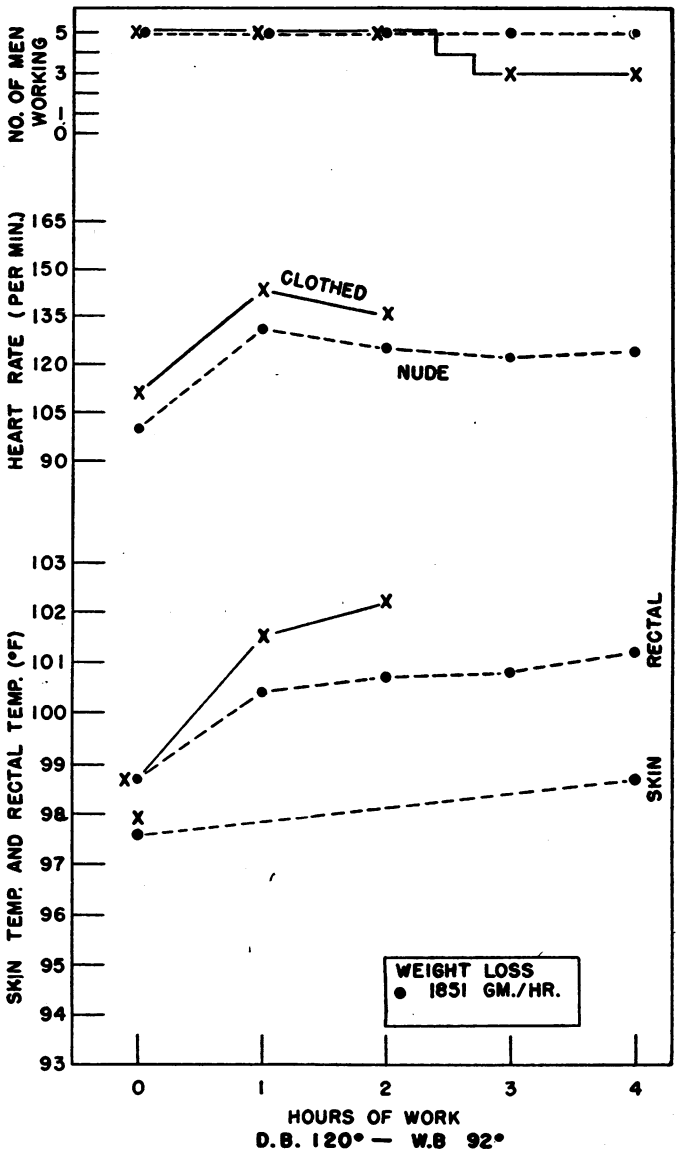

FIG. 3. AVERAGE PHYSIOLOGIC EFFECTS OF WEARING STANDARD HERRINGBONE TWILL UNIFORMS ON ACCLIMATIZED MEN MARCHING 3 MPH. AT D.B. 120°—W.B. 92° F.

This is above the upper limits for four hours of work for the group when clothed since two men failed to finish. Unless group finishes comparable period of work data not plotted. Key, •---• nude; x——x clothed.

wet bulb temperatures above 88° F. Hence it was found (Figure 6) that the upper limiting wet bulb temperature for successful group performance of 4 hours of marching at D.B. 120° F., was 92° F. for nude men, 90° F. for herringbone twill clothed, and 88° F. for men wearing the specially treated herringbone twill uniform.

Environments with D.B. 93° and 95° F.

At D.B. 95° F., the group when nude was able to march 4 hours at wet bulb temperatures up to and including 94° F. This demonstrates the importance of the wet bulb temperature in this zone of evaporative heat regulation, in critically limiting man's performance since a reduction of the dry

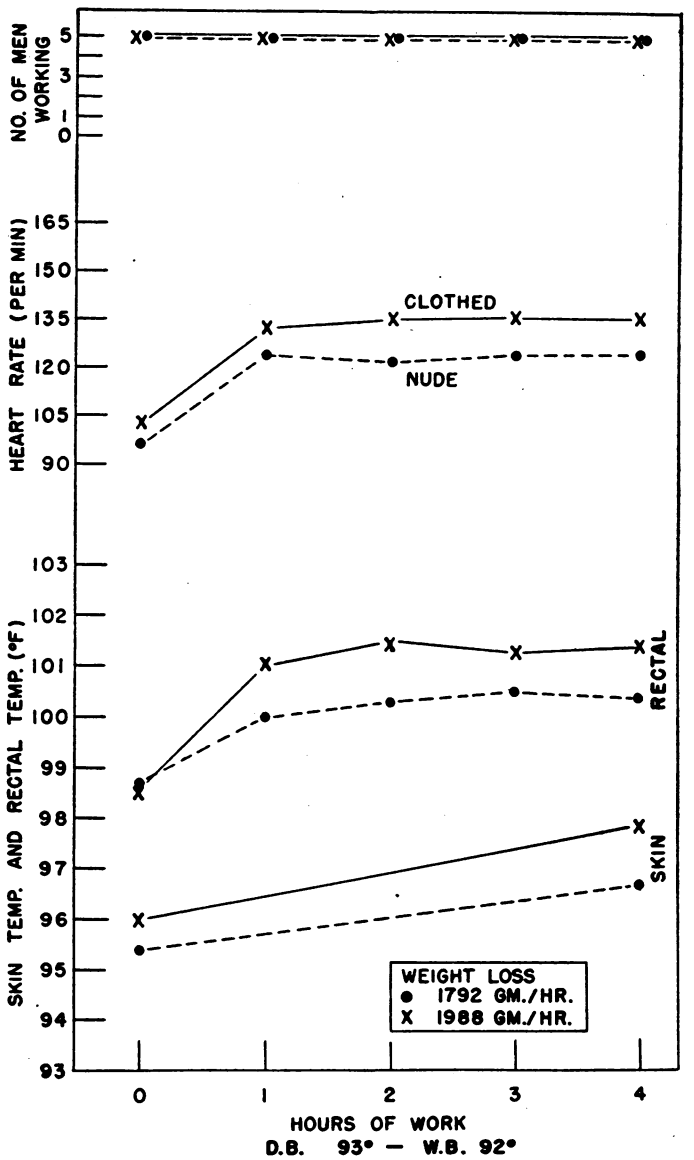

FIG. 4. AVERAGE PHYSIOLOGIC EFFECTS OF WEARING STANDARD HERRINGBONE TWILL UNIFORMS ON ACCLIMATIZED MEN MARCHING 3 MPH. AT D.B. 93°—W.B. 92° F.

This is one of the upper limiting environments for four hours of work in the clothed man. Key, ·----· nude; x——x clothed.

bulb temperature by 25° resulted in elevating the wet bulb upper limit by only 2° F. When the men worked in either the untreated or treated herringbone twill, the upper limit was D.B. 93°—W.B. 92° F. Thus, in the saturated environment, the two types of clothing could not be clearly distinguished on the basis of group performance.

Physiological Responses

The effect of clothing is not restricted to its effect on work performance alone, but it is reflected also in significant physiologic changes in the rectal and skin temperatures and pulse of men working in hot climates. These physiological changes (Tables II toV) should be contrasted with the minimal effect of clothing on these men performing the standard work in a relatively cool environment. The following data compare the group averages of the nude and clothed men at the

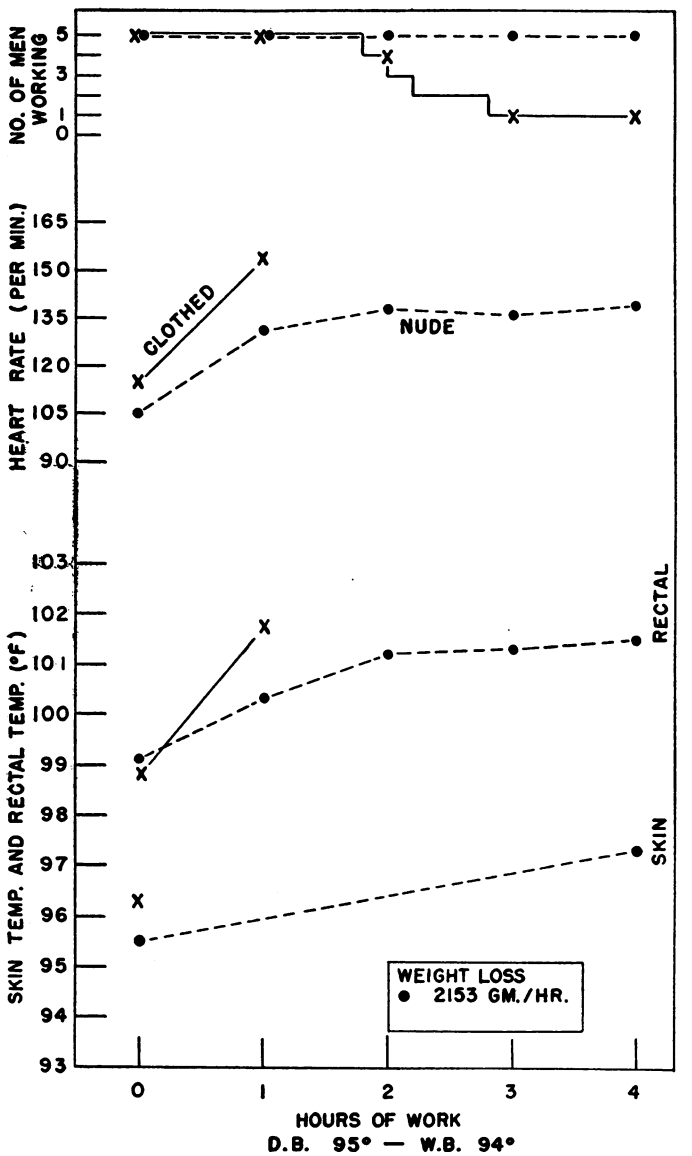

FIG. 5. AVERAGE PHYSIOLOGIC EFFECTS OF WEARING STANDARD HERRINGBONE TWILL UNIFORMS ON ACCLIMATIZED MEN MARCHING 3 MPH. AT D.B. 95°—W.B. 93° F.

This is above the upper limits for four hours of work for the group when clothed since four of the five men failed to finish. Unless group finishes comparable period of work data not plotted. Key, ·---· nude; x—— x clothed.

end of the four hours of marching at D.B. 77°—W.B. 62° F.

	Rectal temp. °F	Heart rate per min.	Skin temp. °F	Weight loss grams per hour
Nude	99.6	91	90.8	143
Clothed	99.8	106	91.3	281

Clothing imposed a significant heat load in the hot environments studied. At the end of four hours in the two environments in which all men finished, whether nude or clothed (Tables II and IV) the rectal temperature of the clothed men ranged from 0.1° to 1.5° F. higher than the same man nude; the skin temperature of the clothed man from 0.0° to 1.6° F. higher than nude; the pulse

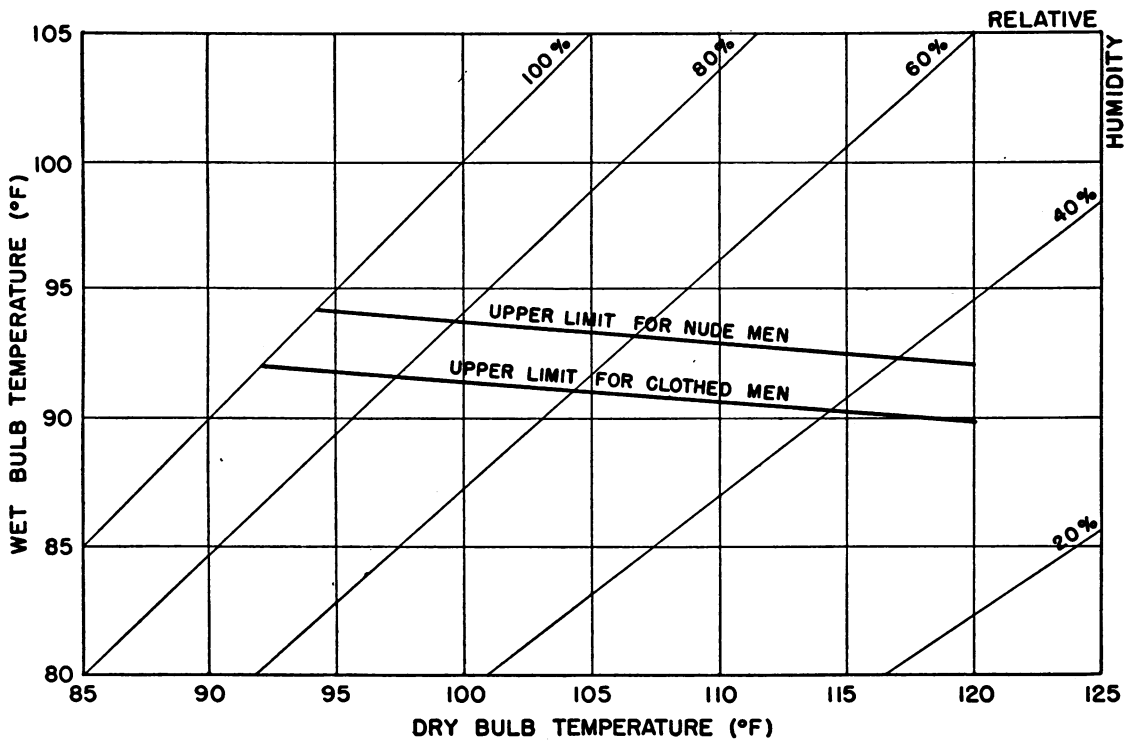

FIG. 6. EFFECT OF WEARING STANDARD HERRINGBONE TWILL UNIFORMS ON THE UPPER LIMITS OF HEAT TOLERATED BY WORKING ACCLIMATIZED MEN

The group nude or clothed was unable to work at a rate of 250 Cal. per hour for four hours at levels of heat above those shown.

rate from 3 beats lower to 18 beats higher than the nude; the sweat rate from 24 grams lower to 454 grams higher. The wearing of the special impregnated clothing resulted in proportionately greater changes which ranged up to approximately twice as great as those induced by wearing ordinary herringbone twill.

In addition to the physiologic cost, the men exhibited striking subjective reactions. These responses correlated well with the physiological findings. The men felt much cooler in the nude than when they wore either the untreated or treated clothing. In addition, the treated clothing was considered to be appreciably warmer than ordinary herringbone twill uniforms.

Weighing the clothing before and after each wearing revealed the herringbone twill clothing had absorbed approximately 1400 grams of sweat, the special clothing absorbed only half as much as this.

DISCUSSION

This study has described the acute physiological heat tolerance of a group of clothed acclimatized men exposed to several controlled external and internal heat loads. It confirms and complements observations made previously at this laboratory (6) on the upper limits tolerated by nude men. It must not be expected that industrial workers can work effectively at these levels. Rather do these upper limits indicate the maximal performance that is physiologically attainable by a group in severe heat. They may serve, therefore, as a rough guide of endurance of men in industrial operation in which optimal conditions cannot be achieved.

The specific type of work and environment, the acute nature of the experiment, the high state of acclimatization, motivation, and physical fitness of the subjects, all limit extensive direct application of this and other laboratory data. For example, the presence of a large source of radiant heat would considerably lower the limiting wet bulb temperature (10). As Von Schlictegroll (11) has stressed, ideally, specific practical studies should be carried out in the hot industries.

It is important to stress the great individual variability seen in the data. From a practical standpoint the reactions are analyzed in terms of

the average group response. However, any individual's performance and reactions may depart significantly from that of the group.

In additional work on another problem (12) at this laboratory, twelve men clothed in herringbone twill were fully acclimatized to marching at D.B. 120°—W.B. 93° and D.B. 120°—W.B. 90° F. It was found that D.B. 120°—W.B. 93° F. was above the upper limits while all the men were able to work for four hours (250 Cal. per hour) at D.B. 120°—W.B. 90° F. This finding confirmed one of the upper limits described in the present paper.

Robinson, Turrell and Gerking (8) approached the problem of limiting hot environments from the standpoint of thermal equilibrium while this laboratory has used different criteria; nevertheless, both agree as to the upper limits for the nude men. At equivalent work rate (130 Cal. per M^2 per hour) Robinson found the limiting environments for nude men similar to those reported by this laboratory, *i.e.* D.B. 95°—W.B. 94°; D.B. 122.0°—W.B. 92.0° F. In clothed men the limits determined by Robinson and by this study are similar for the saturated environments, but not for the 120° F. environments. Robinson's group, studying windbreak poplin, set the limit at about D.B. 122° —W.B. 86° F., while this study indicated the limit to be D.B. 120°—W.B. 90° F. for men clothed in herringbone twill and D.B. 120°—W.B. 88° F. for men in impregnated herringbone twill.

The explanation for the difference at the 120° F. environment is felt to be related to the type of clothing worn by the subjects. In these environments clothing plays a decisive rôle in determining upper limits, since evaporation and its cooling effect is limited by the type of clothing. On the other hand, in hot saturated environments evaporation of sweat is critically limited by the humidity, and the type of clothing plays a less important rôle.

SUMMARY

The effect of wearing two types of clothing on the ability of acclimatized men to work at the upper limits of heat has been evaluated in laboratory studies. The upper limiting wet bulb temperature for successful group performance of 4 hours of marching at 3 mph (250 Cal. per hour) in an environment with D.B. 120° F., was 92° F. for nude men, 90° F. for herringbone twill clothed and 88° F. for men wearing an impregnated herringbone twill uniform. The upper limiting wet bulb temperature at a D.B. 93° to 95°, was 94° F. for nude men and 92° F. for men clothed either in treated or untreated herringbone twill uniforms.

At the upper limits of environmental heat, the wearing of a single layer herringbone twill (8 oz.) uniform imposes a heat load equivalent to a 2° F. increase in the wet bulb temperature.

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