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PHYSIOLOGICAL RESPONSES OF MEN
TO WET TROPICAL ENVIRONMENTAL CONDITIONS
(OPERATION SWAMP FOX II)

Arthur A. Woodward, Jr.

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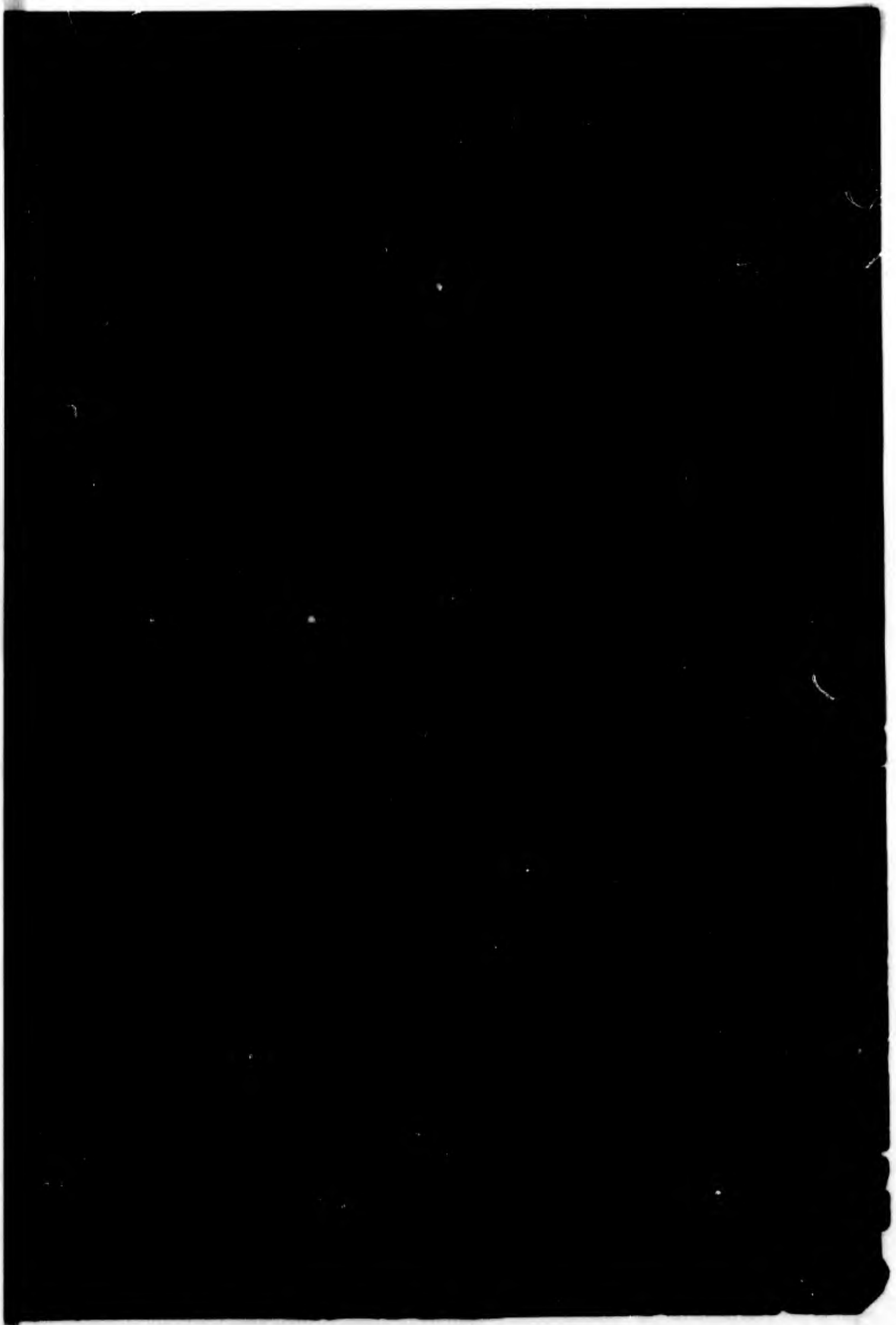
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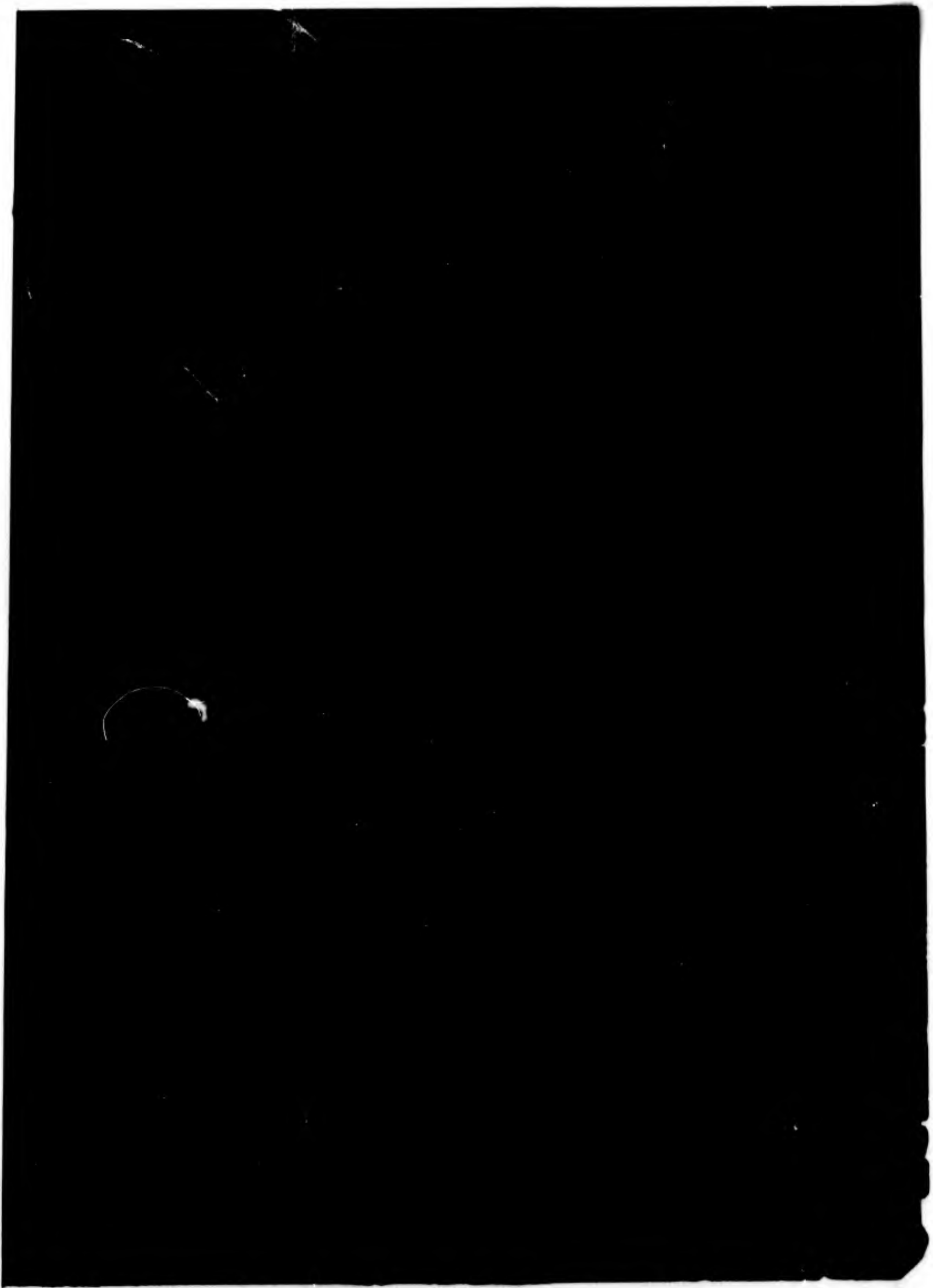
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TO WET TROPICAL ENVIRONMENTAL CONDITIONS
(OPERATION SWAMP FOX II)

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January 1964

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ABSTRACT

↓ Army personnel
~~During Operation SWAMP FOX II in Panama, men~~ under heat stress were observed while walking up and down a 12.5° *degree* slope and while confined (as a squad) for up to six hours in an armored personnel carrier at an unforested tropical site. Measurements of bodily temperature, pulse rates, and sweat production were used as indices of heat strain in the men.

Subjects walking in the sun, unloaded, did not suffer excessive heat strain under midday tropical conditions. About two-thirds of the sweat produced was evaporated for body cooling. Data on confined men showed there was little risk they would become heat casualties when exposed to Effective Temperatures up to 33.3° C. (92.0° F.) for as long as four hours. The men showed physiological adjustments to changes in environmental stress in less than 10 minutes. ()

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CONTENTS

ABSTRACT	iii
INTRODUCTION	1
METHOD	
Body Temperature	2
Heart Rate	2
Sweating Rates	2
Environmental Measurements	3
PROCEDURE	4
SUBJECTS	4
RESULTS	7
Confinement Studies	7
Grade Walking	9
DISCUSSION	19
Walking Studies	23
Performance of Infantry and Non-Infantry Subjects	39
SUMMARY	42
REFERENCES	43

FIGURES

1. Confinement Runs -- 13, 15 Sep	8
2. Confinement Runs -- 17, 19 Sep	10
3. Confinement Runs -- 21, 23 Sep	11
4. Confinement Runs -- 25 Sep, 2 Oct	12
5. Confinement Runs -- 5, 7 Oct	13
6. Confinement Runs -- 8, 11 Oct	14
7. Confinement Runs -- 12, 14 Oct	15
8. Confinement Runs -- 16 Oct	16
9. Individual Changes in Oral Temperature During a Single Confinement Run	17
10. Walking Trial -- 9 Oct	27
11. Walking Trial -- 10 Oct	28
12. Walking Trial -- 13 Oct	29
13. Walking Trial -- 15 Oct	30
14. Walking Trial -- 11 Oct	31
15. Walking Trial -- 11 Oct	32
16. Walking Trial -- 12 Oct	33
17. Walking Trial -- 14 Oct	34
18. Walking Trial -- 16 Oct	35
19. Relation of Total Sweat Production to Work Rate and Environment Stress	36
20. Relation Between Sweat Evaporation and Walking Speed	37
21. Relation of Steady-State Pulse Rate to Work Rate and Environment Stress	38

TABLES

1. Characteristics of Subjects -- Fourth Battle Group Infantrymen	5
2. Characteristics of Subjects -- Enlisted Specialists	6
3. Sweating and Walking Rate of Men on a Hill Course	18
4. Hours of Exposure to Excessive Levels of Effective Temperature During Confinement	20
5. Comparison of Performance of Infantrymen and Enlisted Specialists . .	40

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PHYSIOLOGICAL RESPONSES OF MEN
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INTRODUCTION

During the period August through October 1962 the U. S. Army conducted a field Research and Development expedition -- Operation SWAMP FOX II -- in the eastern part of the Republic of Panama. A team from the U. S. Army Human Engineering Laboratories (HEL) was invited to participate. A primary goal of this team's effort was to conduct a series of studies of men's responses to prolonged confinement in military vehicles. Earlier studies by Hicks (2) had been carried out at Aberdeen Proving Ground, Md. During these studies the variability of the climate, even in the warm months, resulted in no tests being run under truly hot conditions. Operation SWAMP FOX II provided an opportunity to continue the series of confinement studies in a region where the environmental conditions promised more certainty of observing the effects of maintained thermal stress on subjects. In addition, the team could also observe the responses of men exposed to a natural hot-wet environment, an area where data are all too meager.

Men were observed under two types of environmental conditions. A series of 16 trials was conducted in which a squad of infantrymen was confined within an M113 Armored Personnel Carrier for periods up to six hours in the middle of the day. Physiological responses were measured on each subject during the confinement period, and the effects of the exposure on combat relevant psychomotor performances were measured at the end of the confinement period. The results of the latter studies are reported separately by Hicks (3). A second series of 17 trials was carried out in which military men walked up-hill and down-hill in the sun. Closer physiological observations were possible on these men than on those in the confinement studies. The physiological measurements made in either series were directed toward assessing the degree of heat stress imposed by the environments on the men. No attempts were made to investigate either internal thermoregulatory mechanisms or processes of acclimatization.

All of the experiments described in this report were conducted in the area of the SWAMP FOX II Base Camp. This site and the environmental conditions that prevailed there are described in detail in a separate report by Woodward (11). This report does contain relevant environmental data collected during the progress of the experiments described. It is sufficient to say of the site that it was in an area that had been cleared for agricultural use; in no sense was it a "jungle."

METHOD

Body Temperature

All body-temperature measurements were made with thermistor instruments. Sub-lingual temperatures and skin temperatures (when taken) were made with commercially available appropriate probes connected to a multichannel read-out meter. The sensitivity of the galvanometer on the read-out meter made it unusable in the armored personnel carrier while the vehicle was in motion. The requirement that the vehicle be kept in motion as nearly continuously as possible made it practical to measure only sub-lingual temperatures, and no more often than at half-hour intervals, during the confinement studies. During the hill-walking studies the sub-lingual temperature was taken as a measure of internal temperature, and skin temperature was taken as well. For the latter purpose a single reading was made on the medial surface of the thigh, following the finding of Teichner (10) that such a measurement is in generally good agreement with weighted means derived from six to ten skin-temperature measurements on various parts of the body. This practice was resorted to after much difficulty was experienced in keeping thermistor discs fixed to the skin with any kind of adhesive tape. The latter difficulties were the product of continuous sweating and conditions of minimal personal sanitation found in the field. Average body temperature was taken as the sum of $2/3$ the sub-lingual and $1/3$ the thigh skin temperature.

Heart Rate

Pulse counts were made by palpation for 30 or 60 seconds. Counts were made whenever temperatures were measured.

Sweating Rates

Body-weight changes were measured on a platform balance both sensitive and accurate within 5 g. Change in nude body weight over an experimental period was taken as a measure of total sweat production. Change in clothed body weight was taken as a measure of total sweat evaporated. The men did not sweat so profusely as to cause a serious error through loss in sweat dripped on to the ground. Rainfall during the course of an experiment and mud accumulation on boots of course vitiated

estimations of sweat evaporation by means of weight changes. These problems were avoided as much as possible by starting walking experiments only at times when the weather was promising (mostly in the morning) and when the ground was not excessively muddy. The latter condition was not as difficult to avoid as might be thought; the walking course involved mostly either the well-grassed pasture in which the field laboratory was located or the coarsely graveled surface of the nearby road.

Environmental Measurements

The details of the instruments used and procedures for making measurements of the human thermal environment are given in reference 11. Not all of the environmental data were directly relevant to interpretation of the results discussed below. The environmental data cited include, briefly: (1) air temperature, measured with a shielded mercury thermometer; (2) humidity, measured with an electrically driven aspirated psychrometer; (3) solar radiation, measured with a horizontal pyrheliometer; and (4) the Wet Bulb-Globe Thermometer (WBGT) Index, measured with a kit fabricated at HEL according to the method of Minard, Belding, and Kingston (6). For the environment inside the armored personnel carrier, the effective temperatures (E.T.) were computed from psychrometric measurements using the nomograms of Houghten and Yaglou (4, 12).

PROCEDURE

For the confinement studies oral thermistor probes were permanently mounted in the armored personnel carrier at each man's position. These were run to the read-out instrument located near the inside technical observer who always occupied one position during these runs. This observer halted the vehicle and took temperature readings and pulses every 30 or 60 minutes. He was instructed to eliminate promptly from the test any subject whose pulse exceeded 150 beats per minute, whose oral temperature exceeded 102° F., or who either showed or complained of any signs of heat pathology. Any subject who showed any signs of ill-health at the beginning of the day was not included in that day's run. This latter procedure was invoked especially during a mild epidemic of an unidentified disease that swept through the camp and involved some of the volunteer subjects used in the HEL studies.

For the walking studies a course was laid out that ran on the level from the field laboratory to the road outside the camp area, thence up to the top of a 12.5° grade, and return to the field laboratory. The course was 490 yards long, of which 180 yards were level grassland and 310 yards were graveled roadbed on a 12.5° grade. At each lap of the course the subject stopped at the field station for temperature and pulse measurements, and the time at which he started each lap was recorded. A pair of subjects was used during each of these tests, the second being started on the course as soon as the first reached the halfway point on the course. Subjects were instructed to try to maintain a normal military marching pace, but in any case to keep a constant pace without respect to the progress of the other subject. The average walking rates were calculated from the course length and the intervals between lap startings, and so these rates average in the 35 to 50 seconds standing at the field laboratory at the end of each lap. The men walked for one hour, the condition under which volunteers could be acquired.

SUBJECTS

The subjects for the confinement studies were infantrymen from the 4th Battle Group, 10th Infantry, Ft. Davis, Canal Zone. The data relevant to their physiological performance is summarized in Table 1. With the exceptions noted, all were native-born, white, U. S. citizens. The one Negro and the subject born in England were not physically unusual, but the subject JJ, born and raised in Peru, was an ex-Olympic athlete whose physical performance in several areas set him aside from all others involved in these observations.

TABLE 1

Characteristics of Subjects -- Fourth Battle Group Infantrymen

Subject	Age (yrs.)	Height (cm.)	Weight (kg.)	Body Area (m. ²)	Time stationed at Ft. Davis (mo.)**
LA	20	190.5	70.5	1.92	24
GB*	24	182.8	92.8	2.12	3
ED	21	168.9	63.6	1.72	16
DH	28	181.6	69.1	1.84	30
RH*	20	176.9	79.8	1.93	14
JJ*	27	178.8	78.1	1.93	13
WK*	20	169.9	65.9	1.76	28
WM*	19	181.5	65.2	1.81	12
HS*	20	172.1	62.2	1.72	18
RS*	38	185.6	77.3	1.96	30
PU*	31	174.0	68.2	1.79	24

* These men were included in walking tests.
 Subject ED born in England, raised in U. S.
 Subject RH was the only Negro in any study.
 Subject JJ born and raised in Peru.

** At the time of assignment to Operation SWAMP FOX II.

All of these subjects were accustomed to a weekly routine that involved nearly daily cross-country marching through undeveloped rain forest. It was assumed they were fully acclimatized to the Canal Zone thermal environment at the time the observations reported here began.

A second group of men, volunteers from the group of enlisted specialists of SWAMP FOX II, were used for walking tests. Data relevant to these men is included in Table 2. All of these men were native-born, white U. S. citizens. All had been in the Panama area for nearly two months before the tests began, and were assumed to be fully acclimatized to the local environment at their usual work levels before these tests began.

TABLE 2
 Characteristics of Subjects -- Enlisted Specialists

Subjects	Age (yrs.)	Height (cm.)	Weight (kg.)	Body Area (m. ²)	Military Duty	Permanent Duty Station
DEA	20	170.4	65.3	1.75	Mechanic	Ft. Knox
ADB	23	174.6	74.9	1.88	Driver	Ft. Knox
JRB	25	172.0	62.4	1.73	Driver	Ft. Hood
GDF	23	176.3	74.5	1.88	Mechanic's Helper	Ft. Knox
JHG	22	171.5	90.8	2.04	Cook	APG
DEH	28	167.9	83.0	1.93	Driver	Ft. Sill
FAK	20	174.0	59.2	1.67	Tank Driver	Ft. Eustis
WEO	38	193.0	79.4	2.02	Driver	Ft. Hood
W-P	20	180.3	65.9	1.81	Driver	Ft. Eustis

For comparisons made on walking test data, the two groups were generally similar with respect to distribution of ages, heights, and weights, but the infantrymen were generally in better over-all physical condition than the enlisted specialists. The former were, of course, much more accustomed to marching.

RESULTS

Unlike those made in controlled climatic chambers, observations of the effects of environment on men in the field are made under constantly changing conditions. How best to summarize data collected under the latter condition is not always obvious. Indiscriminate pooling of data risks the possibility of obscuring significant variations from unexpected sources. In view of the limited information about the environment of the region under consideration and its effects on men, it seemed most useful to present the results primarily in the form of protocols of each of the tests performed.

Confinement Studies

Observations on the infantrymen during confinement in an armored personnel carrier are summarized in Figures 1-8. The data on oral (sub-lingual) temperatures and pulse rates are given as means of all subjects involved in each test. Either the effective temperature or the WBGT Index is presented as a measure of the thermal environment inside the vehicle. In addition the data on solar radiation is presented, inasmuch as this appeared to be the only factor of the external ambient environment that showed a causal relation to the conditions inside the carrier.

Whether presenting the means for temperatures and pulse rates is a valid procedure needs consideration. All of the temperature data for the confinement run of 11 October are given in Figure 9. The record of each individual subject is represented. Prior to 1200 hours no definite signs of excessive thermal strain are evident, i.e., no maintained elevation of oral temperatures occurs. During this period the variability from subject to subject is high, with respect to both level and direction of change of temperature. From 1200 hours onward the temperatures of all subjects began to climb. From this point the range of temperatures among the subjects decreased, and the changes grew more parallel as the degree of environmental stress increased. With a relief from environmental stress, all temperatures dropped quickly together. These characteristics appeared in all the data of this kind during the confinement studies. It may be concluded that the temperature means of all subjects fairly represents the response of the group and will reveal the onset of thermal stress in the subjects accurately. The same is true for data on heart rate.

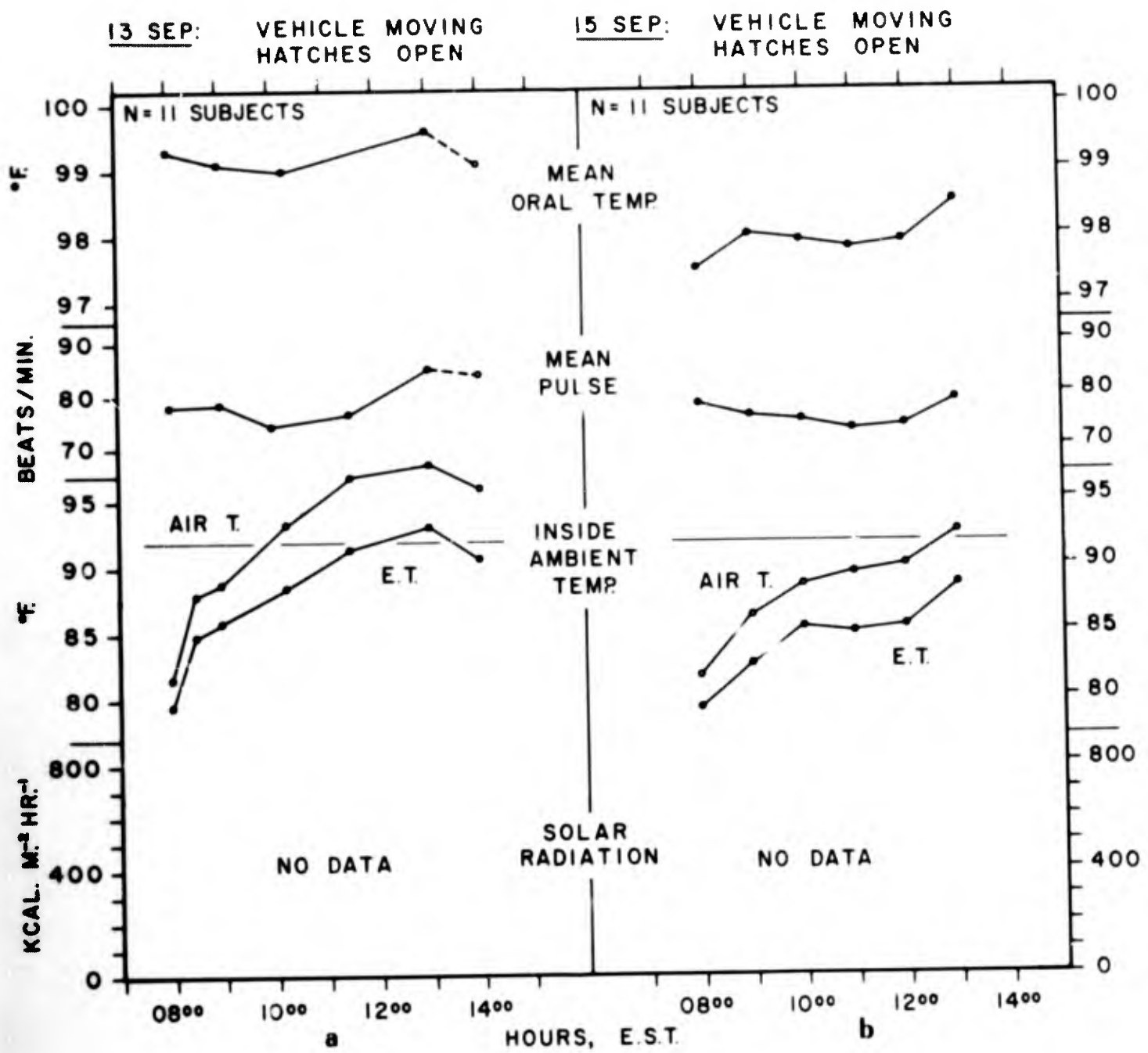


Fig. 1. CONFINEMENT RUNS -- 13, 15 SEP
ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

(The final points on the body temperature and heart-rate curves on 13 Sep are based on means for three subjects only.)

The WBGT Index was measured in some of the later runs because of the breakdown of the aspirated psychrometer. Fortunately these later runs were static so that it was practical to use a WBGT set in the vehicle. As Minard, et al. (6), point out, the WBGT Index is in fact a close measure of the effective temperature corrected for solar radiation. Inside the carrier full of subjects the dry-bulb and globe thermometers gave readings within 1.0° C. in all but a very few instances. It seems safe to conclude that these two measures of the environment within the carrier are directly comparable between the various sets of data for the different runs.

Grade Walking

Most of the observations on men walking up and down a 12.5° grade are presented as protocols, similar to those described above, in Figures 10-18. Only two measurements of the ambient environment are included, the WBGT Index and the total solar radiation in 15-minute intervals. Of the omitted environmental measurements, air temperature closely parallels (several degrees higher) the WBGT Index, but absolute humidity and wind-speed data show little relation either to the WBGT Index or to the performance of the men. The data on sweating, necessarily measured over the whole test period, are presented separately in Table 3.

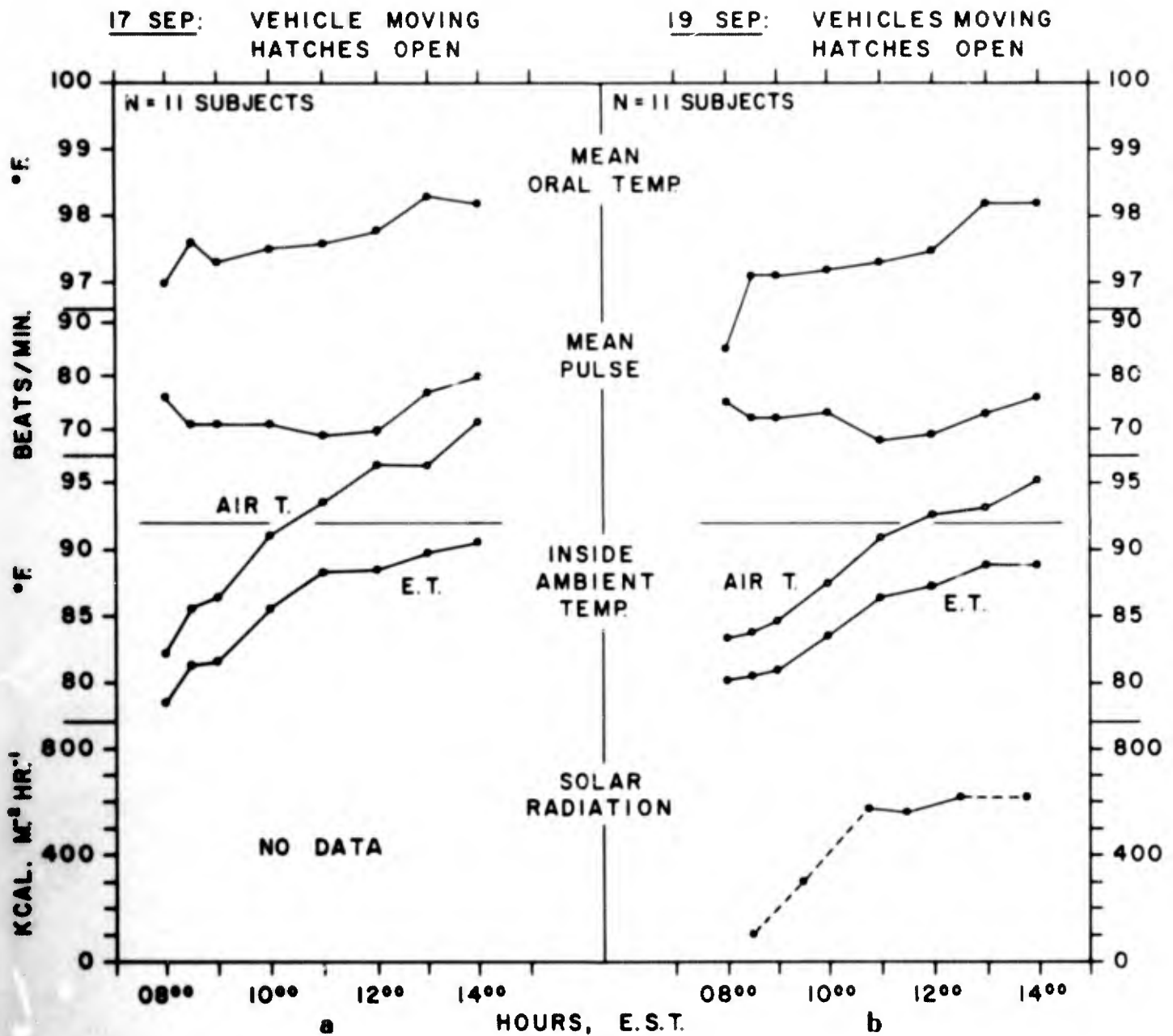


Fig. 2. CONFINEMENT RUNS -- 17, 19 SEP
 ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

(The broken portion of the solar-radiation curve for 19 Sep is based on the best estimations from incomplete data.)

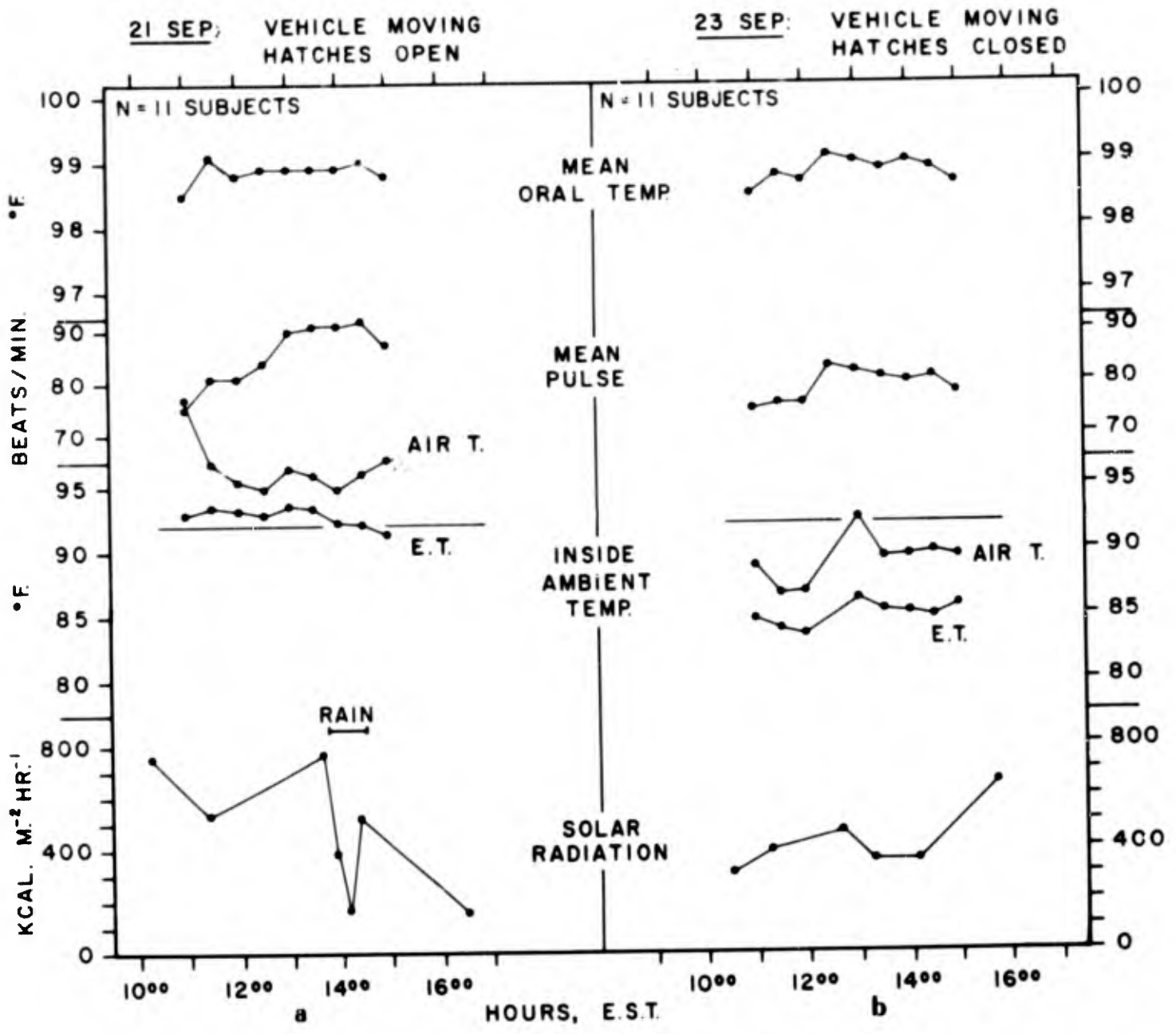


Fig. 3. CONFINEMENT RUNS -- 21, 23 SEP
 ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

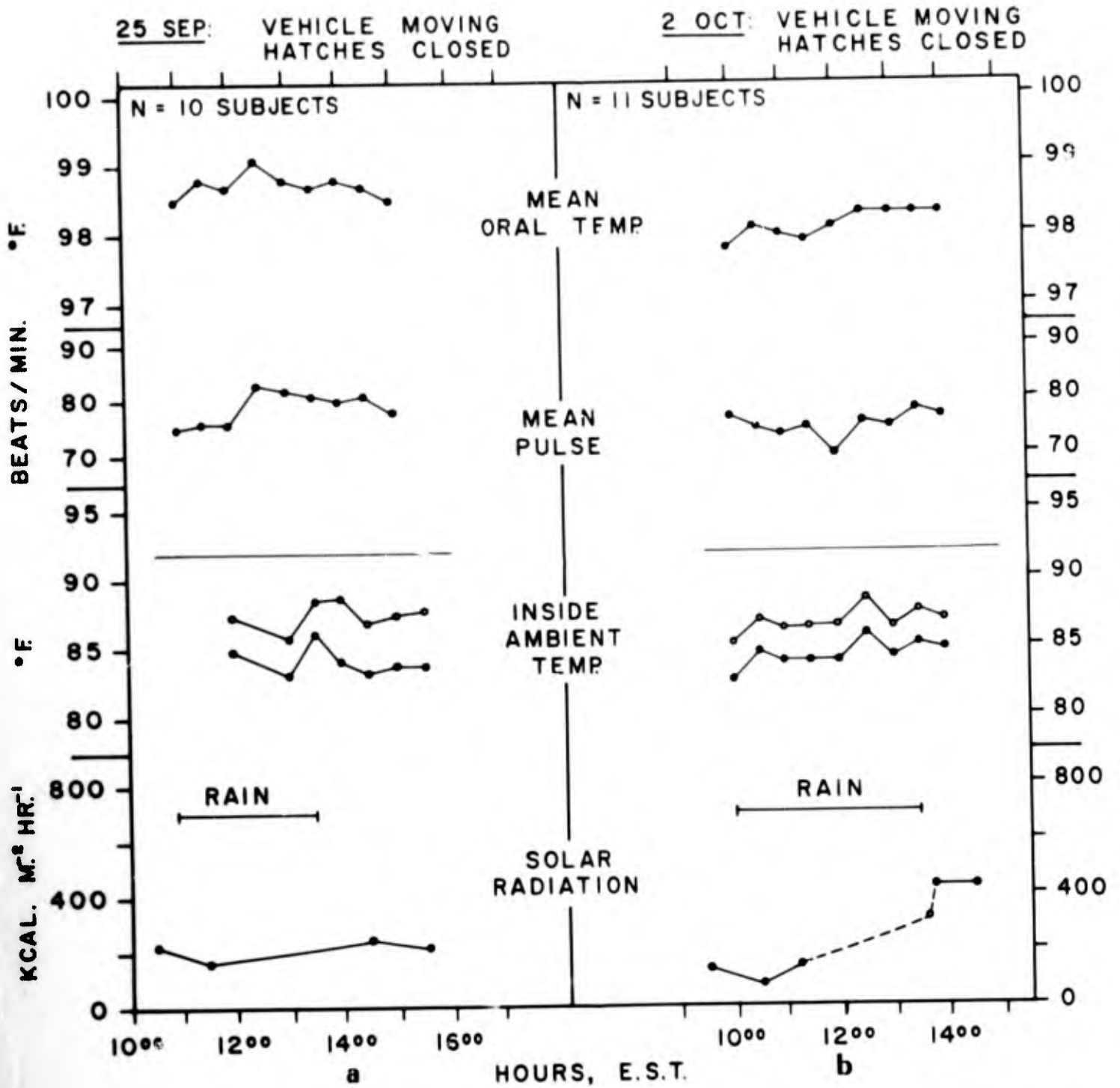


Fig. 4. CONFINEMENT RUNS -- 25 SEP, 2 OCT
ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

(The broken portion of the solar-radiation curve for 2 Oct is based on the best estimations from incomplete data.)

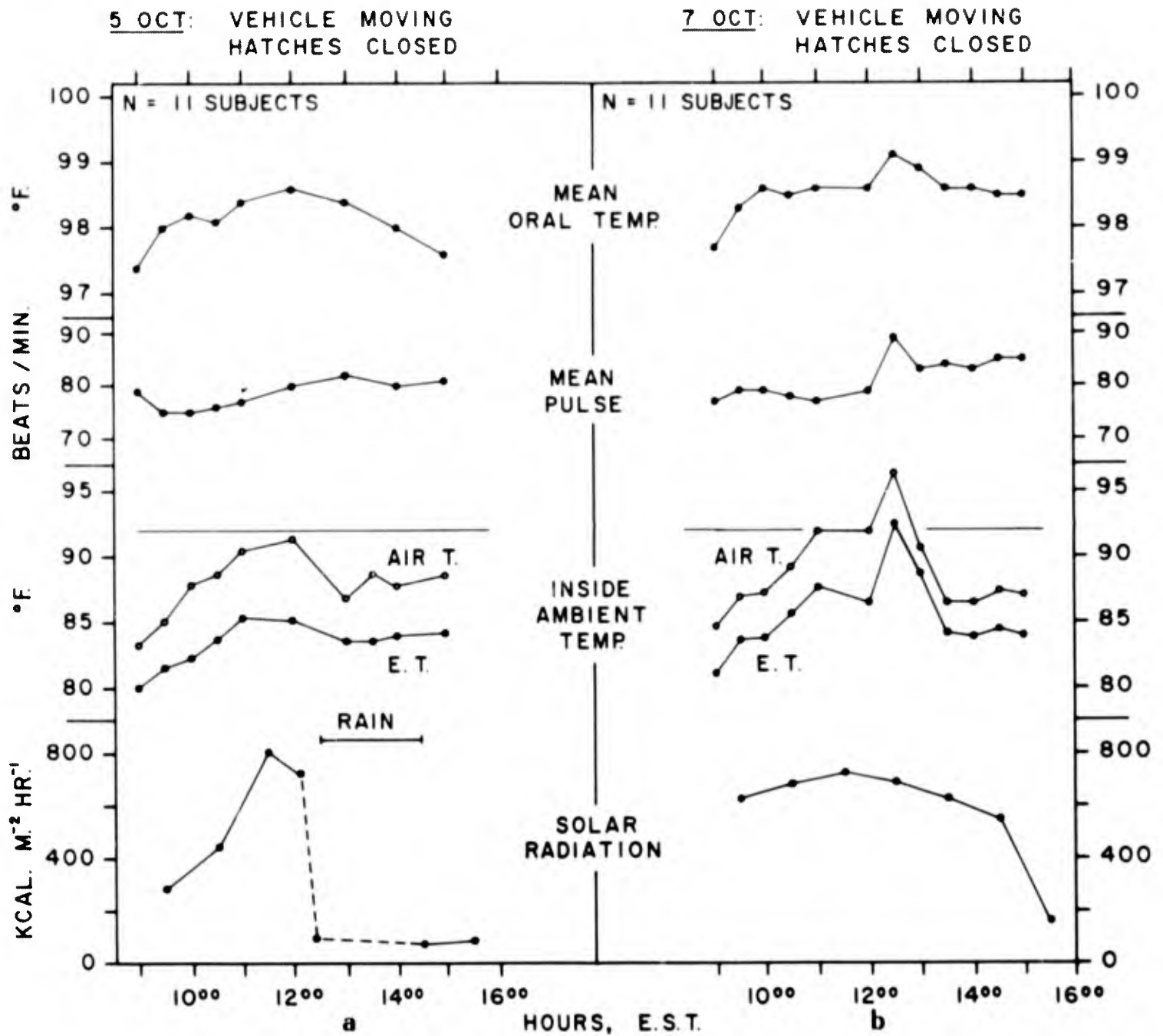


Fig. 5. CONFINEMENT RUNS -- 5, 7 OCT
ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

(The broken portion of the solar-radiation curve for 5 Oct is based on the best estimations from incomplete data.)

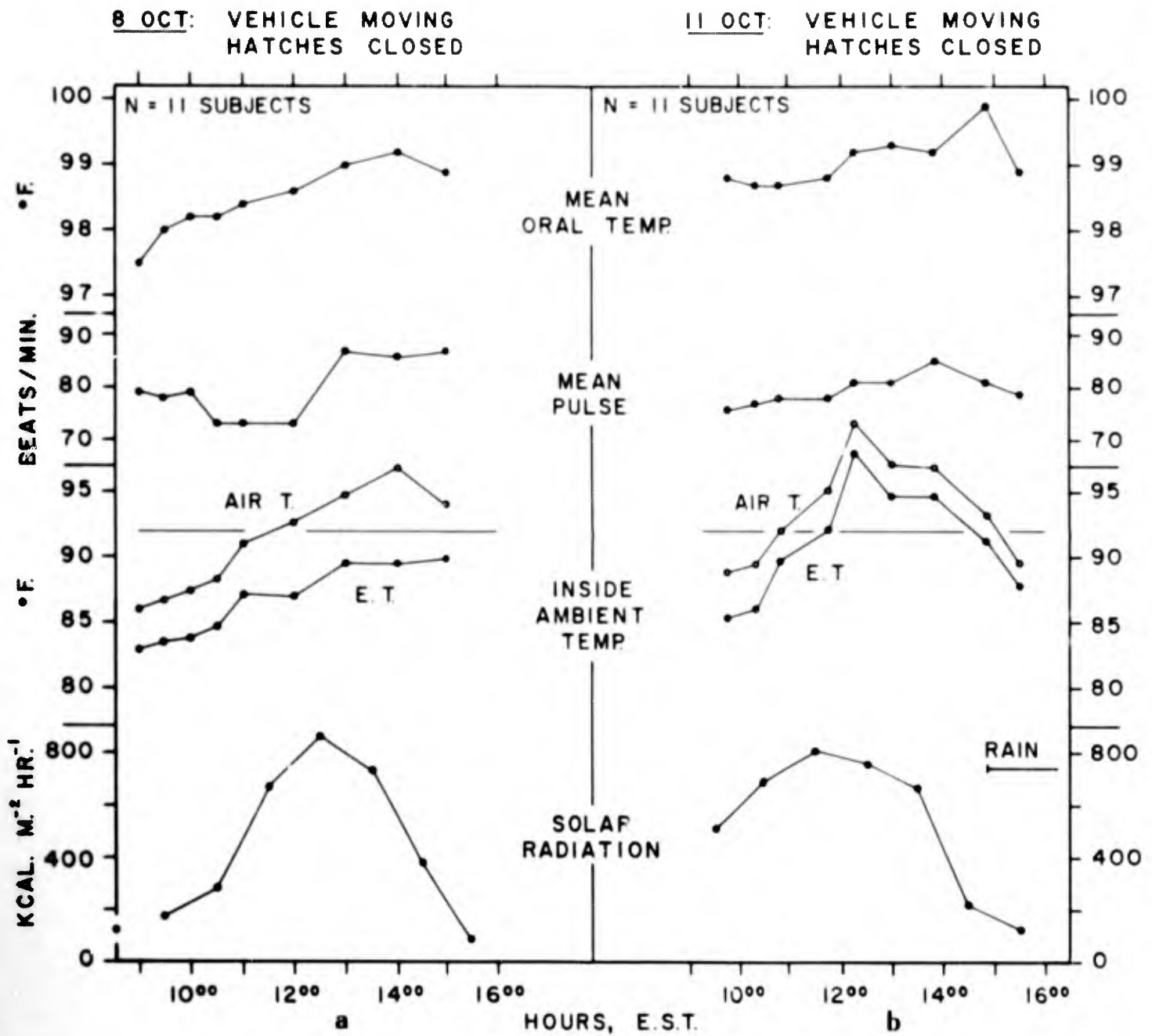


Fig. 6. CONFINEMENT RUNS --8, 11 OCT ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

12 OCT VEHICLE STATIC
HATCHES CLOSED

14 OCT: VEHICLE STATIC
HATCHES CLOSED

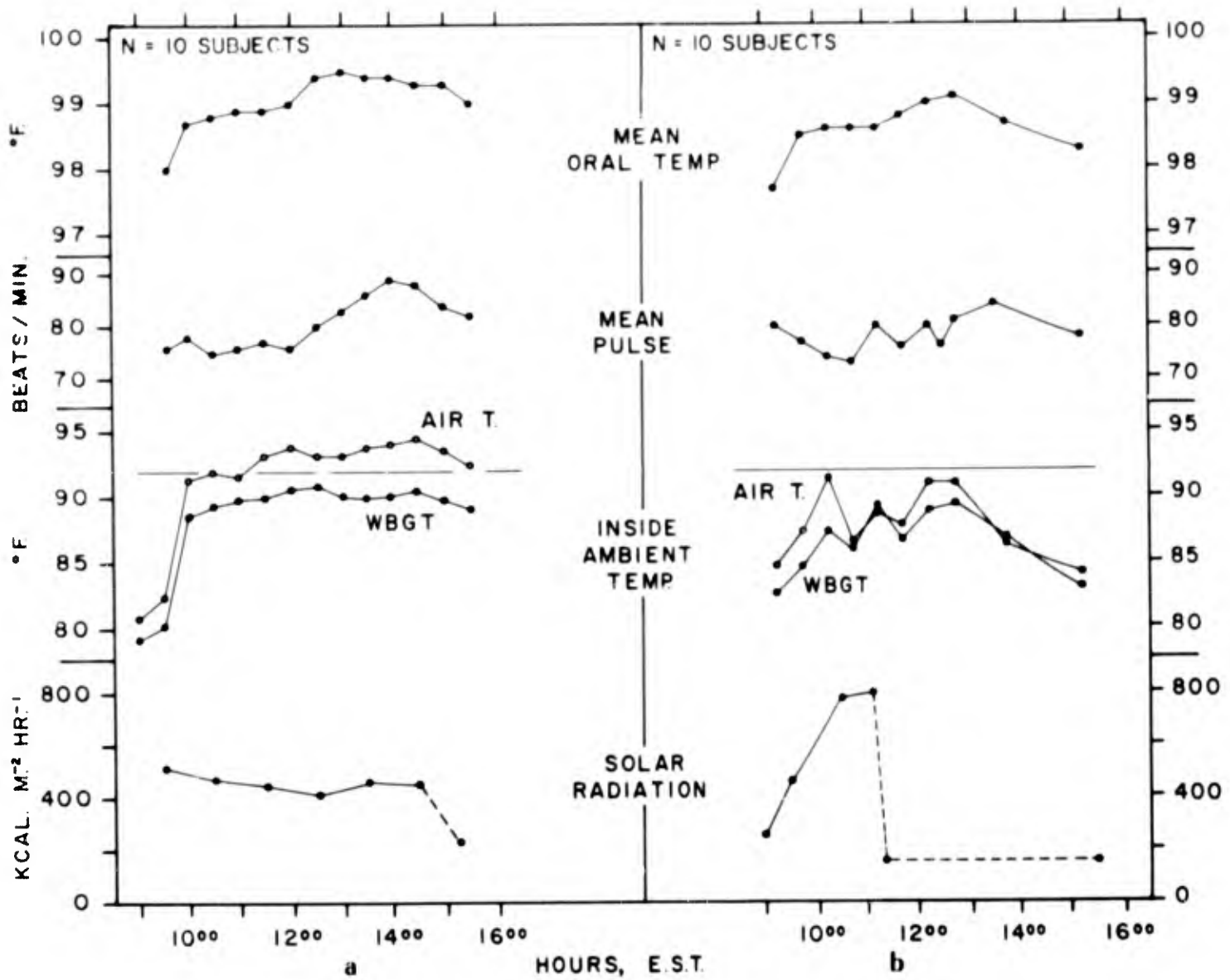


Fig. 7. CONFINEMENT RUNS -- 12, 14 OCT
ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

(The broken portions of the solar-radiation curves are based on the best estimations from incomplete data.)

16 OCT: VEHICLE STATIC
HATCHES CLOSED

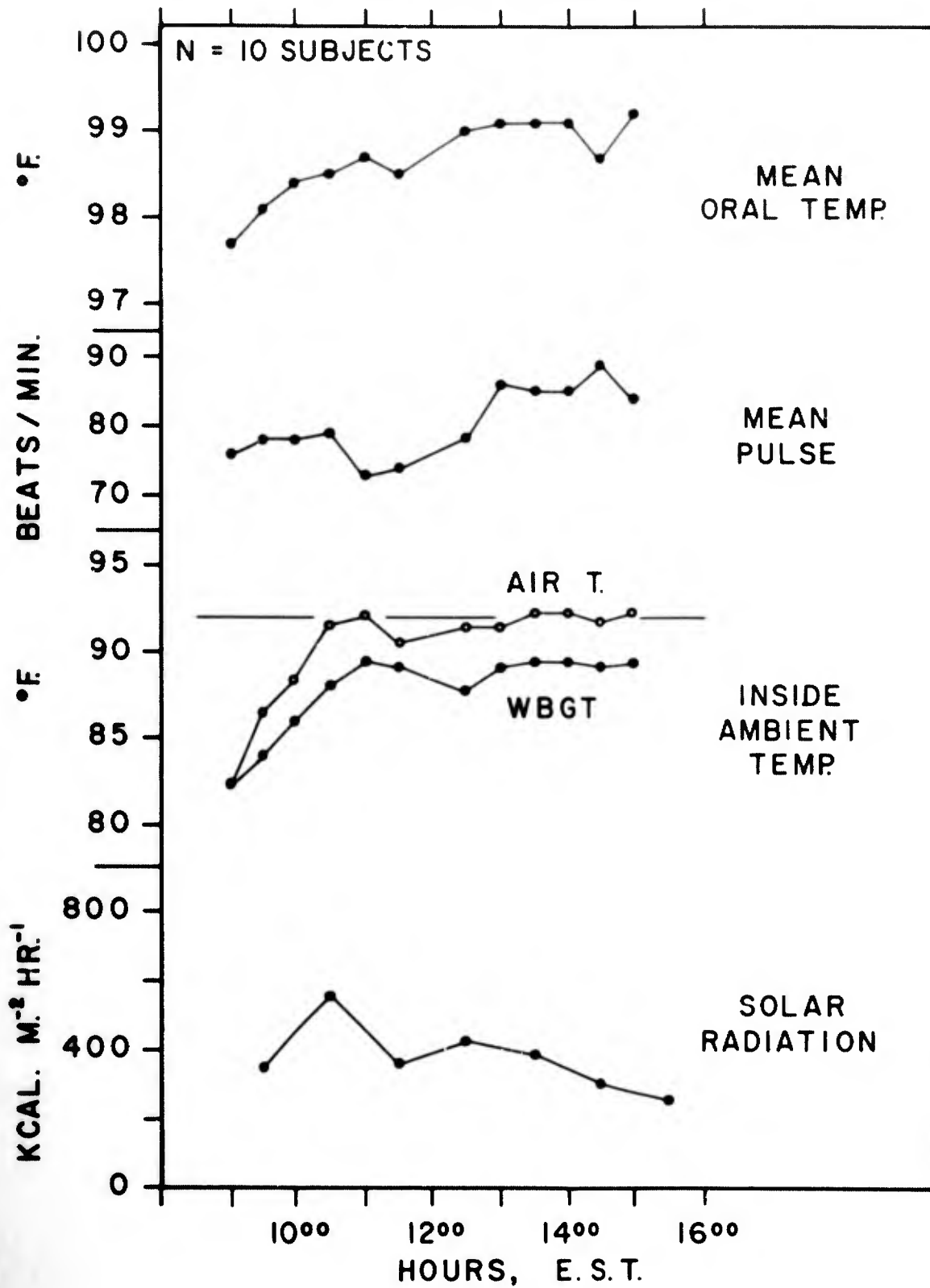


Fig. 8. CONFINEMENT RUNS -- 16 OCT
ENVIRONMENTAL CHANGES AND PHYSIOLOGICAL RESPONSES OF SUBJECTS

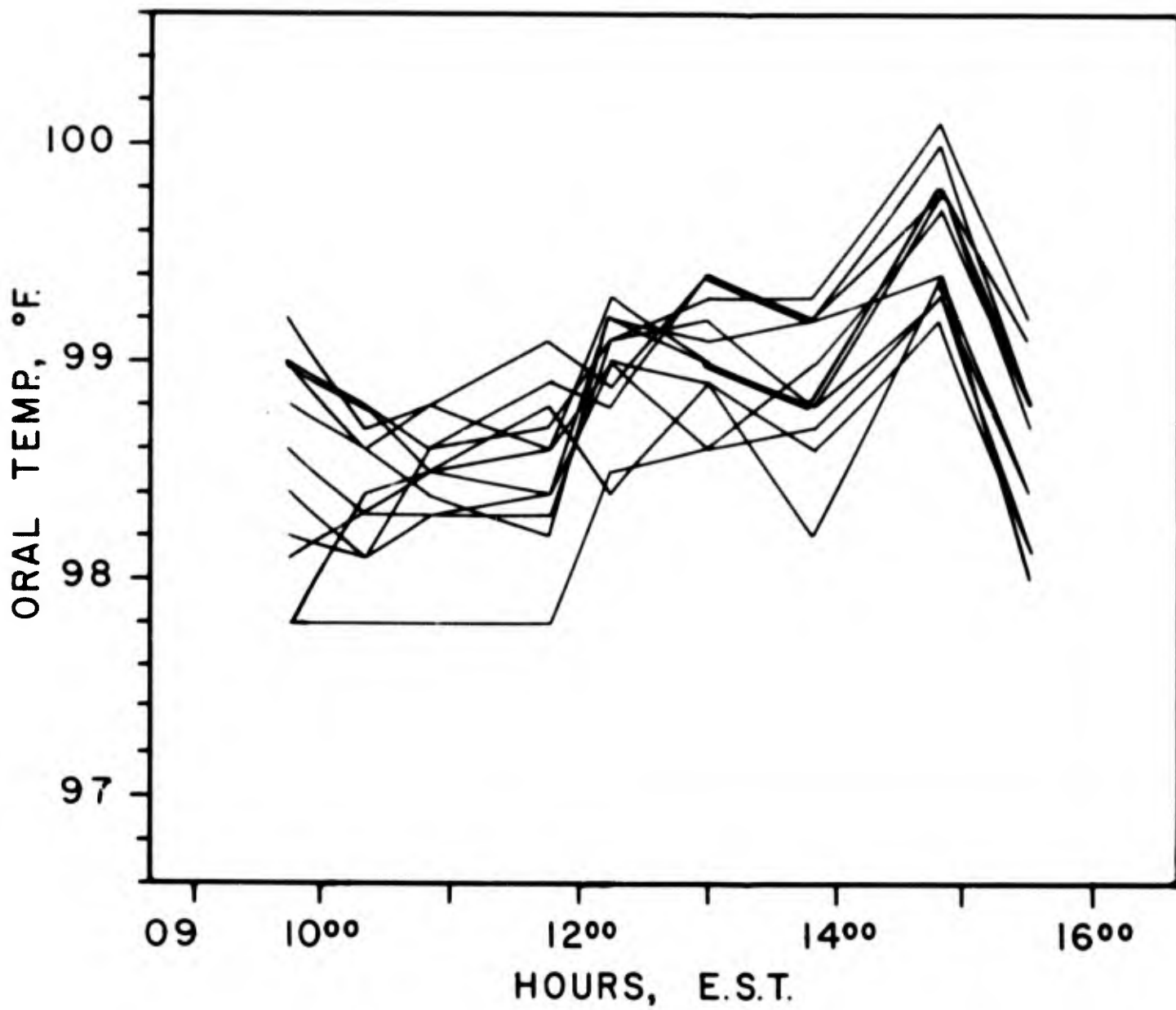


Fig. 9. INDIVIDUAL CHANGES IN ORAL TEMPERATURE DURING A SINGLE CONFINEMENT RUN

(Compare with the top curve of Figure 6b, which gives the means for the same set of data. Each curve connects the temperature readings for a single subject. Notice the convergence both in value and in pattern of response as thermal strain increases.)

TABLE 3

Sweating and Walking Rates of Men on a Hill Course

Subject	Sweat Production, kg m ⁻² hr ⁻¹	Sweat Evaporation, kg m ⁻² hr ⁻¹	% Sweat Evaporated	Heat Absorbed, kcal m ⁻² hr ⁻¹	Avg. walking rate, mph
Infantry Subjects					
JJ	.690	.506	73.3	293	3.46
WM	.608	.406	66.8	235	2.77
RS	.545	.446	81.8	259	3.09
PU	.600	.373	62.2	216	2.91
GB	.344	.210	61.0	129	2.68
WK	.489	.246	50.3	143	3.00
RH	.361	--	--	--	2.32
HS	<u>.608</u>	<u>--</u>	<u>--</u>	<u>--</u>	<u>2.67</u>
Averages	0.532	0.365	65.9	213	2.86
Enlisted Specialist Subjects					
WEO	.406	.321	79.1	186	2.32
W-P	.430	.344	43.7	200	2.54
JHG	.352	.213	60.5	124	2.48
FAK	.294	.146	49.7	85	2.54
GDF	.417	.336	80.6	195	2.48
DEA	.354	.265	74.9	154	2.48
DEH	.520	.297	57.1	172	2.48
ADB	.420	.259	61.7	150	2.55
JRB	<u>.289</u>	<u>--</u>	<u>--</u>	<u>--</u>	<u>2.24</u>
Averages	0.387	0.273	63.4	158	2.45

DISCUSSION

An examination of the two top curves in Figures 1-8 reveals two things with ease, despite the variations in the environmental conditions during the runs and the responses of the men to them. First, the mean oral temperature and the mean heart rate vary generally in a parallel manner, particularly after the first hour of the run. The first pulse count in every run, made immediately after the men enter the personnel carrier, reflects the activity prior to personnel loading, including an occasional quarter-mile run of late-comers from the quarters area to the field laboratory site. Second, the levels of oral temperature and heart rate reveal in no case evidence of really severe heat stress. The most severe exposure of the men occurred on 11 October (Fig. 6b), and the consequences might have been serious had the exposure been maintained. Instead, the afternoon rainstorm developed, bringing with it thermal relief inside the vehicle as well as outside. The highest single oral temperature measurement in any run was 100.6° F. (8 Oct), and readings of over 100° F. were logged in only six other instances. The highest single pulse rate measured was 122 beats per minute (7 Oct), and rates over 110 beats per minute were logged in only three other instances (all of these values were given by one subject on two different days, 7 and 8 Oct). Thus in no case did any subject approach the conservative maximum strain criteria (102° F. oral temperature or 150 beats per minute pulse) for removing a man from the test. The case of the civilian observer who did become a heat casualty during the run of 19 Sep (Fig. 2b) was complicated by a prior history of dehydration. It is unfortunate that the observer involved, possibly as a result of excessive heat stress, failed to take measurements on himself. Thus the conditions observed during the confinement runs were a good deal less severe than had been feared at the time the plans were being laid for SWAMP FOX II.

The measured values of sublingual temperature are generally lower than might be expected. In a few instances (as 17 and 19 Sep, Fig. 2) one could possibly attribute the especially low initial means to the early hour and the habit of all personnel of sleeping without cover on cots with air mattresses, but in all other instances the instrumentation itself seems suspect. Repeated calibration checks against a mercury thermometer revealed no detectable fault in any of the oral thermistor probes used, nor were the connectors of these probes mounted on the subject and thus exposed to sweat. The source of trouble apparently lies within the thermistor read-out instrument, which did not have sealed circuitry. Observations of the behavior of the thermistor instrumentation in the field laboratory under the worst thermal conditions (high temperature, high humidity) suggest that when moisture condensation conditions develop low readings are obtained, presumably due to small leakages in the bridge circuits of the read-out instrument but possibly in the probe connectors. The use of rectal thermometers to measure internal body temperatures is considered by many environmental physiologists to be a rite almost as inviolable as sacred dogma, despite evidence to the contrary that is well enough known. The latter has been

TABLE 4

Hours of Exposure to
Excessive Levels of Effective Temperature (E.T.) During Confinement

Date of run	Duration of run (hours)	Hours during each run spent at E.T. (°F.) in excess of:			Peak E.T. during run (°F.)
		88.0	90.0	92.0	
13 Sep	6	4	2 1/2	1 1/2	93.0
15 Sep	5	< 1/4	0	0	88.5
17 Sep	6	3	1/2	0	90.5
19 Sep	6	1 1/2	0	0	88.8
21 Sep	4	4	4	3 1/2	93.6
23 Sep	4	0	0	0	86.2
25 Sep	4	0	0	0	85.2
2 Oct	4	0	0	0	85.9
5 Oct	6	0	0	0	85.4
7 Oct	6	1 1/4	1/2	< 1/4	92.5
8 Oct	6	2 1/4	0	0	88.9
11 Oct	6	5	4	3	98.0
12 Oct	6	5 1/2	3	0	90.9
14 Oct	6	1 3/4	0	0	89.4
16 Oct	<u>6</u>	<u>4 1/4</u>	<u>0</u>	<u>0</u>	<u>89.4</u>
Total hours	81	32 3/4	14 1/2	8 1/4	--
% of total	--	40.5	17.9	10.2	--

recently reviewed by Renbourn (9). In the cases under present consideration, rectal measurements would have been subject to the same instrumental errors as oral measurements. In any case the levels of heart rate observed indicate that no gross underestimations of body temperature are involved in the data here discussed.

Nevertheless, uncertainties are involved, and it is necessary to look in the data for instances of consistent increase of both oral temperature and pulse rate as indications of the development of thermal strain in the subjects. This did occur on a number of occasions during the confinement runs, as an examination of Figures 1-8 will show. In almost every case (neglecting changes that occurred during the first hour of each run), oral temperatures and pulses began to climb above steady-state levels whenever the air temperature in the personnel compartment of the carrier rose to 92° F. (33.3° C.). The only marked exception to this behavior occurred during the run of 21 Sep (Fig. 3b), for which no ready explanation is available. The 92° F. level has been marked on each figure for easy visualization of this point.

The dry bulb temperature and the effective temperature (E.T.) within the personnel compartment of the carrier ran consistently parallel and about 4° F. apart in all of the studies. This is not hard to understand. Soon after the subjects were closed up in the carrier the vapor pressure inside, increased by moisture from expired air and evaporated sweat, rose to a level of saturation at the temperature of the coolest compartment wall on which moisture began to condense. From that point on the vapor pressure in the personnel compartment could vary only as the temperature of the coolest wall changed. Generally this would be the floor, which is least subject to warming by solar radiation. In addition, the rates of air movement within the M113 Armored Personnel Carrier personnel compartment are very low, especially when the vehicle is not in motion or when the hatches are closed. Thus one would expect the E.T. to be a close function of the air temperature except for periods when rapid changes were occurring. The 4° (approximate) differential between the two temperature measures would set a level of 88° F. E.T. as a limit above which men would begin losing temperature control.

To say that men exposed to an E.T. of 88.0° F. or above suffer a degree of heat stress that will ultimately prove intolerable provides inadequate guidance for conducting operations in a hot-wet environment. Heat exposure must be considered as a dosage phenomenon; that is, not only the amplitude factor but also the time of exposure must be taken into account. In turn, level of physical activity of the men is a factor, for this determines the rate of metabolic heat production. Once a man enters a state of inevitable body heating, his rate of body heating will govern the time limit of exposure to a given thermal stress. Consider the data given in Table 4. During the confinement studies men were under sufficient thermal stress to produce body heat accumulation about 40 percent of the time (one must remember that the confinement runs were made only during the day and always included the midday hours). Yet more than half of these hours of exposure were at an E.T. between 88.0° and 90.0° F., and Yag'ou and Minard (13) have found that heat-acclimatized men in training camps may carry on limited activities for periods up to six hours a day in

this range. Infantrymen during transit in an armored personnel carrier are near a state of rest, muscular effort being required primarily only to maintain posture when a vehicle is pitching during passage over rough terrain. Since these men showed no serious degree of heat strain on six occasions of exposure up to four hours at E.T.s in the range from 90.0° to 92.0° , operations in this range would seem to involve a small and quite acceptable risk. Maintained exposures at E.T. in excess of 92.0° occurred on only two runs out of 15, those of 21 Sep and 11 Oct (Fig. 3a, 6b). Although excessive heat strain was not experienced on these occasions either, in this range of E.T. probabilities begin to be involved. Consider the run of 11 Oct. At the time when an oncoming rainstorm provided a decrease in solar heat loading on the vehicle (1400-1500 hours), all of the men (Fig. 9) were showing rates of temperature increase that might have easily brought them to hazardous levels of body heating in another hour. Had the E.T. reached 92° much earlier, as it did on 21 Sep (Fig. 3a), or had the sun continued to heat the vehicle unshielded by storm clouds, as occurred on 8 Oct (Fig. 6a), the results might have been serious indeed.

One may fairly conclude that, under the environmental conditions that characterized the Base Camp area (11), operations with infantrymen in the M113 Armored Personnel Carrier may be carried out at any time with little probability of the men suffering excessive physiological stress, but that a small chance of incurring heat casualties does exist.

A few additional points should be made. First, the vehicle used for these studies was painted International Orange, as were all SWAMP FOX II vehicles. This paint reflects much more sunlight than does the standard olive drab paint used on military vehicles. There is no doubt that conditions inside a normal military vehicle would have been measurably more severe; the author of this report has tested this directly during Operation SWAMP FOX I in the Rio Bayano valley by shifting seats atop an M113 carrier from orange to olive-drab-colored areas (the instrument was uncalibrated). The conclusions drawn above have been taken somewhat conservatively in order to allow for this effect in absence of an opportunity to make appropriate measurements. Second, during moving confinement runs the carrier was stopped about noon to eat lunch. On such occasions the E.T. usually rose, as is seen in Figures 1, 3, 4, 5, and 6, presumably due to engine heat flowing into the personnel compartment. The subjects responded to this peak in thermal stress within the half-hour minimum interval between temperature and pulse measurements. A decrease in thermal stress (Fig. 6) is followed by as rapid a drop in thermal strain in the subjects. It seems clear that, in the state where men are near a limit of thermoregulatory capability, physiological adjustments to changing environmental stresses are prompt and continuous. Third, the environment inside the armored personnel carrier is much affected by the solar radiation load on the vehicle. The effect is more pronounced at the more severe levels of internal E.T. The curves suggest that a lag period of up to an hour separates a drop in external solar heating from a resultant decrease in internal environmental severity. On hot days rainfall accelerates the relief afforded the passenger personnel (Fig. 6b). Finally, although it was impractical to measure sweat production on the men during the confinement

studies, the condition of the clothing at the ends of the runs could be observed. Sweating through the fatigue clothing at such points as shoulders was neither common nor extensive, and in no case were the clothes of any subject completely sweat-soaked. Since ventilation within the armored personnel carrier was limited, these observations may be taken to confirm other evidences that the men were not under thermal stress that approached intolerability.

Walking Studies

Simple walking experiments were performed for several reasons. For one, the confinement studies made possible the observation of men under only moderate thermal stress at worst, contrary to expectation. In addition, the studies permitted only limited physiological observations, as explained previously. Finally, a number of persons were curious whether differences could be demonstrated between infantrymen and other types of enlisted personnel with respect to response to thermal stresses.

Walking was selected as a simple, well-studied exercise, familiar to military personnel, that could be manipulated to produce high levels of thermal stress by increasing internal heat production. The tests were run only during relatively clear periods to avoid interference with sweat measurements and to provide the best chances for maximum heat load from solar radiation. Tests were run within the periods 0930-1115 or 1400-1500 hours (symmetrical with respect to local solar noon), so that the radiation environment would be the same during either period save for random cloud behavior.

The enlisted specialists were volunteers. They were neither free nor generally willing to participate for more than one run of about an hour's duration, so there was no opportunity to train them in any way. Nonetheless they did maintain fairly constant walking speeds (individually) as may be seen from an examination of the lowest curve in Figures 10-18.

The same figures show that the walking did have the desired effect of putting the men under substantially greater thermal stress than had been experienced during the confinement studies. Heart rates of the order of 150 beats per minute were regularly obtained, and the average body temperatures climbed to levels comparable to the oral temperatures only observed on the men during confinement in the personnel carrier.

These figures also show some of the problems of handling data gathered in the field. Both the environment and the physiological behavior of the men change constantly. Data-pooling techniques used in the analysis of experiments carried out in

constant-environment laboratory chambers are often either unsafe or unfruitful. Thus it is not meaningful to compute or discuss the mean solar radiation intensity during any appreciable period of such runs as those shown in Figures 12 or 14.

Measurements of sweat production, one widely used index of total thermal stress, are necessarily made over the whole test period. One has little choice but to accept and average variations in environmental conditions or human performance during the measurement period. Fortunately the variation in walking speed during any individual run was modest in these tests. Figure 19 summarizes the analysis of the data on total sweat production. The top graph indicates that the rate of sweat production, as expected, is a function of walking speed. Presumably the spread in values is due partly to inherent experimental errors and partly to variations from run to run in the thermal environment, which would also be expected to affect sweat production. However, the relation between severity of thermal environment, as measured by the WBGT Index, and total sweat production is even less regular, as shown by the middle graph in Figure 19. In this case another source of variation enters, that of the WBGT Index during the course of an individual run. Examination of Figures 10-18 shows that this may be considerable on some days. In a case of this sort, where two independent variables are mutually confounding with respect to observation of the relation between either and any given dependent variable, one should get good curve fitting by plotting the product of the two against the dependent variable if no other factors are operative. The lowest graph in Figure 19 is such a plot. The fit in this case is slightly better than that in the upper graph, but a close examination of the individual points in the two graphs shows them to be quite similar. Granting that errors of measurement must account for much of the distribution spread in any of these graphs, one must conclude from them that the total sweat production by these men was much more a function of rate of walking than of the severity of the thermal environment. In other words the metabolic heat generated by walking up- and down-hill makes a greater contribution to body heat content than does the heat input from the tropical environment. The difficulty with such a conclusion is that the straight fitted curves extrapolate to absurd values, e.g., 0 sweat production for men walking nearly two mph with WBGT Index generally above 30.0° C. (86.0° F.). The errors involved in measurement of total sweat production (nude body weight changes to the nearest 5 g.) are not large enough to account for this, nor does it seem likely that any non-linear curve fitting will afford the answer. Clearly, some factor is operating to which the available data give no clue.

In a similar way the rate of sweat evaporation appears to be related to the walking rate, as shown in Figure 20. In this case the curve fitting is less satisfactory, due partly at least to the greater measurement errors involved in assaying clothed-body weight changes. No relationship could be demonstrated between evaporative weight loss and the thermal environment as measured by the WBGT Index.

From Tables 1, 2, and 3 it is shown that the total sweat production by these men was 0.850 g. per hour, an abundant amount, but one that men can maintain for considerable periods if water is available. Table 4 shows that the men evaporated about

2/3 of the sweat produced, or about 0.560 g. per hour on the average. Thus even in the high humidity environment of the tropics sweat evaporation may be a more effective thermoregulatory mechanism than is often supposed.

During these studies the men were able to unload generous amounts of heat through evaporative cooling. Table 3 shows that the infantry subjects were able to lose over 200 kcal. $m^{-2} hr^{-1}$ in this manner. References to tables of metabolic costs of different conditions of exercise, such as those given in Newburgh (8), allow one to estimate the metabolic heat production of these men, even though direct measurements were unfortunately not possible. Assuming a metabolic output of about 330 kcal. $m^{-2} hr^{-1}$ for the up-hill third of the course, 250 for the down-hill third, and 130 for the level third, and allowing for standing still at 60 kcal. $m^{-2} hr^{-1}$ for one minute out of five at the field station, one gets an average value very near 200 kcal. $m^{-2} hr^{-1}$ for the metabolic output of men walking the course. It appears that even in a tropical environment sweat evaporation will handle a cooling load of the same order of magnitude as the heating load involved in doing moderately heavy work.

Molnar (7) estimates that clothed men in the tropic sun have a heat gain from the environment of about 85 kcal. $m^{-2} hr^{-1}$ on the average. Even allowing for peak periods when the solar load at Panamanian latitude during unclouded periods might drive this value higher, it is clear that men can readily accommodate this heat load through sweat evaporation alone.

The second measurement utilized to detect thermal stress was that of the heart rate. Examination of Figures 10-18 shows that the pulse rate climbed for about the first 30 or 40 minutes of each run and in every case but one (Subject RH, Fig. 13) achieved a steady state. Most of the rise must be attributed to physiological accommodation to a sudden increase in work load. Whether the steady-state level of pulse rate is wholly due to this is explored in Figure 21, in which the data are handled in much the same manner as were the sweat production data for Figure 19. The upper graph shows that the pulse rate is a very close function of the average rate of walking on the hill course. The two lower graphs indicate that the thermal environment contributes very little to the steady-state level of pulse rate. Attempts to get better correlation between pulse rate and WBGT Index by means of non-linear relationships proved fruitless. This is not surprising in view of the average resting pulse rates shown in Table 5; these were measured on each subject immediately before each walking trial began.

The third measurement made for the detection of thermal stress was that of average body temperature. As Figures 10-18 show, the variation in average body temperatures was more complex than that of the heart rate, to the extent that any attempts to average these values would tend to obscure useful interpretations rather than to illuminate them. In general, and particularly for the infantry subjects (Fig. 10-13), the body temperatures tended to rise over the first 20 minutes or so of walking. Where the initial WBGT Index was moderate and decreased rapidly during the course of the trial, even this initial rise in temperature was not observed (Fig. 15).

On the other hand, when the WBGT Index remained at or above Minard's "red flag" limit (31.1°C . or 88.0°F .) for an appreciable time, average body temperatures continued to rise, as shown in Figures 11 and 13. A sudden drop in environmental stress (WBGT Index) was capable of producing a dramatic response in the form of a drop in average body temperature, particularly when the latter indicated a condition of heat accumulation. This is shown most clearly in Figure 13, where a suddenly developing rainstorm brought quick relief from thermal stress. In numerous other instances the data indicate the ability of the thermoregulatory mechanism to respond quickly to even small changes in the thermal environment, but most especially when the subjects were accumulating heat.

In numerous cases there was a tendency for a small drop in temperature to occur after about 20 minutes of walking. This suggests that a sweating through of clothing (always worn bloused) may have become appreciable at about this time. If so one might expect a sudden increase in the efficiency of evaporative cooling. Unfortunately no records were kept of the onset of clothing sweat-through.

In only one instance did there appear to be any evidence of effects of air movement on the thermal behavior of the subjects. This is partly a result of the pattern of air movement, which generally tends to be small with rapid low-level fluctuations. During the trial on the afternoon of 11 Oct (Fig. 15), the wind increased from around one mph to over five mph, between 1400 and 1420 hours, and remained that high until 1500 hours. Such breezes, as in this case, herald an oncoming storm. The body-temperature curves indicate that the breeze continued long enough to dry the clothing to the point where it began to lose its effectiveness in facilitating evaporative cooling and to act as a vapor barrier instead. In the absence of a log showing the state of the clothing at any given time, such an interpretation is, of course, tentative.

In any case the body temperature data reveal that the thermoregulatory machinery is promptly sensitive to changes in the thermal environment in a manner that one cannot easily observe in a constant-temperature chamber. The gaps in data that make firm interpretations difficult serve to emphasize the need for a more extensive study of human thermoregulatory behavior in dynamic environmental situations. Information of this kind has an important bearing in the application of environmental physiological information to military problems. The problems are rarely those in which one needs to know the limits of stress which a man can tolerate indefinitely but rather those in which the knowledge required is of probabilities of occurrence of excessive stresses with which a man can cope for a limited time. Only an accumulation of detailed information about the short time responses of men to dynamic environments can provide the basis for answers to the latter kind of problem.

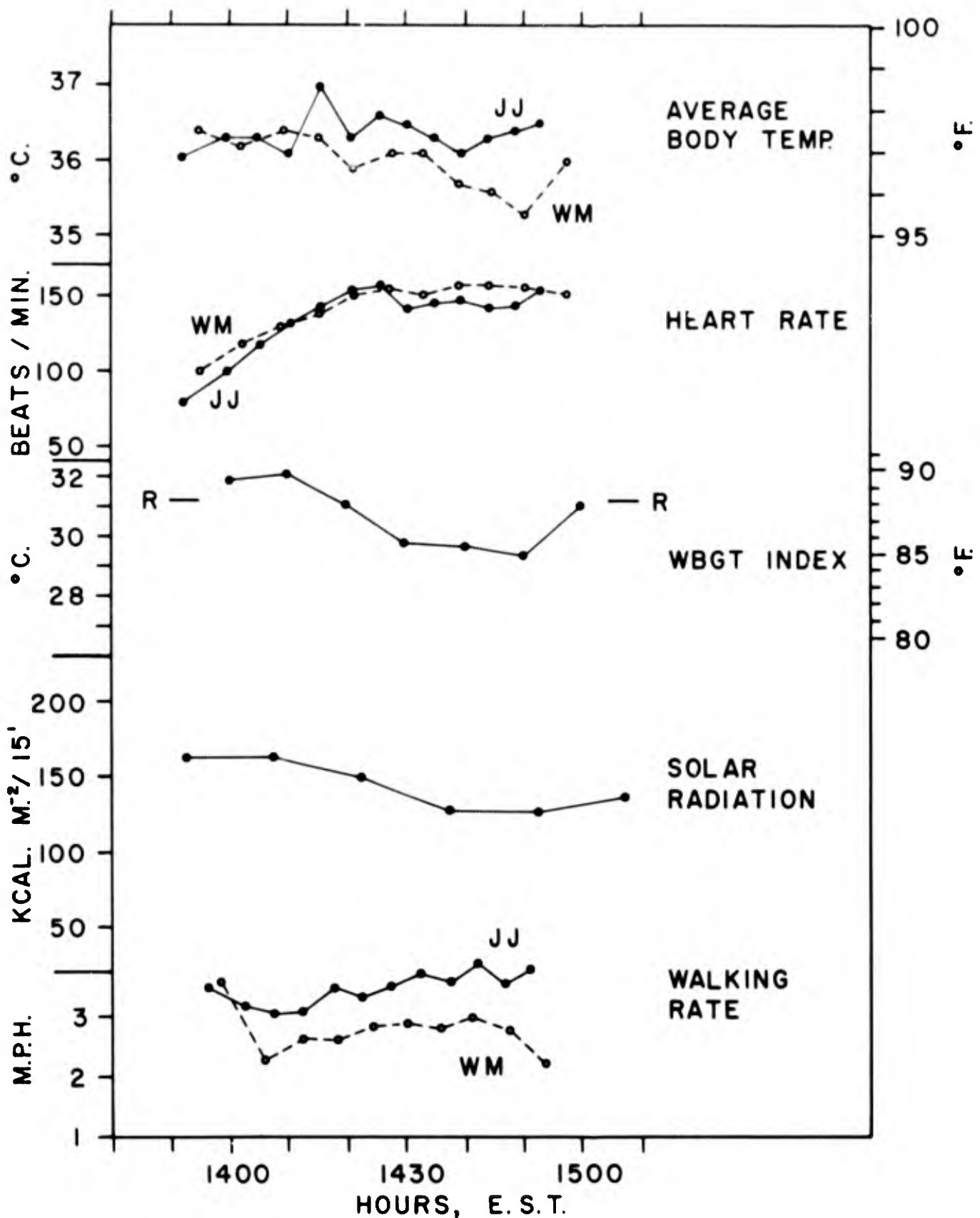


Fig. 10. WALKING TRIAL -- 9 OCT

(Infantry subjects JJ and WM. Subject JJ is a former Olympic swimming athlete whose physical condition was apart from that of all other subjects. He could not restrain a competitive urge to post a top walking speed rather than to maintain a more nearly normal marching pace.)

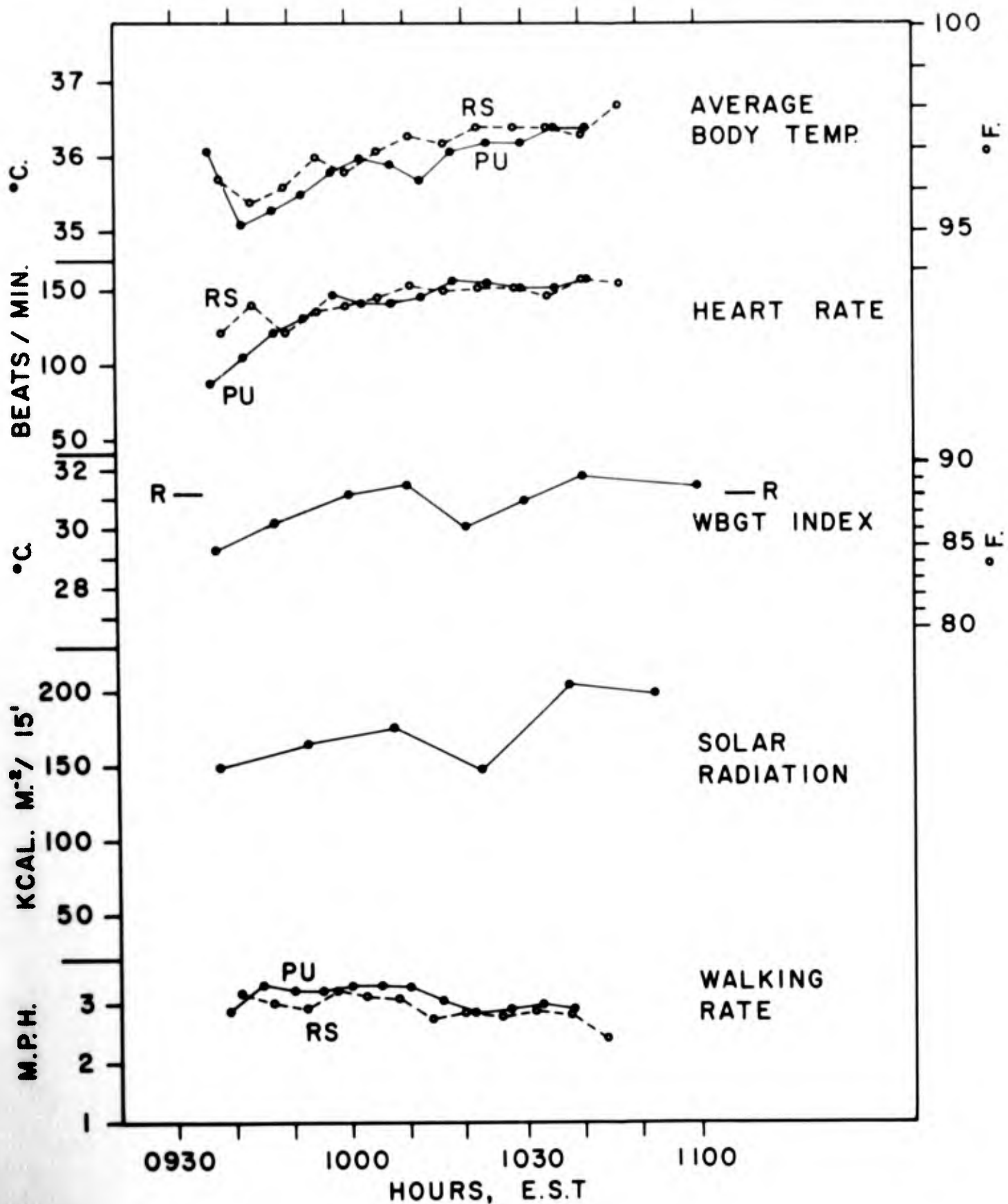


Fig. 11. WALKING TRIAL -- 10 OCT

(Infantry subjects RS and PU. Both were older than all other infantrymen, and both were sergeants. RS was NCO in charge of the infantry squad.)

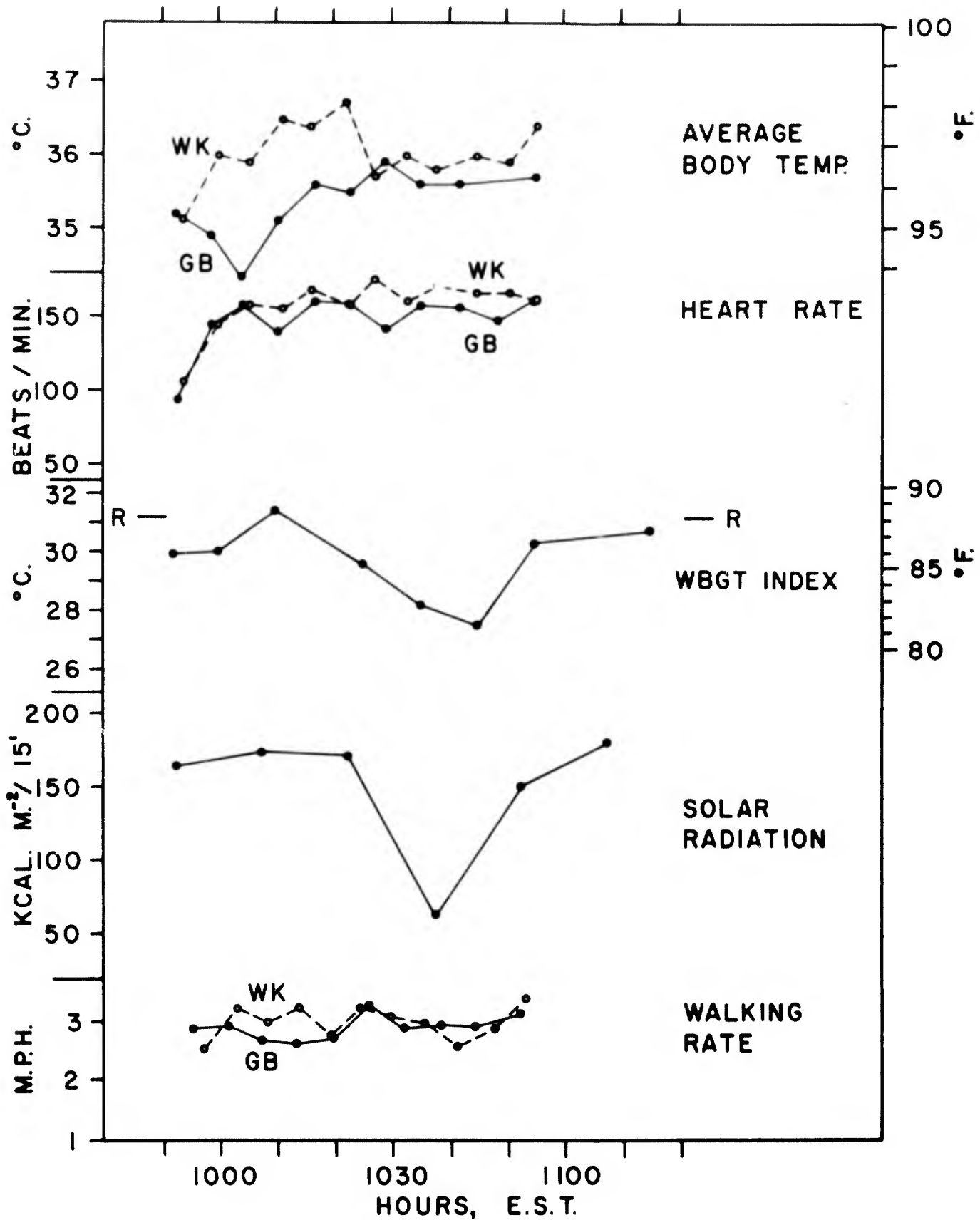


Fig. 12. WALKING TRIAL -- 13 OCT

(Infantry subjects WK and GB. GB was far the most recently stationed in the Canal Zone -- three months -- whereas WK had been stationed there for 28 months.)

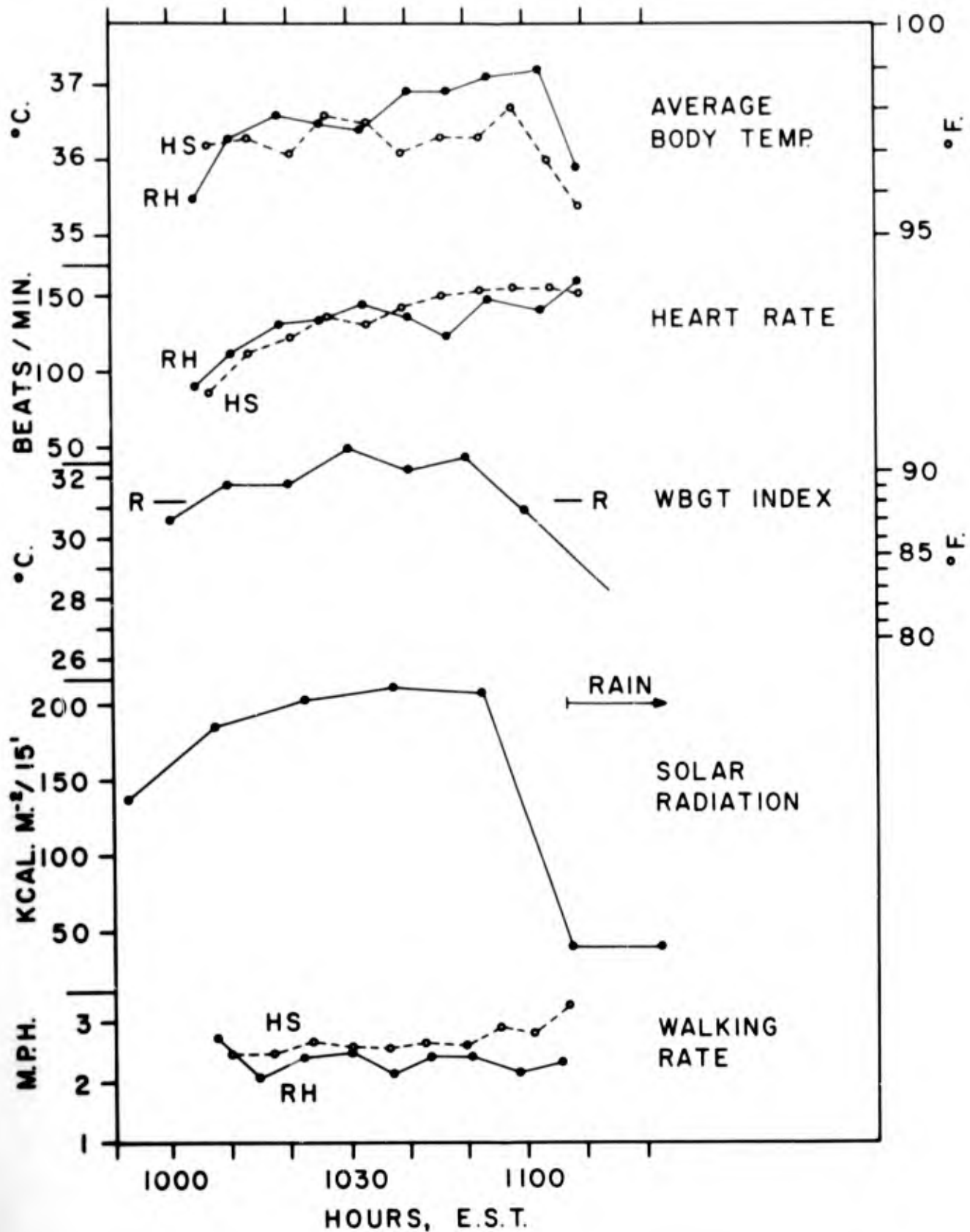


Fig. 13. WALKING TRIAL -- 15 OCT

(Infantry subjects RH and HS. RH was the only Negro subject to participate in any of the HEL studies.)

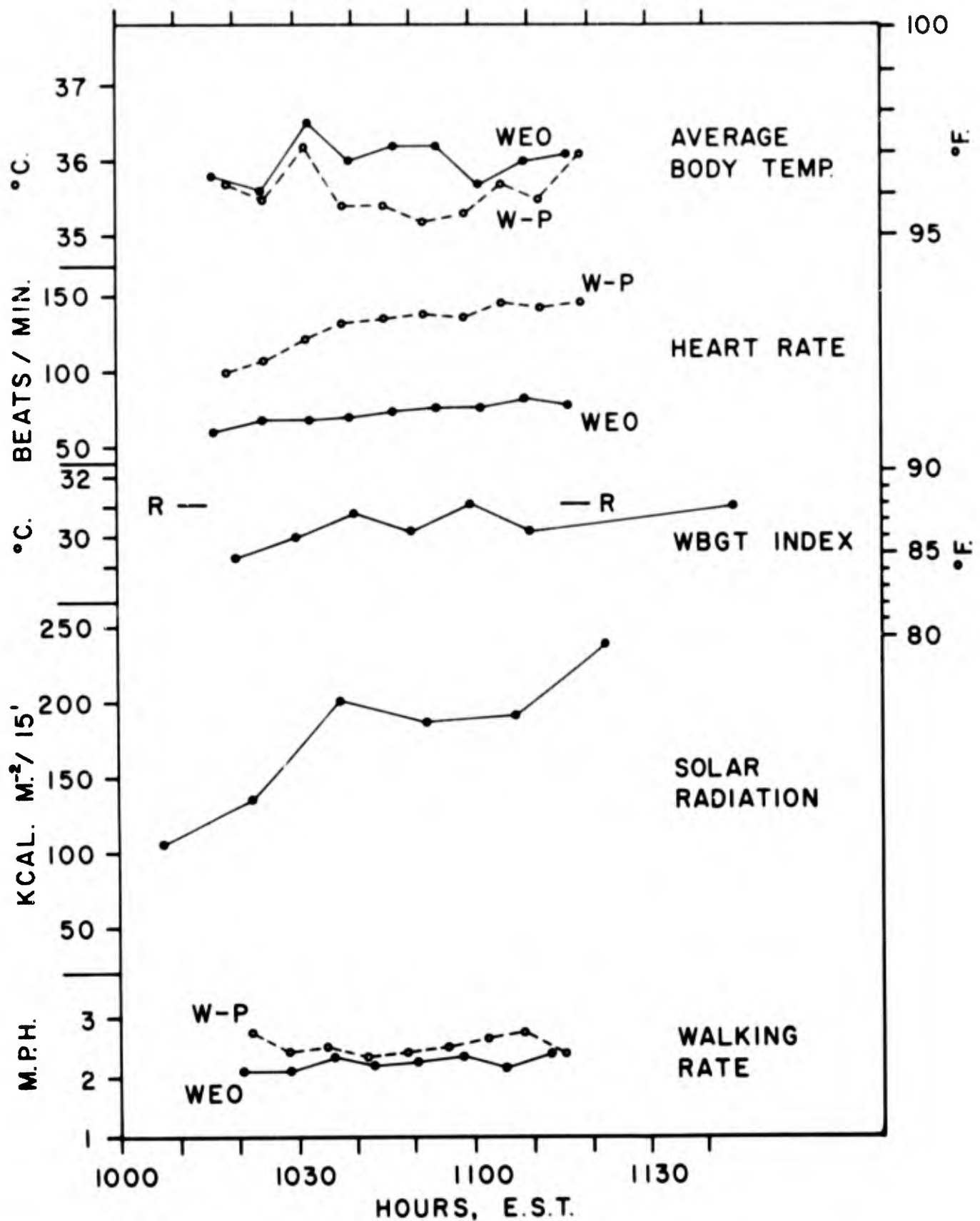


Fig. 14. WALKING TRIAL -- 11 OCT

(Enlisted Specialist subjects WEO and W-P. WEO was the oldest of the non-infantry subjects. He had had extensive amateur athletic experience and was conscious of his physical performance to the extent that he paced himself to try to maintain a constant pulse rate, self-observed.)

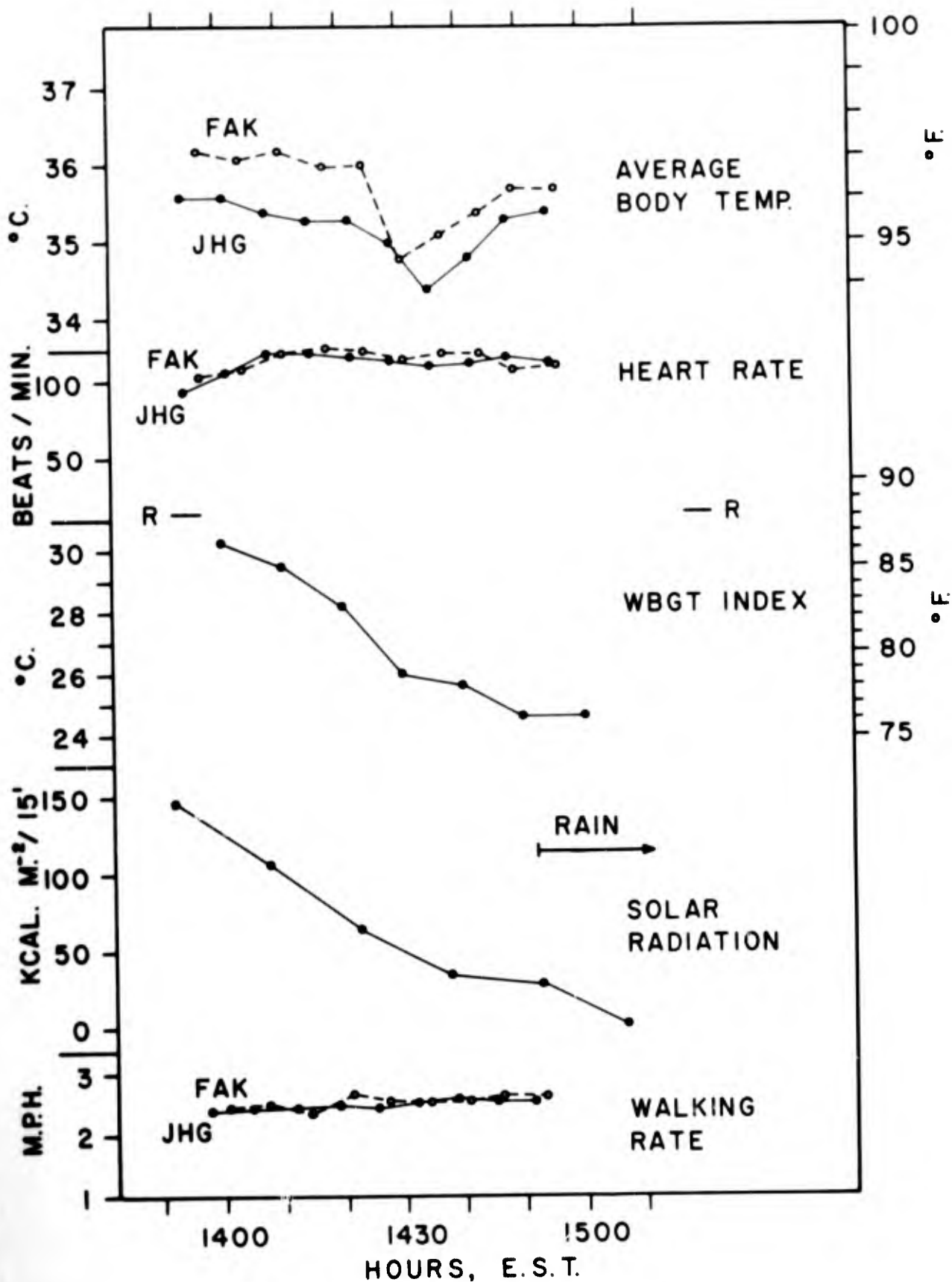


Fig. 15. WALKING TRIAL -- 11 OCT

(Enlisted Specialist subjects FAK and JHG. JHG was a cook; he was noticeably overweight and judged to be in the poorest physical condition of any of the participating subjects. This condition was not poor, however, by civilian standards.)

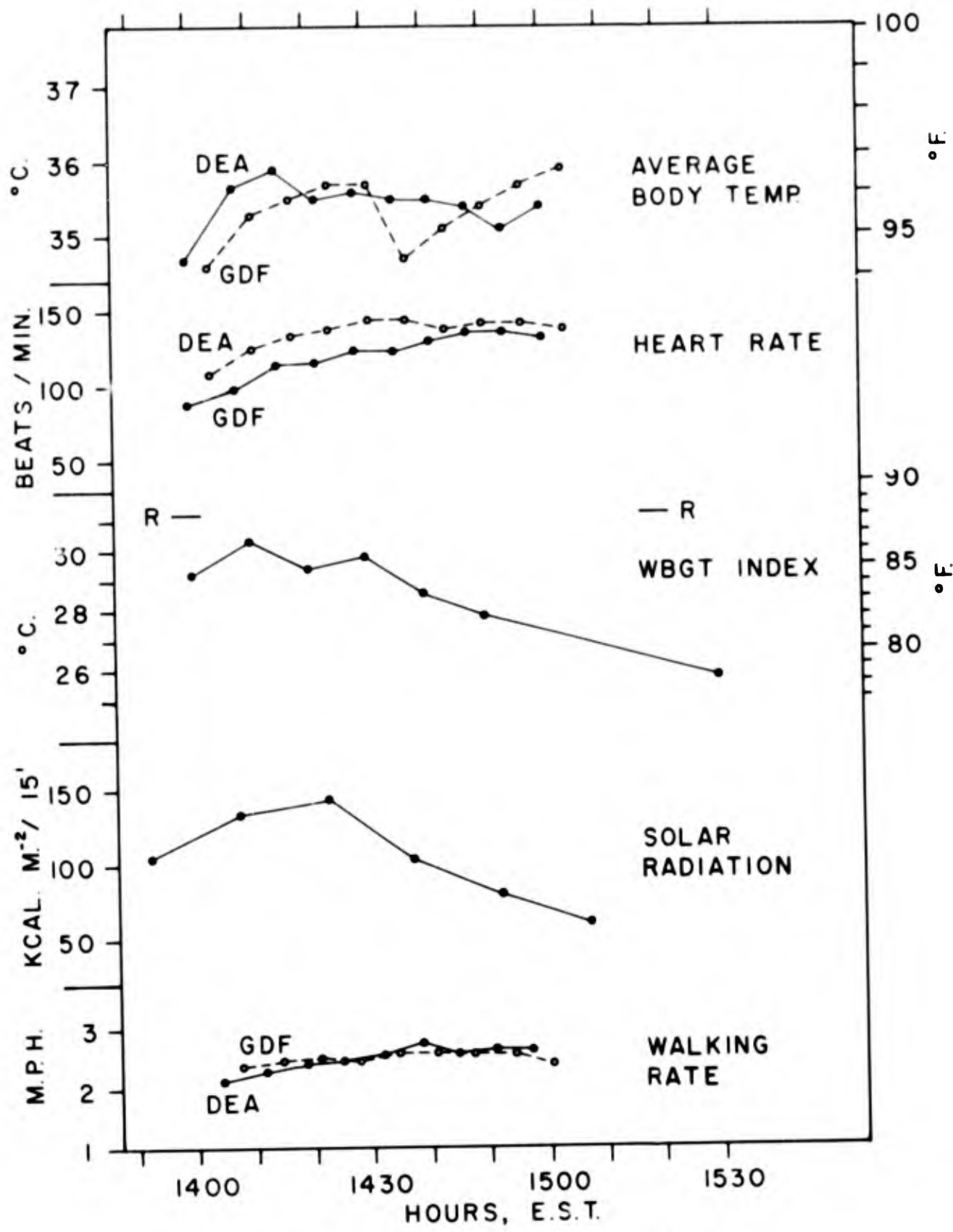


Fig. 16. WALKING TRIAL -- 12 OCT

(Enlisted Specialist subjects DEA and GDF.)

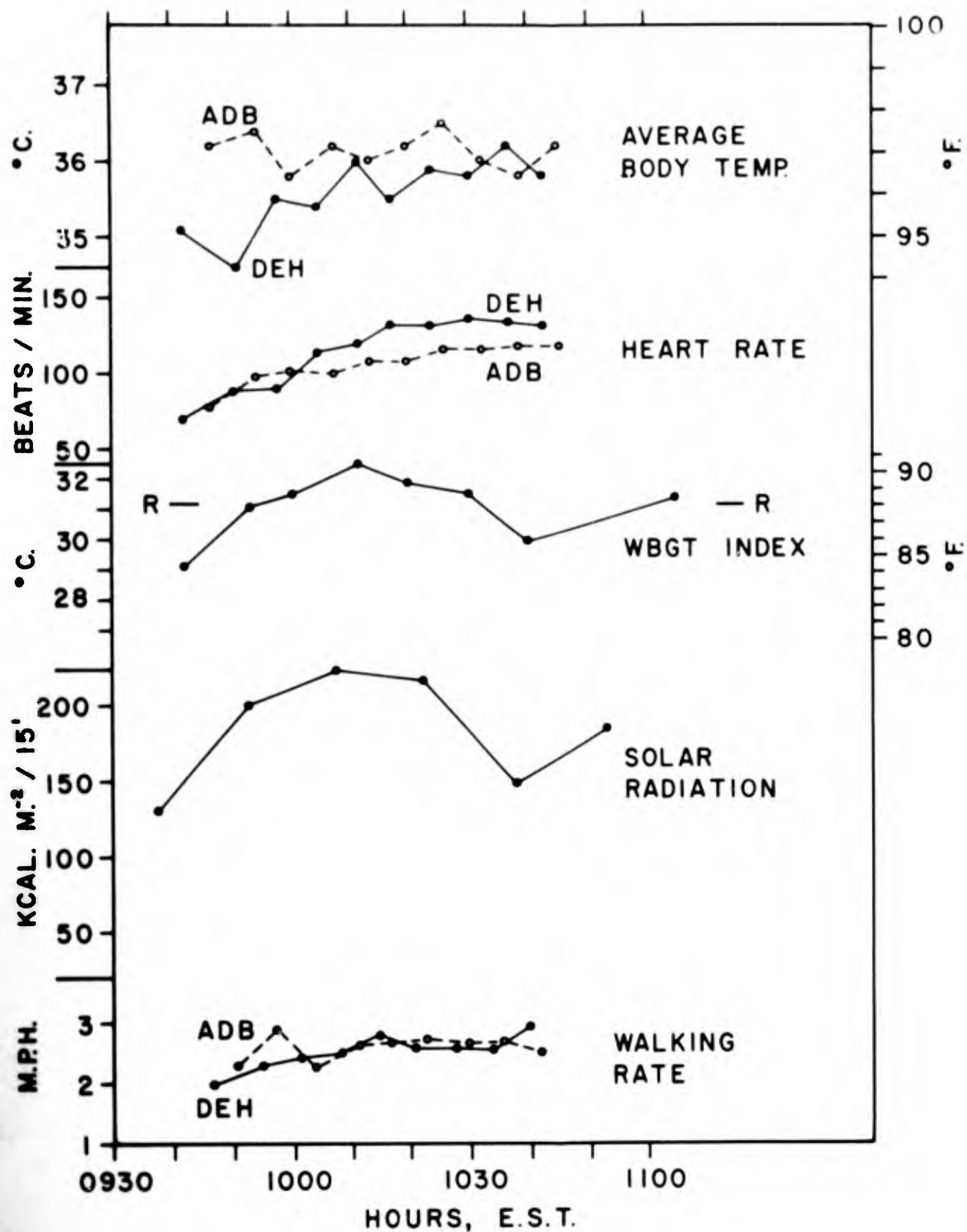


Fig. 17. WALKING TRIAL -- 14 OCT

(Enlisted Specialist subjects ADB and DEH.)

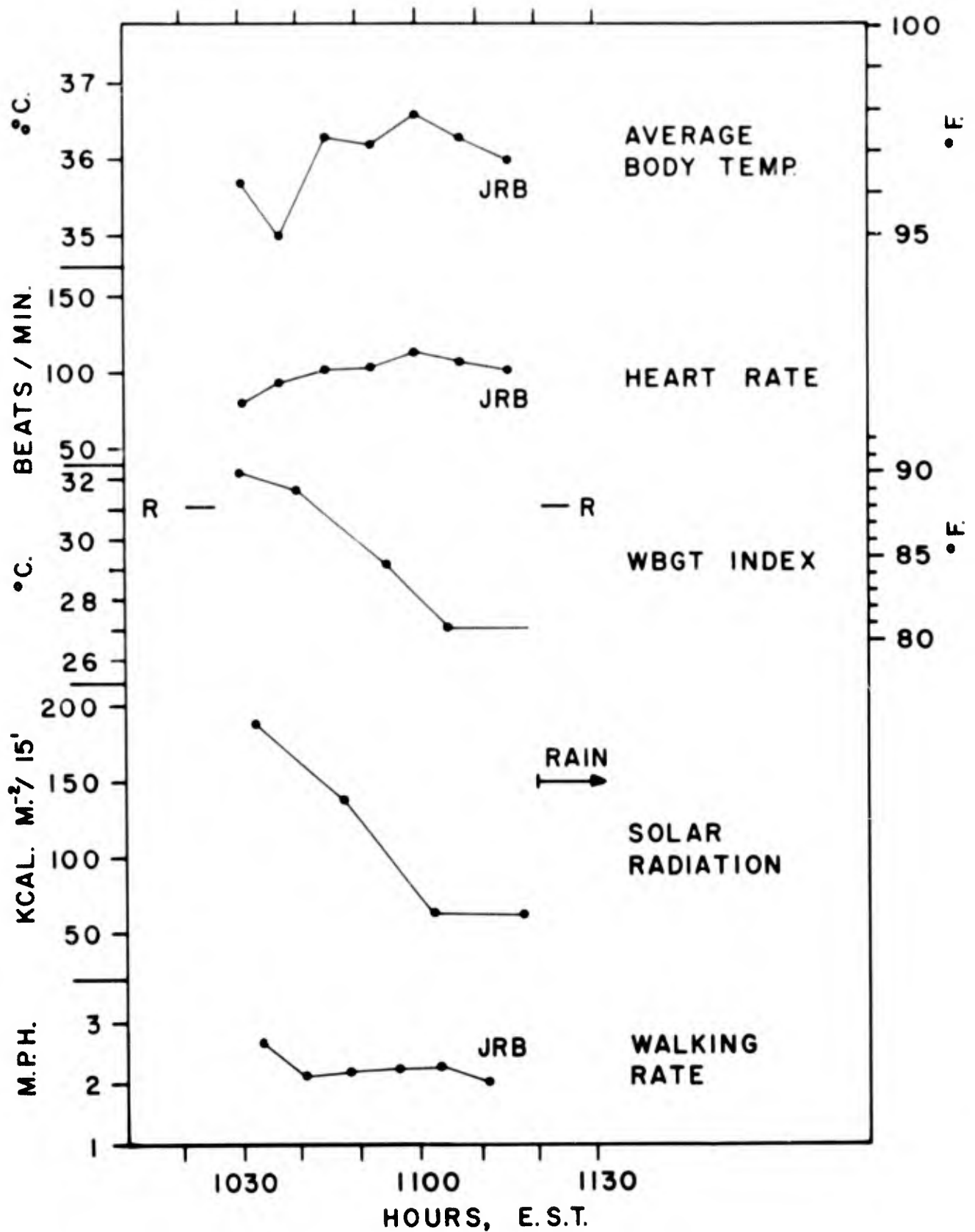


Fig. 18. WALKING TRIAL -- 16 OCT

(Enlisted Specialist subject JRB.)

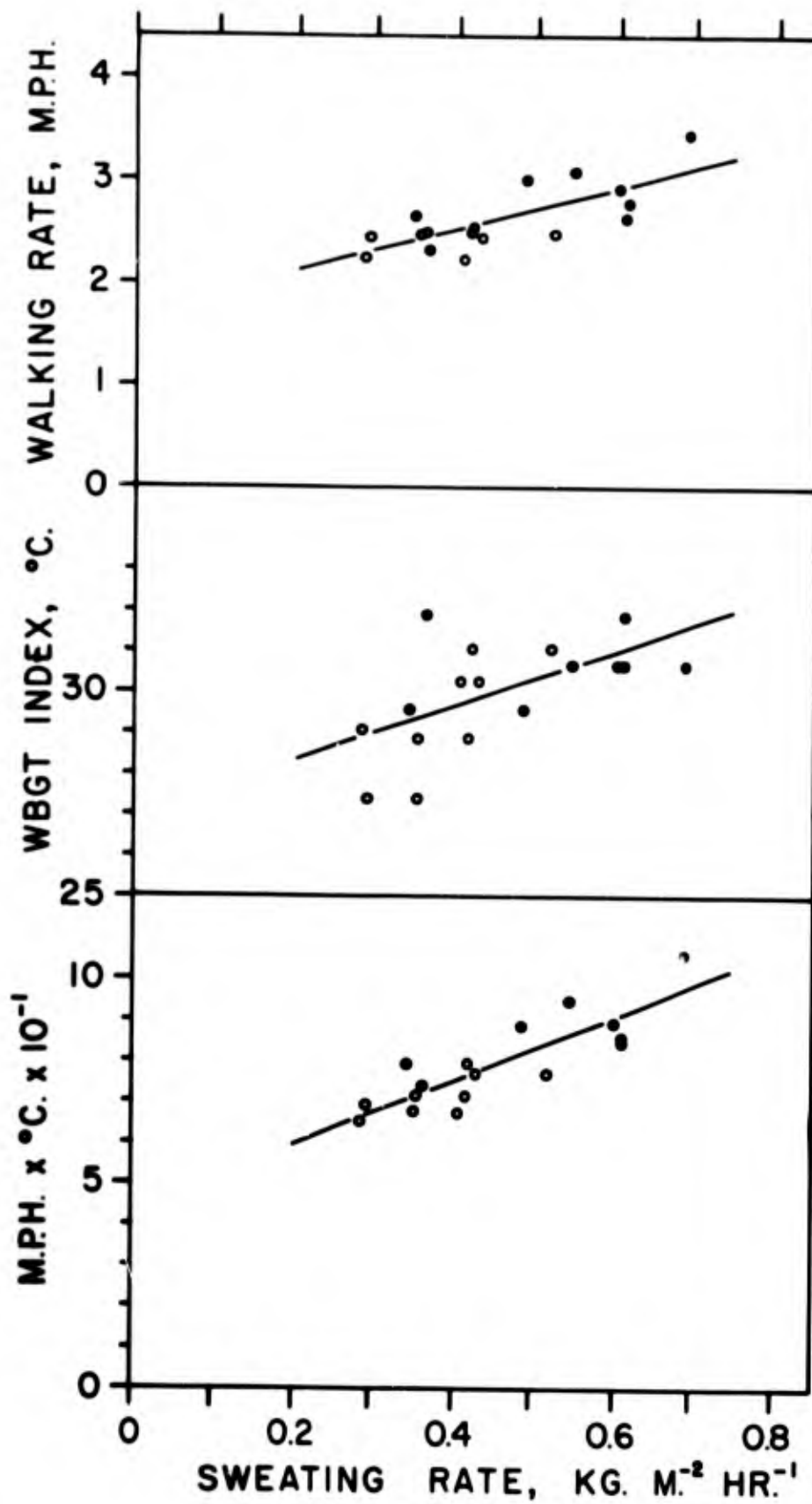


Fig. 19. RELATION OF TOTAL SWEAT PRODUCTION TO WORK RATE AND ENVIRONMENTAL STRESS

(The curves drawn through the plotted points were fitted by the method of least squares. Closed circles are values for infantrymen; open circles are values for enlisted specialists.)

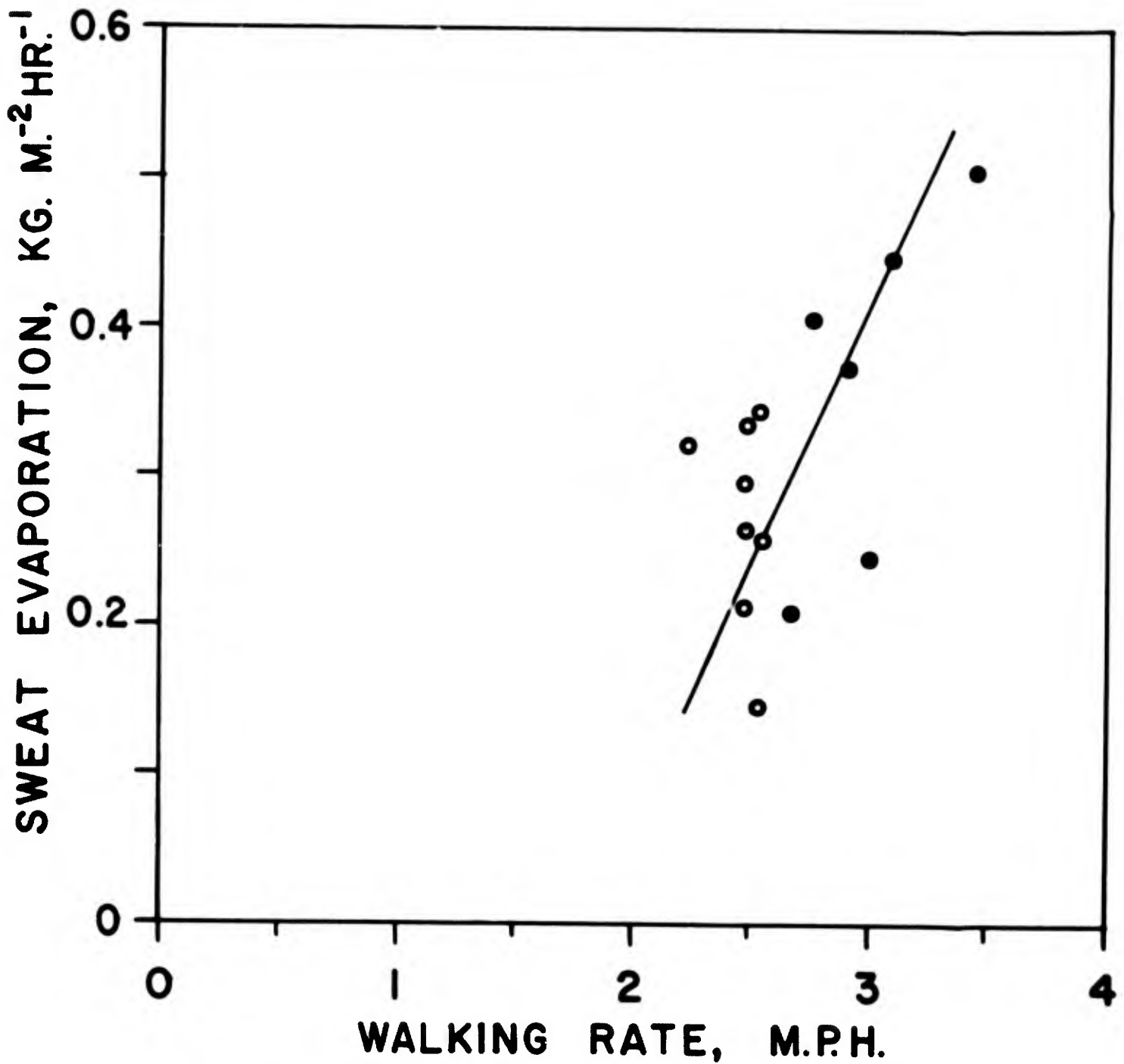


Fig. 20. RELATION BETWEEN SWEAT EVAPORATION AND WALKING SPEED

(The curve was fitted by the method of least squares. Closed circles are values for infantrymen; open circles are values for enlisted specialists. No correlation at all was found between rates of sweat evaporation and variations in the thermal environment.)

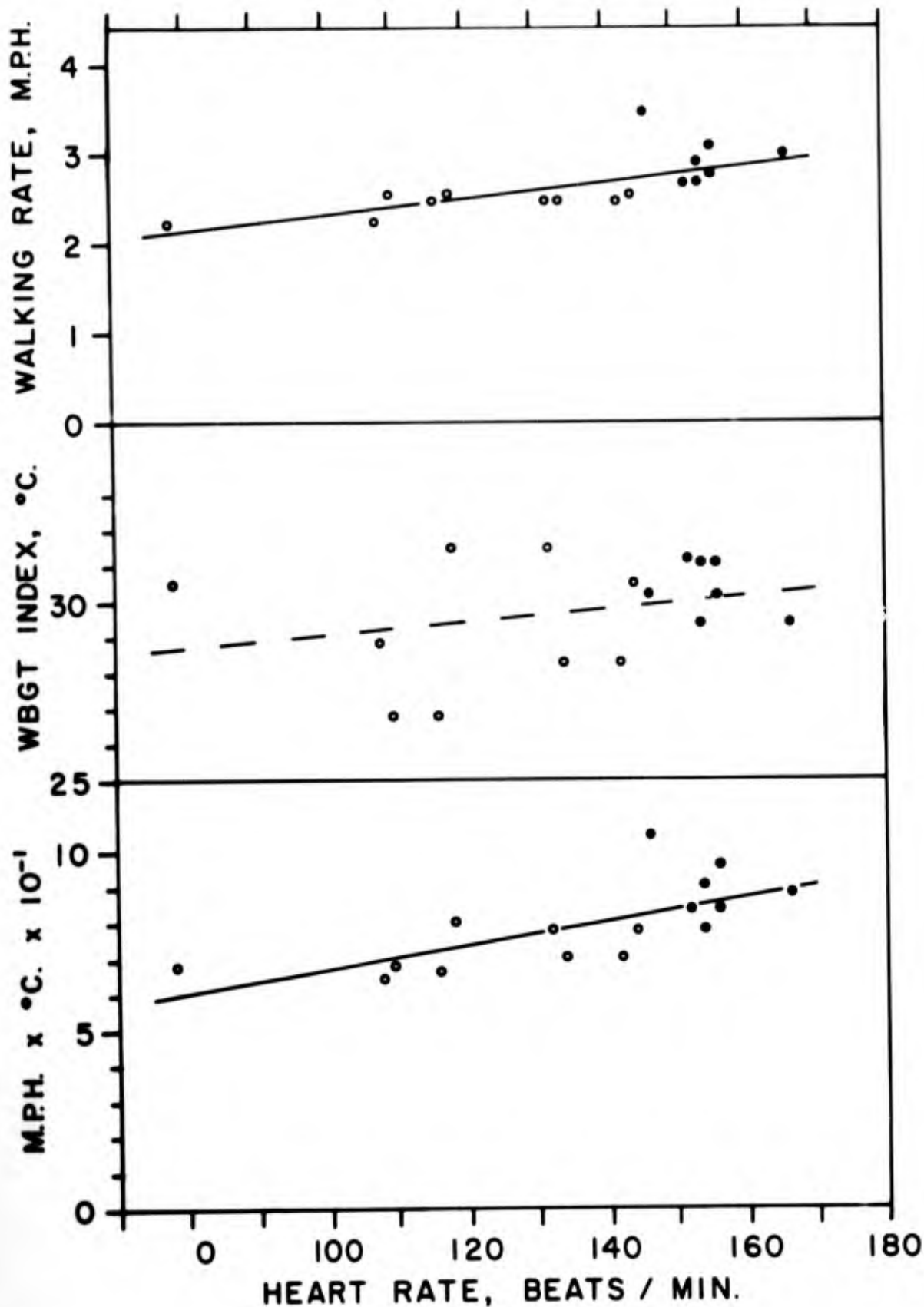


Fig. 21. RELATION OF STEADY-STATE PULSE RATE TO WORK RATE AND ENVIRONMENTAL STRESS

(The curves drawn through the plotted points were fitted by the method of least squares. The broken curve in the middle graph indicates that there was little justification for such curve fitting in this instance. Closed circles are values for infantrymen; open circles are values for enlisted specialists.)

Performance of Infantry and Non-Infantry Subjects

The different measures utilized to test for differences in performance between the two classes of subjects are summarized in Table 5. The essence of the comparisons is included in the last two columns of this table. The condition of the men at the beginning of the walking trials did not differ between the two groups, as measured by pulse rates and average body temperatures taken while standing quietly in the shade. During the course of the walking periods the men in the two groups differed by every measure used, and the infantry subjects invariably achieved the higher levels. Yet there is little evidence of any differences between the groups that can be attributed to differences in tolerance to thermal stress. The higher levels of sweat production and sweat evaporation and the higher pulse rates, all shown by the infantrymen, have already been shown to be functions of their higher walking speeds. The statistically significant differences in average body temperatures involve actual differences of about 0.4° C. (0.7° F.). Almost certainly these can be attributed to the higher internal heat production generated by higher work output involved in faster walking rather than to any significant differences in thermoregulatory efficiency.

The higher walking speeds of the infantrymen are not necessarily an indication of superior physical capability. Among other factors, the two groups had different motivation levels. By chance, subject JJ, who in some sense was in a physical class by himself, participated in the first walking trial and posted a respectable record speed. The men in the infantry squad had a high morale and were noticeably competitive within the group. As a result the infantry subjects in subsequent trials, although aware that they could not match the performance of this exceptional physical specimen, were consciously attempting to achieve performance levels that would not be sources of embarrassment. The enlisted specialists were not themselves a part of any regular unit group and did not share in this competition either among themselves or as a group against the infantry squad. As shown in Table 2, these men were drawn from various duty stations in CONUS and assigned temporarily to Operation SWAMP FOX II in various capacities. The only enlisted personnel that might have been expected to have any group cohesion were those from the U. S. Army Transportation Board, Ft. Eustis, but these men with two exceptions did not volunteer for the walking trials.

The military background of the men in the two groups differed significantly. The infantrymen had been accustomed to almost daily cross-country marches in the Ft. Davis area, and were given a timed march once a week. Under the circumstances one is less surprised that the infantrymen generally walked more rapidly than the enlisted specialists (over what must have seemed relatively easy terrain) than that the latter performed so consistently among themselves, as indicated by the lower standard deviation of their scores.

That no differences in heat toleration seem to be indicated between the two groups of subjects is not surprising. The trials were performed after the SWAMP FOX II personnel had been in the Panama area for nearly two months and in the field

TABLE 5

Comparisons of Performance of Infantrymen and Enlisted Specialists

Measure Compared	Means \pm 1.0 standard deviation		Difference btwn means	t [†]
	Infantry	Enl. Specialists		
Walking rate (mph)	2.86 \pm 0.36	2.45 \pm 0.13	0.41	3.447**
Sweat production (kg m ⁻² hr ⁻¹)	0.53 \pm 0.133	0.387 \pm 0.077	0.144	2.957**
Sweat evaporation (kg m ⁻² hr ⁻¹)	0.365 \pm 0.090	0.273 \pm 0.063	0.092	1.881*
Avg. body temp., at rest (° C.)	35.78 \pm 0.50	35.51 \pm 0.62	0.27	1.038
Avg. body temp., walking (° C.)	36.09 \pm 0.38	35.70 \pm 0.34	0.39	2.391*
Avg. body temp., max. (° C.)	36.59 \pm 0.43	36.18 \pm 0.35	0.41	2.294*
Pulse at rest (beats/min.)	95.8 \pm 14.3	86.8 \pm 17.0	9.0	1.242
Avg. pulse, walking (beats/min.)	146.1 \pm 8.6	114.7 \pm 19.9	31.4	4.367**
Max. pulse, walking (beats/min.)	160.4 \pm 6.1	123.3 \pm 21.4	37.1	5.004**

† t-test for the standard error of the difference between the means, unpaired observations.

* $\underline{p} < .05$

** $\underline{p} < .005$

for most of that time. During the two weeks of the preparatory phase, the men worked daily in a hot location under conditions of urgency to meet a deadline for departure to the field. The heat exposure and work levels at this time were sufficient to produce profuse sweating and high levels of water intake among almost all personnel throughout the working day of eight hours. As Lind and Bass (5) have shown most recently, a maintained exposure to thermal stress of 100 minutes a day produces a maximum rate of heat acclimatization, so that it may reasonably be assumed that the military personnel from CONUS were fully heat acclimatized before departure to the Base Camp, at least with respect to moderately heavy work loads.

As the HEL observers found by trial, walking up and down a 12.5° slope in the sun at a latitude of 9° in a tropical environment is hardly a game of choice to be elected by effete young men (or tired old ones). Neither is it one that calls for absolutely maximum effort. Had the latter been an objective of this study, somewhat different results may have been obtained. But soldiers are in fact rarely called upon to perform to maximum limits of physical capacity, and the HEL team, with limited capability, chose to concentrate its effort on observations of activities at work levels more representative of the typical work load of soldiers.

Finally, the importance of solar radiation as a dominant factor in the thermal environment in this area must again be stressed. Figures 10-18 show clearly how closely the total thermal environmental stress (as measured by the WBGT Index) follows the intensity of solar radiation. That this must necessarily happen in an environment of the type under discussion has been discussed by Woodward (11). Even though dominated by the thermal consequences of the work involved in hill climbing, the physiological behavior of the men here described appears to be capable of quick response to environmental changes that are in turn functions of solar radiation. The magnitude of the direct thermal effects of solar radiation will vary with the orientation and degree of exposure of a man with respect to the sun at any given time, but problems thus posed cannot be explored without making direct measurements of the radiant environment concomitant with physiological observations. This task must be accomplished at a future date with the appropriate instrumentation.

SUMMARY

Military subjects were confined in an M113 Armored Personnel Carrier for periods of up to six hours during the midday in an open, tropical environmental location during the rainy season. The thermal environment developed within the vehicle in no case provided sufficient stress to precipitate heat casualties, and in no case did it generate thermal strain in the subjects severe enough to remove a subject from any experiment.

The results indicate that in the situations studied men may tolerate, without undue physiological strain, exposures of up to four hours at effective temperatures (E.T.) up to 33.3° C. (92.0° F.). Exposures to E.T. above this level were rare. The responses of the men under the most extreme conditions and the low probability of long, maintained, extreme conditions indicate that men in armored personnel carriers operating in a tropical environment of the type observed will be subject to very low risk of suffering heat casualties.

The thermal environment within the armored personnel carrier follows closely the level of solar radiation intensity in an open area. The internal vehicular thermal environment appears to follow changes in solar radiation level with a lag time of less than one hour. Men within the vehicle respond physiologically to such changes in less than one-half hour.

Military subjects in two groups, infantrymen and enlisted specialists, were studied while walking on a course laid out on a hill slope of 12.5° . Measurements of body temperature, heart rate, and sweating were used as indices of thermal stress during the walking periods. Substantial thermal stress was experienced by all subjects, but no intolerably severe strain was observed.

Measurements of sweat production and sweat evaporation were primarily a function of walking speed, and showed little relation to variations in the ambient thermal environment. The heat absorbed by sweat evaporation appeared to be of the same order of magnitude as that produced by the work of walking the hill course.

Measurements of pulse rate showed that the steady-state level, achieved in all but one instance, was a function of walking speed and showed little relation to variations in the thermal environment.

Measurements of average body temperature did show correlations between the physiological behavior of the men and variations in the thermal environment. Changes in body temperature followed in many cases within a few minutes upon environmental changes, particularly those due to variation of solar radiation and due to air movement. The level of solar radiation is a primary factor in determining the severity of the total human thermal environment.

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PHYSIOLOGICAL RESPONSES OF MEN TO WET TROPICAL
ENVIRONMENTAL CONDITIONS (OPERATION SWAMP FOX III)
Arthur A. Woodward, Jr.

Technical Memorandum 2-64
AMCMS Code 5610.11.70100
Unclassified
January 1964

During Operation SWAMP FOX II in Panama, men under heat stress were observed while walking up and down a 12.5° slope and while confined (as a squad) for up to six hours in an armored personnel carrier at an unforested tropical site. Measurements of bodily temperatures, pulse rates, and sweat production were used as indices of heat strain in the men.

Subjects walking in the sun, unloaded, did not suffer excessive heat strain under midday tropical conditions. About two-thirds of the sweat produced was evaporated for body cooling. Data on confined men showed there was little risk they would become heat casualties when exposed to Effective Temperatures up to 33.3° C. (92.0° F.) for as long as four hours. The men showed physiological adjustments to changes in environmental stress in less than 10 minutes.

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