HEAT STRESS AND STRAIN IN MEN WEARING IMPERMEABLE CLOTHING

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY

Adolph Richard Dasler

1966

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ABSTRACT

HEAT STRESS AND STRAIN IN MEN WEARING IMPERMEABLE CLOTHING

by Adolph Richard Dasler

The purpose of this study was to realistically determine the physiological tolerance of man to heat stress while wearing unventilated, impermeable, full body clothing that barred evaporative heat loss.

The ambient environmental temperatures ranged from DB 18.3°C and WB 12.2°C (65 and 54°F) to DB 32.2°C and WB 26.6°C (90 and 80°F). Air velocity over the surface of the suit was controlled <50, 250 and 1000 feet per minute. The variable of physical activity was limited to standing at rest, work by stepping up two 6" steps and then stepping back down at a regulated rate of 10 round trips per minute, or a combination of rest and work. A total of 10 combinations of the above variables were investigated.

The parameters measured included temperature of the rectum, tympanic membrane, deep esophagus, 10 individual skin sites and mean skin temperature. In addition, metabolic rate, heart rate and blood pressure were determined. Computations and data were presented for first order

partitional calorimetry, estimated cardiac output, and peripheral blood flow by use of the Thermal Circulation Index.

Due to the lag in rectal temperature during transient thermal states and the decrease of skin temperature during work, a series of theoretical equations were developed for mean body temperature when an unsteady state exists in man.

Upon onset of work the internal temperatures increased sharply, followed by an abrupt decrease in skin temperatures. The responses were partially reversed upon onset of rest. The least active skin site (head) and more active site (calf) were most different from any intervening skin temperature site. These findings indicate that during hyperthermia, with small heat losses, the skin temperature directly over active muscles are inversely related to temperatures of the active muscles. It is hypothesized that the observed responses reflect changes in local blood flow.

Partitional calorimetry showed that radiative and respiratory evaporative heat losses changed little with varying air velocity. Convective heat loss was directly related to but non-linear with air velocity. Tolerance time was extended as much as 93 per cent by increasing air velocity up to 1000 feet per minute.

Circulatory instability was observed as the most prominent response when tolerance to acute heat stress was exceeded. Circulatory failure was indicated by both subjective and objective observations. Under the specific conditions of this study, the upper limit of "safe" tolerance can be defined as body temperature not exceeding 39°C, heart rate not exceeding 180 beats per minute, and/or blood pressure not less than 90/40 mm Hg.

HEAT STRESS AND STRAIN IN MEN WEARING IMPERMEABLE CLOTHING

By

Adolph Richard Dasler

A THESIS

Submitted to
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in partial fulfillment of the requirements
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Department of Physiology

1966

DEDICATED TO

My wife, Louise

for continued faith, support, tolerance and encouragement

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INTRODUCTION

One rarely considers the physiological consequences of wearing clothing. It is generally understood that the basic reason for use of clothing is that of protection. However, in thinking of protection, thoughts lean toward defending the body from unwanted external forces. Rarely is thought given to the harmful effects of wearing clothing as a barrier to the liberation of metabolic heat. Therefore, when protection is emphasized, one should consider the external and internal factors that contribute to man's well-being and function. In this light, the more important factor for consideration is the maintenance of body heat equilibrium.

The current status of man's reaction to upper levels of heat stress is summed up by Macpherson (1960) as follows:

> It seems clear that none of the methods available at the present time for predicting the probability of endurance of extremely warm conditions is satisfactory. The only way to determine with confidence how men will react is to expose them to the conditions in question and see what happens.

The purpose of this study was to realistically determine the physiological tolerance of U.S. Navy personnel to severe heat stress while wearing unventilated, impermeable, full-body clothing. The availability of this clothing provided the unique opportunity to study the avenues of heat loss and tolerance to heat stress when evaporative cooling from the skin was completely blocked.

Throughout the course of this dissertation first consideration was given to the physiological significance of heat stress and heat strain in men forced to dissipate excess heat like non-sweating animals. Principal attention was given to the study of deep body and skin temperatures, partitional calorimetry, cardiovascular responses and the upper limit of physiological tolerance under the given conditions. Mental performance was evaluated and was included as an appendix.

HISTORICAL BACKGROUND

Medical sciences have long recognized the serious problems of heat stress. Fiske (1913), Wakefield and Hall (1927), Hall and Wakefield (1927) and Whayne (1951) have described a number of situations where heat impaired man as a functional unit. Wakefield and Hall (1927) made note of the effects of heat described in the Bible. There seems to be little question that the more stressful situations deal with industrial and military operations. Unfortunately, military settings frequently demand more prolonged exposures to wider extremes of wet- and dry-bulb temperatures than the usual civilian occupations.

Further insight into the effects of heat stress may be obtained through the following selected examples cited by Minard and Copman (1963a) and Dasler·(1965):

a) The notorious incident known as the Black Hole of Calcutta occurred in 1756. A recent detailed description of all factors related to the tragedy had been presented by Barber (1966). One hundred forty-six prisoners were forced to occupy the extremely small prison space of Fort William, at eight o'clock the evening of June 20, 1756. This space measured 18 ft long by about 15 ft wide. "Only two holes, barricaded with iron bars, admitted air from the dark, vaulted arcade still red with the reflected glow of the fires outside." By the time captives were released from the Black Hole, 10 hours following confinement, only 22 men and the sole woman were alive.

b) Two hundred years later, in 1956, the tragedy of the Black Hole incident was repeated in Kosti town of the Sudan (Haseeb and Fayiz, 1958). Two hundred eighty-one prisoners were locked overnight in a closed ward, 63 ft long by 18 ft wide by 12.5 ft in height, which was intended for quartering 16 soldiers. The following morning 187 captives were found dead, many with pools of sweat on their depressed abdomens. Eleven of the 94 survivors were in shock; two of the 11 died on the way to the hospital and five of the remaining nine died on the day of admission.

c) In 1918 the ventilation of a fire room aboard the USS Kentucky broke down, resulting in 20 heat casualties among the fireroom watch (Hall and Wakefield, 1927).

d) More recently, during sea trials aboard the USS Des Moines in 1951, outside ventilation was secured to all vital spaces in order to simulate nuclear-bacteriological-chemical warfare operational procedures (Yaglou and Minard, 1952; Minard, 1961). Fifteen minutes after ventilation was secured in a machinery room space, at cruising speed where the thermal load was considerably less than at full or flank speed, three of the watch standers had to be removed because of their poor physical condition. The remainder of the crew became incapacitated and had to be removed within the next five to 15 minutes. A total of seven of the 12 man crew in the space had to be helped up the ladders and treated in the sick bay; and,

e) A U.S. Marine Corps Division conducted an amphibious combat exercise on Mindoro Island, P.I., in the spring of 1962. Approximately 75 heat casualties, including one fatal heat stroke, were encountered by the Division.

> Although the incidence rate of heat casualties in the landing force was by no means inconsequential, the number was small compared to the estimated 300 rifle infantrymen rendered ineffective by the heat on the day the amphibious assault was launched. The effects of heat stress were particularly severe in the units which undertook a forced march of 13 miles to capture the air strip. Observers with the aggressor force state

> that in real combat these units would have been decimated by the well-acclimatized aggressor force which had been on Mindoro for approximately four weeks (Minard and O'Brien, 1964).

This author has personally reviewed more than 560 publications; but, to avoid redundancy attention should be directed toward five comprehensive literature reviews pertinent to factors involved in this study. Reference to other publications will be restricted to the clarification of specific points of concern requiring amplification beyond the review articles.

J. D. Hardy (1961) examined more than 3000 references covering the period from 1885-1959. His final manuscript contained 566 citations, with principal attention to the great surge of literature since 1952. On the subject of heat, the following summary related to this dissertation appears valid:

> The control of internal body temperature is probably directed almost entirely from the central receptors although available evidence indicates that both the central and peripheral drives are required for maximal efforts in meeting the combined effects of high environmental temperature and exercise.
>
> It appears that the physiologic threat of overheating is more serious than overcooling and the effort to protect against overheating of the body tissues is the major function of the physiologic thermoregulator.

Two months following Hardy's 1961 review article, C. von Euler published a review of slightly less than half the length of Hardy's. von Euler's work (1961) dealt with both the physiology and pharmacology of temperature regulation, but covered the literature from 1788 (A. Crawford and J. Hunter) through 1960. von Euler presented ". . . mainly those aspects of thermoregulation which seem to be of significance for the understanding of drug action on the body thermostat." However, neither the reviews of Hardy nor von Euler mentioned the work of Charles Blagden in 1775. According to Blockley and Taylor (1948) Blagden experimented with men exposed to ambient temperatures ranging from 90^{o}F to 260^{o}F. Supposedly Blagden's narrative contained notes on only scattered observations, and one cannot learn precisely the number and duration of exposures. However, Blagden did mention a few specific conditions of exposures to 210^{o}F for three minutes, 211^{o}F for seven minutes, 260^{o}F for eight minutes and 220^{o}F for 12 minutes. In addition, Blockley and Taylor (1948) have indicated that Blagden noted the protective function of clothing, the relief that comes from sweating, the blanket of cooler air which clings to the surface of the body, the heating effect of air movement, and the reduction in tolerable temperature with increased humidity.

E. F. DuBois (1951) believed that very few accurate temperature measurements were made in man in 1740 and that the really important work began about 1850. This latter date coincides with the work of Claude Bernard. Bernard's outstanding _Leçons sur la chaleur animale_, published in 1876, has been cited by numerous authors but none of Bernard's publications have been cited in Hardy's review. According to DuBois, Bernard and others of his time did not appreciate the significance of temperature gradients. This belief is difficult to accept in its entirety since Bernard pointed out the significance of the close arrangement of arteries and veins; therefore, helping to form the basis of what is now termed "countercurrent heat exchange." For the purpose of clarity, the following quotation is offered from Claude Bernard (1876):

> Le point important des études que nous avons faites jusqu'ici, et sur leguel on ne saurait trop s'appesantir, c'est la connaissance de l'antagonisme entre les deux portions du systeme veineux: l'une étant une source d'échauffement, l'authre une source de refroidissement. Cet antagonisme dans l'état normal est constamment réglé par l'harmonisateur de toutes les fonctions, par le système nerveux, l'agent de la conservation de la chaleur animale, du maintien de l'équilibre indispensable au fonctionnement de l'organisme.

There are two other outstanding reviews that are pertinent to this study. Minard and Copman (1963b) evaluated current developments in the determination of body temperature at rest and during work, and discussed opposing opinions relative to the causal mechanisms and consequence of hyperthermia during work. Their experimental evidence, relative to thermal gradients in man at rest and during transient heat storage, indicated that body temperature measured in regions which promptly respond to changing heat loads should be considered a more valid index of heat tolerance than mean body temperature. Two extensions of this review concerning elevation of body temperature in health are found in the work of Copman, Minard and Dasler (1963) and Minard, Copman and Dasler (1964).

The second review that is of importance for this study (Minard and Copman 1963a) cited pertinent reviews dealing with clinical and experimental aspects of fever and induced hyperthermia. A detailed discussion of clinical disorders of thermoregulation was presented emphasizing heat stroke, including the pathogenesis, clinical course, treatment, and pathology. They discussed the molecular basis for thermal injury and concluded that cell death which occurs during uncontrolled hyperthermia, $106^{\circ}F$ or greater, may be described as a time-temperature relationship which may eventually result in irreversible destruction of essential cell proteins.

The rarely cited work of Benedict and Parmenter (1928) indicates that up to about the mid-1920's studies on the physiology of heat emphasized internal body temperature. According to these authors little prior attention had been given to skin temperature. Through a series of experiments, using female test subjects, they observed that metabolism increased "more than five or six hundred per cent" as a result of five minutes of muscular activity. Such a response is not surprising in itself; however, they also observed a distinctly lower skin temperature at the same time. It was rationalized that the lowered skin temperature resulted from the pumping action of clothing, causing an increase in evaporation from the skin. Upon repeating the experiments with a nude test subject they found a similar decrease in skin temperature and an increased metabolism during work. This led Benedict and Parmenter to hypothesize that upon onset of work there may be peripheral vasoconstriction, resulting in a temporary transport of blood from the periphery to the muscles. Burton (1948) disagreed with this hypothesis since sweating and evaporative cooling had not been ruled out, even in the nude state.

The assumption of evaporative cooling which Burton assigned to the response of decreased skin temperature during work has been held by the majority of researchers in the field of temperature regulation until recently. Robinson (1965) presented evidence from man that skin and saphenous vein temperatures decreased during work, which he attributed to heat loss by increased evaporation and convection and decreased peripheral blood flow through possible increase of cutaneous vasoconstriction. Close examination of his data indicates that upon onset of work there are concurrent rises in rectal, femoral vein and gastrocnemius muscle temperatures. In view of recent findings presented by Dasler and Reineke (1965) and Dasler and Minard (1966a, 1966b) further consideration of the work by Benedict and Parmenter and Robinson will be treated in the discussion section of this dissertation. In addition, since there have not been any direct measurements of peripheral and muscle blood flow in man under the given experimental conditions, the literature review by Uvnäs (1960) will lend support to an interpretation of this problem.

To this point, little has been said regarding the balance of heat production and heat loss. The ability of the homeothermic organism to maintain this balance has been recognized since the late 1770's. Crawford (1788) found that the metabolic rate of guinea pig was considerably greater in a cold environment than in a warm one. Greater heat production was obtained by wetting the fur, due to a greater loss of heat by evaporation. Bergmann (1845) demonstrated the importance of regulated heat dissipation to balance changes in heat production.

Adams (1959) described, in first order terms, the interactions between the homeotherm and its environment via avenues of thermal exchange. His treatment of the literature serves as an elementary guide and reference source on this topic. However, to gain a better understanding of the factors involved, the works of Gagge (1936), Winslow, Herrington and Gagge (1936a, 1936b, 1937, 1938), Gagge, Winslow and Herrington (1938), and Winslow, Gagge and Herrington (1940) were carefully studied. In addition, the more recent works of Hertig and Belding (1963) and McDowell _et al._ (1961) were found very valuable. These latter publications provide more workable first order approximation equations for radiation, convection and respiratory heat loss.

A literature review on heat transfer and the influence of man's clothing was published by Mortensen (1957). He emphasized the "critical studies" of heat transfer from nude and clothed men and the mechanism of heat transfer through fabrics. Mortensen's four section publication described detailed physical analysis of heat transfer, specific physiological experimentation, fibers and fabrics, user requirements and protection from special hazards. Mortensen's work is not fitting for the purposes of this dissertation, in that he did not discuss the physical and physiological problems associated with impermeable garments.

Even though government reports are frequently limited in circulation, it was possible to locate eight reports dealing with heat stress in men wearing semipermeable and/or impermeable clothing. The reports of Clanton (1953) and Frankel et al. (1953) dealt primarily with semipermeable clothing. Hall (1952), Craig, Frankel and Blevins (1952) and Garren et al. (1953) were concerned with semipermeable and impermeable garments. Craig (1950a) and Robinson, Marzulli and McFadden (1950) investigated impermeable clothing and the benefits of ventilating the garments. Also Craig (1950b) observed men wearing a polyvinyl alcohol suit without internal ventilation, which is interpreted to mean an impermeable, unventilated garment. Chronogically, the following summary describes the pertinent findings of these military reports:

a) The physiological problem posed by impermeable clothing is the blockade of one of the main avenues of heat loss from the body. Therefore, at ambient temperatures above body temperature the primary avenue of heat loss, namely evaporation from the skin, is of little or no value.

b) Physiological strain was determined by: increases in heart rate, rectal temperature (measured by clinical thermometer before and at the end of each exposure), and rates of sweating (determined from nude weights before and after exposure).

c) Development and subsequent modifications of Craig's formula (1950a) as an index of heat strain; in which terminal heart rate, rise in rectal temperature, and sweat production are combined into a single number; and,

d) An attempt was made to partition heat losses, although radiation, convection and conduction were not separated. Also evaporation was characterized by a proposed conductance term.

Because of the paucity of available information on human responses to thermal stress, when complete coverage with impermeable, unventilated clothing is required, the following study will show that the consequences of wearing such clothing are more complex than previously believed.

Within the limits of the given experimental design, the physical and physiological significance of hyperthermic responses in man were examined. The results will be integrated with those of earlier reports in the discussion section.

MATERIALS AND METHODS

Some of the general materials and methods were described in previous works by Copman, Minard and Dasler (1963), and Minard, Copman and Dasler (1964, 1966). Also, a portion of the procedure was given in recent presentations by Dasler and Reineke (1965) and Dasler and Minard (1966). However, for the purpose of continuity, completeness and clarity, a description of the experimental approach will be given here. Appropriate modifications of the techniques that are specific to this study will be integrated with the previously published information.

Subjects

Navy personnel, assigned duties as laboratory technicians or scientific observers, served as thermal stress test subjects. All of these personnel were volunteers, physically fit, and were familiar with the experimental procedures. No special acclimatizing methods were used, but each subject was usually exposed to heat for 12 or 18 hours each week. No alcoholic beverages were permitted after the evening meal prior to use as a test subject. Diets were not altered in any manner other than restriction to a light breakfast and no excess fluid intake the morning of the test.

No fluid or food was permitted during confinement in the impermeable suit.

Each subject received an abbreviated physical examination upon arrival at the laboratory. Routine hematology studies included: red, white and differential cell counts, and micro-hematocrit. Routine urinalysis included volume, specific gravity, pH, color, appearance, ketone bodies, albumin and microscopic examination. Extreme care was taken that the test subject for the day presented no evidence of recently past or present upper respiratory infection, fatigue, or any other symptoms which might interfere with the experiment or precipitate an incapacitating illness.

Table 1 indicates the age, weight, height and surface area of the test subjects. The code letter assigned to a given subject has been used to identify the man in an experimental condition, as seen in the 10 figures of Appendix I. Surface area was determined from the DuBois body surface chart (DuBois, 1927).

Temperature Measurements

Rectal temperature (t_r) was measured by a copper-constantan thermocouple embedded in polyethylene tubing and sealed in a copper tip that was attached to a number 16 French catheter. The rectal probe was inserted to a depth of 10 cm. beyond the internal sphincter.

TABLE 1

DESCRIPTION OF TEST SUBJECTS

Subject		Age	Wt.	Ht.	Surface Area
Code	Initials	(Yrs.)	(Kg.)	(cm.)	(m^2)
A	ARD	31	87.86	185.5	2.12
B	RJL	22	78.48	177.0	1.97
C	WKM	23	79.10	185.5	2.03
D	RAA	27	74.12	176.0	1.91
E	JAG	33	73.77	170.0	1.85
F	FR	37	87.37	171.5	2.00
G	JDP	22	68.75	174.0	1.81
H	HKJ	23	74.79	180.0	1.94
	Average =	27.25	78.028	177.44	1.954

Tympanic membrane temperature (t_e) was measured with a thermocouple in the form of a loop which was held in place by a polyethylene brush. Fig. 1 shows the construction of a tympanic membrane thermocouple, and Fig. 2 is a photograph of a tympanic membrane thermocouple magnified 5.7 times. This modification of Benzinger and Taylor's (1963) design was found to be well tolerated and no functional differences were observed between their sensor and that manufactured in the Thermal Stress laboratory.

The tympanic membrane thermocouple and external auditory meatus were provided additional thermal insulation by a sponge rubber cup-shaped insert from an ear defender (MSA Noisefoe Mark II), which covered the pinna.

In earlier experiments the tympanic membrane thermocouple loop was adjusted so that it was in direct contact with the tympanum; however, in later experiments the loop was adjusted first to lightly contact the tympanum and then gently withdrawn approximately 1 mm. This latter procedure provided greater comfort for the subject and did not appear to alter the temperature measurement. Cooper, Cranston and Snell (1964) and Cooper (1965) have confirmed this observation.

Esophageal temperature (t_o) was measured with a copper-constantan thermocouple embedded in the top of a polyethylene tube. The thermojunction was inserted orally until it was located 43 cm. from the incisors.

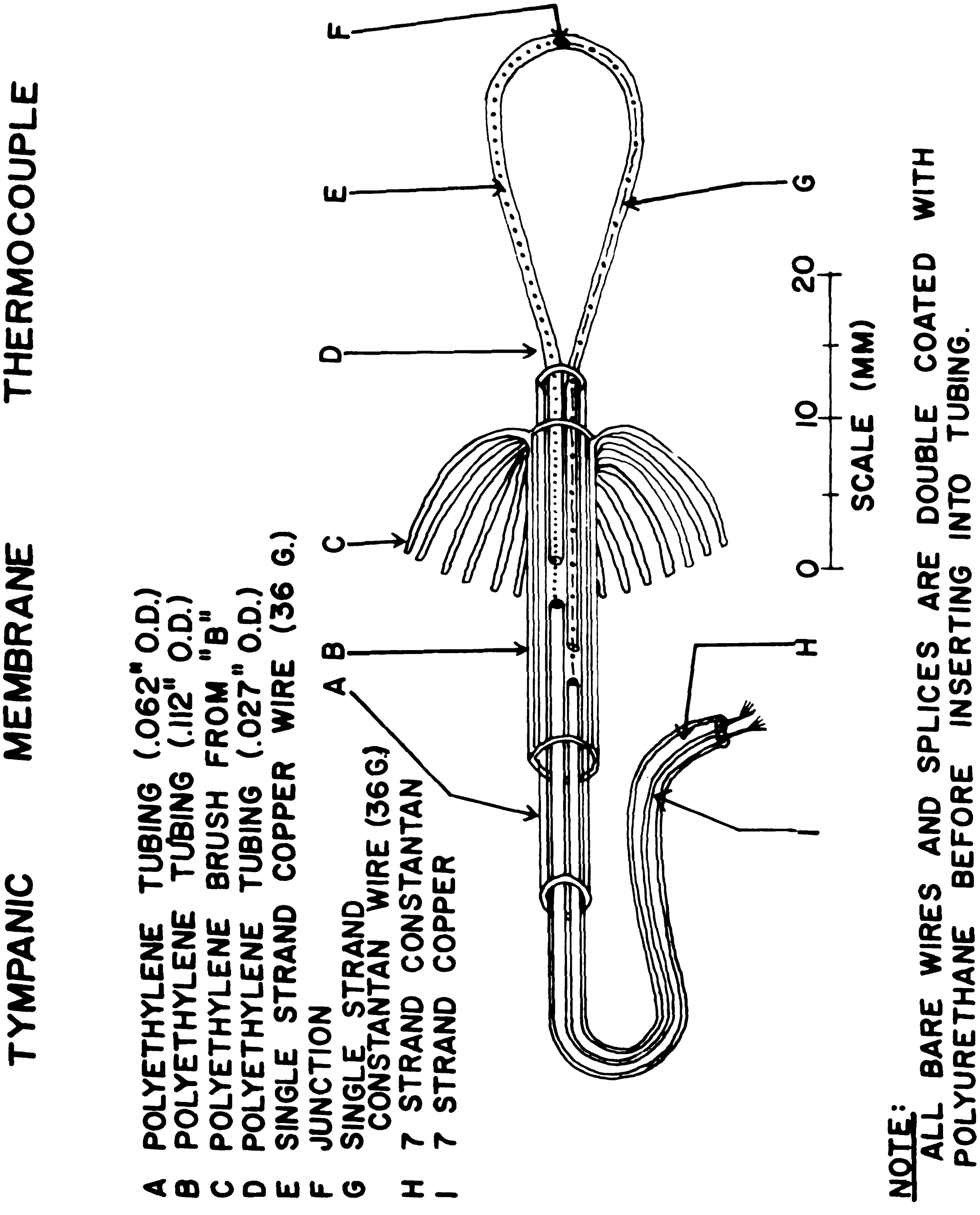

TYMPANIC MEMBRANE THERMOCOUPLE
A POLYETHYLENE TUBING (.062" O.D.)
B POLYETHYLENE TUBING (.112" O.D.)
C POLYETHYLENE BRUSH FROM "B"
D POLYETHYLENE TUBING (.027" O.D.)
E SINGLE STRAND COPPER WIRE (36 G.)
F JUNCTION
G SINGLE STRAND CONSTANTAN WIRE (36G.)
H 7 STRAND CONSTANTAN
I 7 STRAND COPPER
A
B
C
D
E
F
G
H
I
0
10
20
SCALE (MM)
NOTE:
ALL BARE WIRES AND SPLICES ARE DOUBLE COATED WITH POLYURETHANE BEFORE INSERTING INTO TUBING.

Figure 1

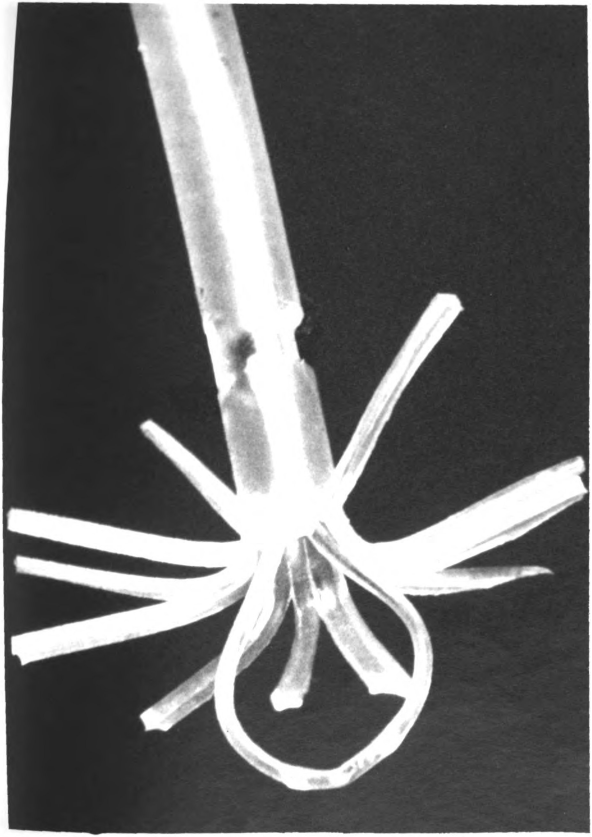


Figure 2. Tympanic membrane thermocouple (enlarged 5.7 times).

In all experiments, skin temperature was measured at 10 points by thermocouple junctions coated with polyurethane and attached to fine mesh copper screen. The screens were held in close contact with the skin using Sanborn ECG straps; however, blood flow was not restricted. Each point was recorded individually, and the mean skin temperature was recorded as the unweighted mean of the 10 junctions. The method of recording the unweighted mean skin temperature followed a modification of the procedure of Teichner (1958). Figure 3 illustrates the positions of the thermocouples employed in these experiments.

The simplified thermocouple wiring scheme, Fig. 4, is an example of how a complete thermocouple loop was related to appropriate components of the temperature measurement and recording equipment. Reference junctions were situated in a stirred water bath accurately regulated at 39.00°C (102.2°F). Bath controls created a temperature cycle of $\pm$ 0.01°C ($\pm$ 0.018°F) which was dampened out by positioning the reference junctions inside a 4-liter Erlenmeyer flask resting at the bottom of the stirred bath.

The thermoelectric emf's from each of the three internal body thermocouples were amplified 100 times by separate Leeds and Northrup stabilized DC microvolt preamplifiers. In turn, the voltage was recorded by a standard 12-channel Leeds and Northrup DC millivolt recording potentiometer, having a 24.2 cm. strip chart with a normal

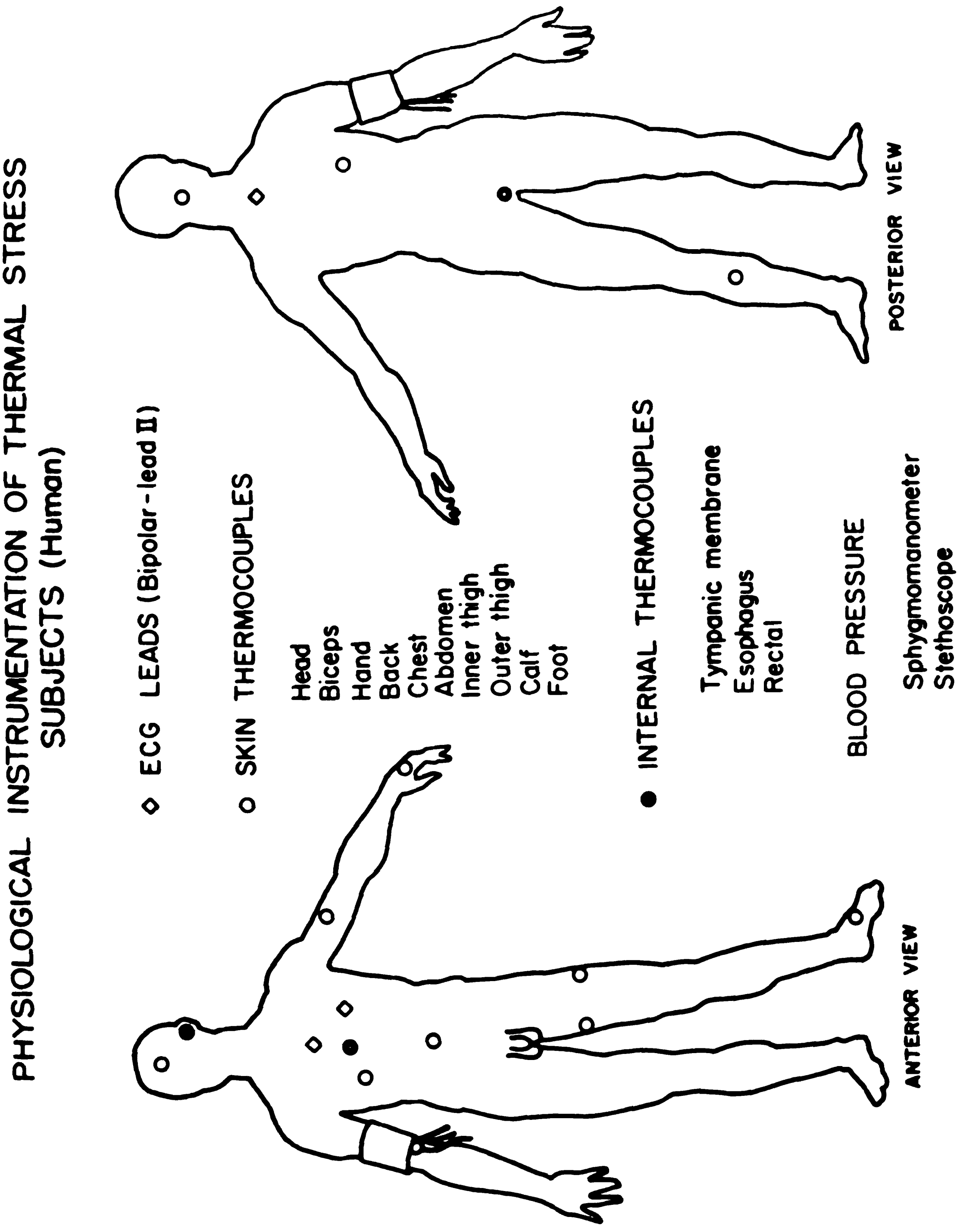

PHYSIOLOGICAL INSTRUMENTATION OF THERMAL STRESS
SUBJECTS (Human)
◇ ECG LEADS (Bipolar - lead II)
○ SKIN THERMOCOUPLES
Head
Biceps
Hand
Back
Chest
Abdomen
Inner thigh
Outer thigh
Calf
Foot
● INTERNAL THERMOCOUPLES
Tympanic membrane
Esophagus
Rectal
BLOOD PRESSURE
Sphygmomanometer
Stethoscope
ANTERIOR VIEW
POSTERIOR VIEW

Figure 3

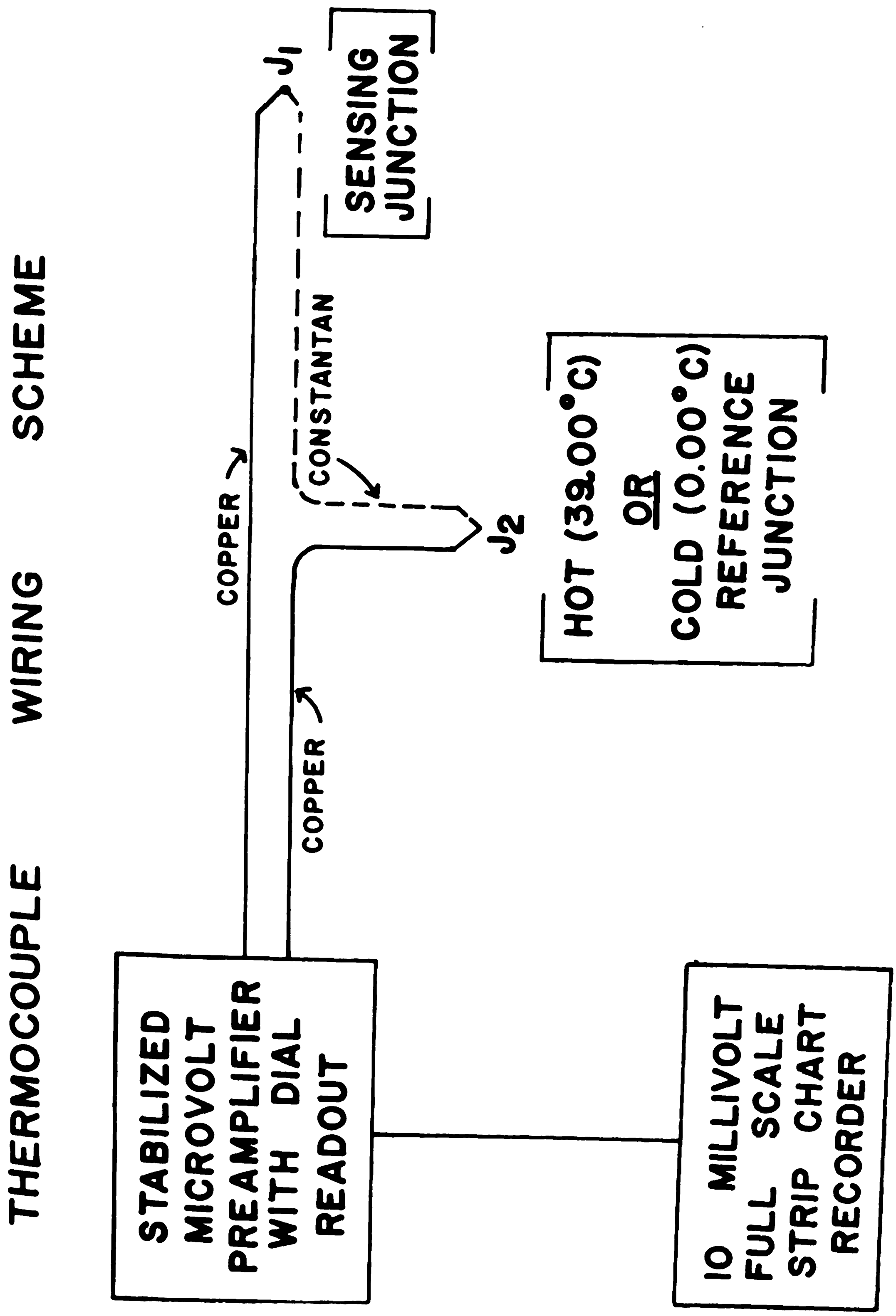

THERMOCOUPLE WIRING SCHEME
SENSING JUNCTION
J1
CONSTANTAN
COPPER
COPPER
J2
HOT (39.00°C)
OR
COLD (0.00°C)
REFERENCE
JUNCTION
STABILIZED MICROVOLT PREAMPLIFIER WITH DIAL READOUT
10 MILLIVOLT FULL SCALE STRIP CHART RECORDER

Figure 4

recording range of 36.60 to 39.00°C (97.9 to 102.2°F). Appropriate adjustments of the preamplifiers lowered the range to 35.40°C (93.9°F), and by flipping a switch in the recording potentiometer the maximum range was extended to 40.20°C (104.7°F). The individual skin temperatures were recorded, after intermediate amplification with a Leeds and Northrup stabilized DC microvolt preamplifier, by a 12-channel Brown (Minneapolis-Honeywell) DC millivolt recording potentiometer. The Brown recorder had a 27.9 cm strip chart recording range of 13.80 to 41.80°C (56.8 to 107.2°F). The emf's of the individual skin thermocouples were also connected in series, passed through a resistance box, and recorded as the mean skin temperature by the Leeds and Northrup recorder.

Heart Rate (HR) and Electrocardiogram (ECG)

Electrocardiograms were obtained by what is called "radioelectrocardiography," as described by Bellet, Deliyiannia and Eliakim (1961) and Bellet *et al*. (1962). The radioelectrocardiograph system used was that of the Telemedics RKG 100A telemetry system and a Sanborn electrocardiograph, with Waters Model C224 or C225 (modified) cardiotachometers for heart rate.

The Telemedics RKG 100A system consists of: a pocket-sized 5.5 ounce mercury battery-operated radio transmitter, with a modulated frequency of 148.65 megacycles, ± 10 kilocycles bandwidth and 2 to 3 milliwatts output; a 17 lb. compact portable receiver, with a 3 ft collapsible antenna, channel selector, skin resistance meter, and one millivolt square wave calibration; specially designed disposable snap top electrodes (Telectrodes); high conductance electrode paste; 48 inch patient cable lead; and, muscle noise filter.

Because the problem of profuse sweating and high salt concentrations within the suit was encountered, it was necessary to depart from the usual procedure in utilizing this telemetry system. Following location of the right and left fifth thoracic interspace, forward of the mid-axillary line, a piece of electrical tape was applied to the preferred electrode site. Tincture of benzoin was applied around the tape, forming a solid circle four inches in diameter. When the tincture of benzoin dried sufficiently the tape was removed and the underlying skin was vigorously abraded with Telectrode jelly. The Telectrodes were applied to the abraded areas and the cable lead from the subject was attached to the electrodes. Then a mole skin patch, nearly covering the benzoin covered area, was applied after leaving a small snake-like portion of cable as a strain relief under the covering.

As skin resistance plays an important role in obtaining uniformly good ECG's, the resistance was checked on the receiver's resistance meter. Only rare situations arose where insufficient abrading had been obtained; those few occurrences required repetition of the electrode application procedure.

With the subject cable lead plugged into the RKG 100A transmitter, the telemetered ECG signal was picked up by the receiver and relayed via the muscle noise filter to a Sanborn electrocardiograph and into a Waters Model C224 Cardiotachometer, or a Model 225 (modified) cardiotachometer that served as a backup unit. The output of the cardiotachometer was fed into the Leeds and Northrup DC microvolt strip chart recording potentiometer. In turn, heart rate was obtained continuously and ECG was taken periodically.

Having prevented short-circuiting of the electrodes under the impermeable clothing, it was also necessary to prevent sweat and its electrolytes from shorting the transmitter-subject cable lead junction. The transmitter and all excess cable were tightly enclosed in a saran-type bag. The waterproofing was highly efficient, even with the transmitter inserted in an inner pocket of the experimental clothing.

Attention is called to Fig. 3. The ECG bipolar lead II was deleted from these experiments when it was proven that the transthoracic lead of the RKG unit provided excellent ECG patterns, without the problems associated with clumsy cables and connectors interfering with the subject and observers responsibilities.

Blood Pressure

Indirect blood pressure measurements were determined by the standard auscultatory method. The brachial artery was located and a bracelet-type stethoscope receiver attached to the skin. Care was taken so that the receiver would not slip from its position while at the same time it would not impede blood flow through the arm. A sphygmomanometer cuff was wrapped around the arm, just above the stethoscope receiver, and attached in a similar manner. It became common practice to attach a strip of adhesive tape from the outer portion of the cuff to the subject's shoulder. The tubes leading from the stethoscope receiver and sphygmomanometer cuff were extended to approximately 18 inches in length so the attachments could be facilitated outside of the suit, at the wrist.

Both systolic and diastolic blood pressure determinations were made pre-exposure, normally at one hour intervals during the experiment, and post-exposure. When it was suspected that heat tolerance was being reached, or a subject noted unusual physical symptoms of distress, blood pressure determinations were taken at 10 and then five minute intervals.

Metabolic Rate (MR)

Metabolic rate was estimated by indirect calorimetry. Samples of the subject's expired air were collected in a Tissot spirometer of 150 liter capacity for timed periods of three or five minutes. The oxygen concentration of the inspired and expired air was determined using a Beckman E-2 oxygen analyzer. Gas volumes were corrected to dry STP using the 21" X 7" chart prepared by Robert C. Darling (Consolazio, Johnson and Pecora, 1963). Caloric production was computed using the Weir formula (Weir, 1949).

Weight Loss

Subjects, wearing only undershorts, were weighed using a Buffalo Model 1100 beam-balance scale, specially constructed for use with human subjects and accurate to ± 5 gm. Two weights were taken for each experiment, before and after.

Bacteriological-Chemical Warfare (BW/CW) Protective Clothing

The BW/CW protective clothing used in this study is divided into four basic subdivisions:

a) A special impregnated, two-piece, vesicant gas protective garment, with impregnated socks. Fig. 5 illustrates the impregnated clothing unit.

   In general, the impregnated clothing is effective against chemical warfare agents of a vapor or fine aerosol nature (Fielding, 1964). Because large aerosol particles or droplets can partially penetrate the fabric, an impermeable outer garment provides additional protection.

Figure 5. Impregnated, permeable, vesicant gas protective garment.

b) The impermeable, unventilated, two-piece outer assembly, which is of high-tear-strength double-coated synthetic fiber fabric having good melt-and-flame resistance and a smooth waterproof outer surface. Fig. 6 illustrates the tight closures at the ankles, wrists, neck and face.

Press (1959) briefly described this experimental impermeable garment when he pointed out the challenges for textile research.

c) Heavy rubber gloves and boots; and,

d) The ND MK V protective mask which is intended to provide complete protection to the face, eyes and respiratory system. A general description of the protective mask has been given by Fielding (1964).

Preliminary investigations in the Thermal Stress Laboratory indicated extreme respiratory resistance with the "standard" filter canisters. Upon our request, the Protective Chemistry Branch, Naval Research Laboratory, developed "low resistance" canisters which were far superior in helping to alleviate discomforts from the clothing and heat. "Low resistance" canisters were utilized in all of the experiments reported herein.

Figure 6. Impermeable, unventilated, protective garment.

All of the above protective clothing components were worn simultaneously by all test subjects in the experiments to form a complete impermeable, unventilated protective assembly.

Experimental Variables

Ten experimental conditions were investigated by use of the preceding methods and an attempt was made to measure decrement of mental performance.

The dry-bulb (DB) and wet-bulb (WB) temperatures of the environmental chamber air were regulated at $\pm$ 0.56 $^{\circ}$C ($\pm$ 1.0 $^{\circ}$F) to obtain the combinations of temperatures, indicated in Table 2. The appropriate DB and WB settings provided the approximate vapor pressures (VP) and relative humidities (RH) that were external to the impermeable clothing.

TABLE 2

ENVIRONMENTAL DB AND WB COMBINATIONS

DB		WB		VP	RH
($^{\circ}$C)	($^{\circ}$F)	($^{\circ}$C)	($^{\circ}$F)	(mm Hg)	(%)
18.3	65	12.2	54	7.5	48
23.9	75	18.3	65	13.0	59
29.4	85	23.9	75	19.5	63
32.2	90	26.6	80	23.5	65

Air velocity over the external surface of the suit was varied under certain conditions by use of a wind tunnel. A special wind tunnel, measuring 20 ft long by 5 ft wide and 7 ft 6 inches high, was constructed of stainless steel angle irons and covered with expanded stainless steel with a tight outer layer of clear, heavy, gauge polyethylene sheeting. The front end of the wind tunnel was completely open while the back end was enclosed by a partition that housed six, high velocity, waterproofed, exhaust fans. The maximum air velocity created in this tunnel was approximately 6.6 m/sec (1,300 ft/min or 12.8 knots). By operating selected fans, and appropriate adjustments of the exhaust ports, the relatively constant velocities shown in Table 3 were employed. Winslow Herrington and Gagge (1936b) showed the natural air velocity over man due to a "chimney effect," to be approximately 0.24 m/sec (47 ft/min or 0.46 knots) in a still room.

TABLE 3

AIR VELOCITY IN WIND TUNNEL

m/sec	ft/min	knots
<0.25	<50	<0.49
1.27	250	2.47
5.08	1000	9.87

Physical activity was classified as either rest in a standing position or work while climbing up and down two steps which were 6" high and 14" deep. The resting while standing state corresponded to that of Belding and Hatch's (1955) "light work" activity. The work activity of the test subjects was equivalent to Belding and Hatch's "moderate work" activity. Furthermore, the work rate of the suit subjects was such that they stepped up the two 6" steps and then stepped back down in time to a metronome, at a rate of 10 round trips (80 single steps) per minute. Work periods of 10 minutes duration were cycled with 10 minute rest periods, and this pattern of work-rest continued throughout the designated experiments until heat tolerance was reached or four hours had elapsed.

The interrelationship of ambient air temperatures, air velocity and physical activity for the 10 experimental conditions is given in Table 7 (refer to "Results and Discussion" section).

Partitional Calorimetry

It is well recognized that body temperature remains constant only when the body is in thermal equilibrium. When such a state exists, heat loss equals heat gain. This phenomenon is expressed by the general heat balance equation:

$$M \pm R \pm C - E = \Delta S \quad (1)$$

where; M = metabolic heat gain

R = radiative heat gain (+) or loss (-)

C = convective heat gain (+) or loss (-)

E = evaporative heat loss (-); and,

ΔS = change in heat storage, (+) if a gain and (-) if a loss.

Utilizing this general expression, first order partitional calorimetry was undertaken. Metabolism was determined and evaporative cooling from the skin was demonstrated from a limited number of observations to be essentially zero. Therefore, the approximation equations of Hertig and Belding (1963) were employed for radiation and convection, and evaporative heat loss from the respiratory tract was determined from the approximation equation of McDowell _et al._ (1961):

a) Radiant heat loss--

$$R = 6.27\ (\text{m.r.t.} - 95) \qquad (2)$$

where; R = radiation calculated for nude man (KCal/hr)

m.r.t. = mean radiant temperature ($^{\circ}F$)

95 = assumed skin temperature ($^{\circ}F$)

Radiation calculated from this equation was reduced 30 per cent due to the influence of the clothing, as suggested by Dr. B. A. Hertig in a personal discussion regarding this type of garment. Mean radiant temperature (m.r.t.) was taken as equivalent to the

DB temperature since the DB was approximately the same as the globe temperature. Also, the mean skin temperature measured in the experiments were substituted for an assumed skin temperature of 95°F.

b) Convective heat loss--

$$C = 0.27\ V^{0.6}\ (t_a - 95) \qquad (3)$$

where; C = convection calculated for nude man (KCal/hr)

V = air velocity (fpm)

t_a = DB temperature (°F)

95 = assumed skin temperature (°F)

Calculated convection was reduced 30 per cent due to the influence of clothing, in accordance with Dr. Hertig's suggestion, and the measured skin temperature were substituted for an assumed value of 95°F.

c) Respiratory heat loss--

$$E_v = K\left[V\ (VP_v - VP_a)\right]\ X \text{ Heat of vap. } H_2O \qquad (4)$$

where; E_v = respiratory (ventilatory) evaporation (KCal/hr)

K = 0.000941, which is the coefficient for 1 gm of water vapor in 1 liter of air per mm mercury water vapor pressure

V = ventilatory volume (liters/hr)

VP_v = vapor pressure of expired air at saturation vapor pressure of respiratory temperature (mm Hg)

VP_a = vapor pressure of water was determined at expired air temperature by interpolation from the Handbook of Chemistry and Physics, 39th edition, 1957 (KCal/gm)

Therefore, the left-hand side of the general heat balance equation (1) was determined by utilizing M, that was determined earlier, and using first order approximations for R, C and E_v. In turn, the approximation of heat storage was found by calculating the algebraic sum of the left side of the equation to yield the right-hand side. All final answers were related to surface area.

Cardiac Output

Under the conditions of these experiments it was not feasible to perform venipunctures while the subject was in the suit assembly. Therefore, stroke volume was calculated by a modification of the method described by Starr et al. (1954) and Starr (1954). The last equation given by Jackson (1955) was applied to the two experiments where heat tolerance was cautiously exceeded.

Therefore, cardiac stroke volume was calculated from the following equation:

$$SV = 101 + (0.50\ SP) - (1.09\ DP) - (0.61\ Age) \qquad (5)$$

where; SV = stroke volume (ml)

SP = systolic blood pressure (mm Hg)

DP = diastolic blood pressure (mm Hg); and,

Age = given to the nearest birthday.

All stroke volume values obtained by use of equation (5) were rounded off to the nearest ml.

Cardiac output was merely the product of the below equation:

$$CO = SV \times HR \qquad (6)$$

where; CO = cardiac output (ml/min)

SV = stroke volume (ml)

HR = heart rate (beats/min)

In turn, all cardiac output values were expressed as liters/ min.

Physical Analysis of Heat Flow

The internal thermal gradient between deep body and skin temperatures, and the external thermal gradient between the skin and ambient air temperatures, was used by Burton (1934) to describe heat flow patterns resultant of peripheral blood flow. Burton described the ratio of the internal gradient to the external gradient as a "Thermal Circulation Index (TCI)." The TCI was determined for the least and most responsive skin temperature sites, in accordance with the following equation:

$$TCI = (t_s - t_a)/(t_r - t_s) = \text{External drop/Internal drop} \quad (7)$$

where; t_s = skin temperature (^{o}C)

t_a = air temperature (^{o}C)

t_r = rectal temperature (^{o}C)

In turn, this allows for the consideration of tissue conductance, which is inversely related to tissue insulation.

Statistics

A two-way analysis of variance was performed on skin temperature data from the severe experimental condition of DB 75°F, WB 65°F, work-rest activity and air velocity <50 fpm. In addition, the New Multiple Range Test was applied to the 10 individual skin temperature sites. The basic statistical methods are described by Li (1964).

The most appropriate and efficient statistical design was selected to strengthen the overall analysis. All statistical attempts were made to disprove the possibility that there were differences between the observed temperature patterns. Therefore, the primary analytical method was a two-way analysis of variance with replication and equal sample sizes, with single degrees of freedom and orthogonal distribution, and the significance level was selected as .001. For the New Multiple Range Test the significance level was set at .01, which was the most rigorous test that could be imposed by available statistical tables.

Mental Performance

Dunlap and Associates, Inc., of Darien, Connecticut, conducted a sub-contract study on the accuracy of meter reading under thermal stress induced by wearing the impermeable protective suit. Their assistance was required to determine if members of a decontamination team would be able to take accurate measurements of the levels of contamination of the environment up until the time they found the suit intolerable. The mental performance evaluation had to be restricted such that in no way would the meter reading task interfere with the prime objective of the physiological experiment.

Essentially the mental performance task required a subject to read a meter that had 20 possible settings, ranging from 0.0 to 3.8, which cycled a program of 50 random observations before repeating the cycle. The subject had to locate the correctly numbered button corresponding to the observed meter reading. The correct button had to be depressed prior to a new meter setting for the response to be considered as correct. The total time allowed for this entire operation was two seconds. However, the subject had to continue this procedure for 10 minutes out of every 20 minute period of the physiological experiment.

A general description of the stimulus presentation device, meter and accuracy recording instrumentation, is given in Appendix II with the permission of Mr. M. Eicher, Head of the Medical Instrumentation Laboratory, Naval Medical Research Institute. The final report by Dr. R. D. Pepler, of Dunlap and Associates, Inc., was filed with the author. A copy of Dr. Pepler's conclusions, presented here with his permission, will be found in Appendix III.

RESULTS AND DISCUSSION

The research conducted can be logically broken down into three major areas that will be presented in the following order:

a) Presentation of evidence that heat tolerance was reached and a margin of safety was utilized in all other experiments.

b) The internal body and skin temperature under various conditions, and the significance of these responses; and,

c) The use of partitional calorimetry to determine practical and economical approaches to the reduction of heat strain in man.

Exceeding Heat Tolerance

Throughout the course of the main experiments an attempt was made to allow the subjects to approach their "safe" tolerance limit, but, not to exceed this limit. However, to prove this point was reached it was necessary to determine the consequences of exceeding the "safe" limit.

Fig. 7 shows the blood pressure, heart rate and estimated cardiac output response in a subject at DB 90^{O}F, WB 80^{O}F, standing (no exercise) and an air velocity of 250 fpm. As will be shown later, the average tolerance time under these conditions was 2.29 hours. However, the tolerance of this subject was reached at about 3.19 hours, and the subject volunteered to continue until unquestionably serious responses were obvious. The experiment was allowed to continue for an additional 15 minutes, and it required two more minutes to get the subject completely out of the protective assembly.

The descending pattern of diastolic blood pressure and concurrent rise in heart rate and estimated cardiac output were the dominant objective features of concern. But, the subjective observations were more alarming. The numerals I through VI, in Fig. 7, indicate the approximate times when the subject readily verbalized his feelings:

I "Increased respiratory rate."

II "Feel hot all over."

III "Burning sensation in lower stomach region."

IV "Air hunger, no sense of feeling in distal portions of arms and legs."

V "Euphoria."

VI "Severe frontal headache, almost total loss of sensation in arms and legs."

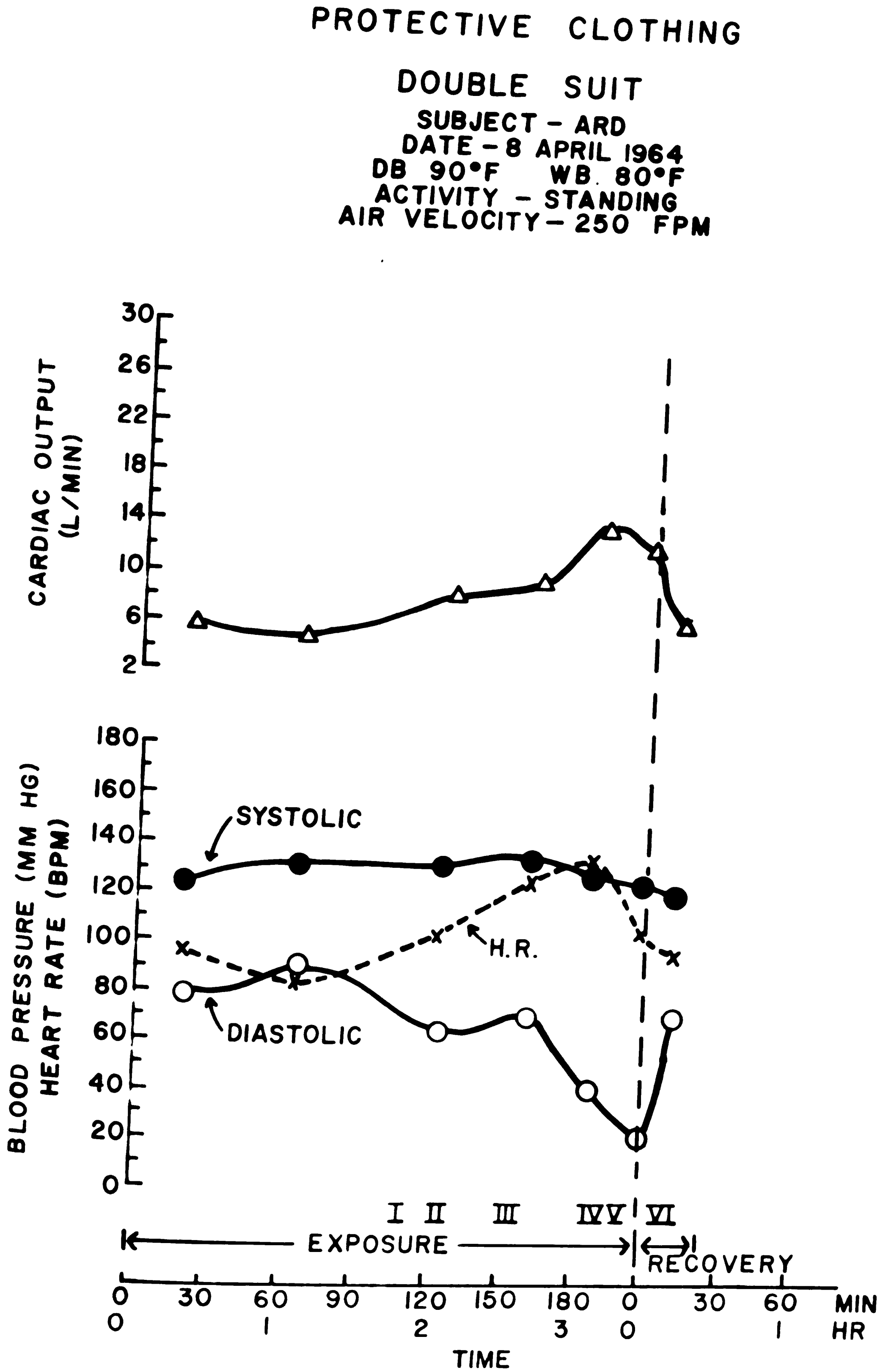


Figure 7. Blood pressure, heart rate, and cardiac output when tolerance was exceeded.

Fig. 8 shows the same determined responses in a different test subject, who also volunteered to exceed "safe" tolerance. The DB and WB temperatures were 5^{O}F lower and the air velocity was four times greater in this experiment; but, the physical activity was moderate in contrast to the light activity in Fig. 7. One other subject in this less severe environment and with greater physical exertion had a tolerance time of 2.00 hours. Subject RAA reached "safe" tolerance 2.50 hours and continued for an additional 40 minutes before the suit assembly was removed.

Diastolic blood pressure fell abruptly and was not even discernable by a muffling of sound at zero pressure with the sphygmomanometer. Systolic blood pressure remained elevated until the last 12 minutes of the experiment, at which time it fell from 138 to 92 mm Hg. The heart rate increase was consistent with other experiments, except for the reduction just prior to a detectable fall in systolic pressure.

Almost identical subjective observations were noted in this second excess of tolerance experiment (see Fig. 8):

II "Feel hot all over."

III "Burning sensation in lower stomach region."

V "Euphoria."

VI "Severe frontal headache, almost total loss of sensation in arms and legs."

CARDIAC OUTPUT

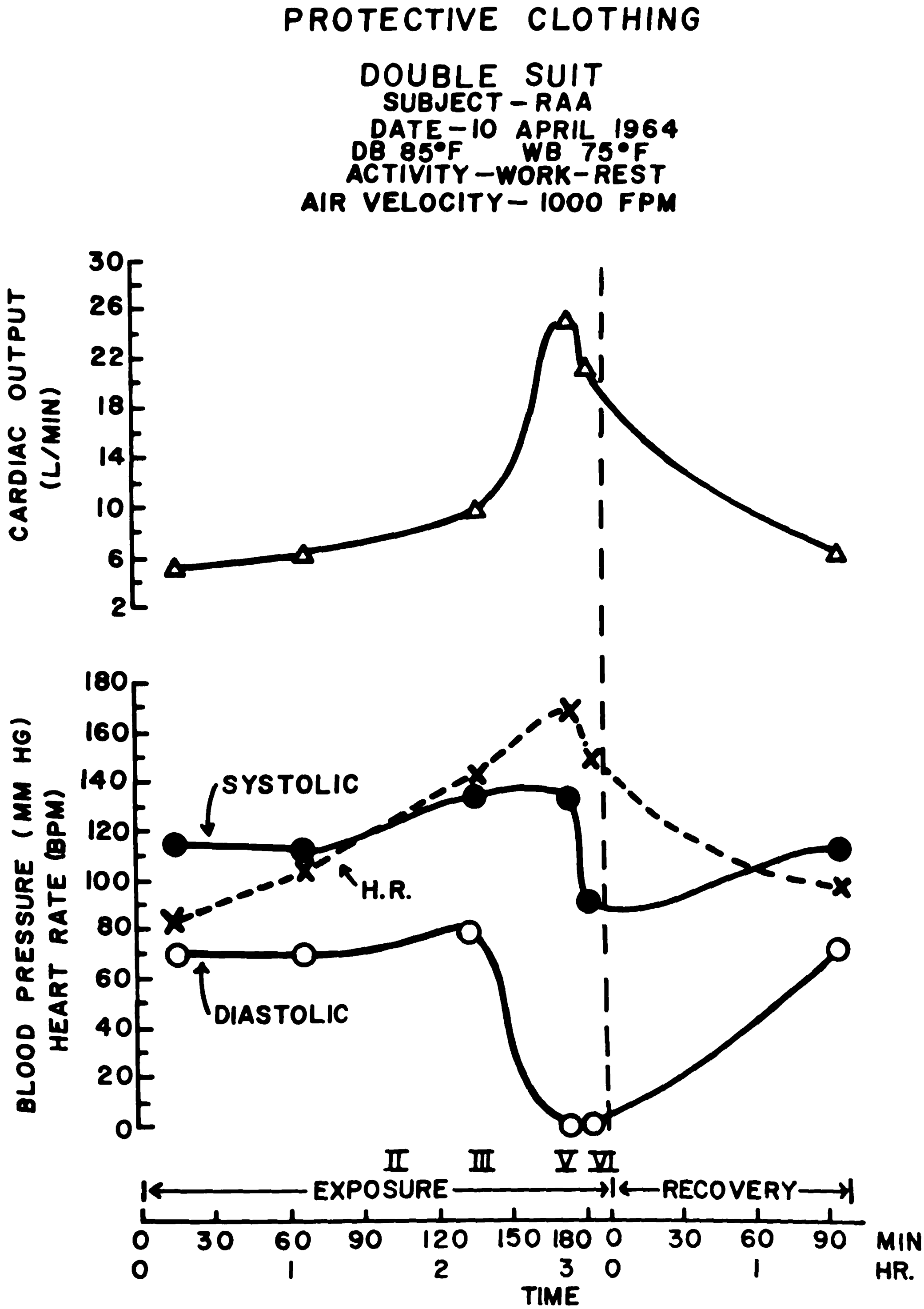


Figure 8. Blood pressure, heart rate, and cardiac output when tolerance was exceeded.

In combining the objective and subjective observations, there are two physiological systems which dominate the noted responses. First, the respiratory system was involved in an increased respiratory rate and sense of air hunger. Secondly, the cardiovascular system involvement was reflected in the blood pressure, heart rate and estimated cardiac output responses.

Bazett (1927) concluded that hyperthermia caused hyperventilation. Cotes (1955) indicated that exercise produces an increase in body temperature, and that an increase in body temperature is a marked respiratory stimulus. Furthermore, Benjamin and Peyser (1964) support the concept that a temperature factor is involved in the hyperventilation of exercise.

Whether a true hyperventilation occurred in these experiments is questionable. For the conditions of Fig. 7 subject ARD, the ventilatory rate at rest was 14.1 liters/minute and 29.2 liters/minute at work. But, for the conditions of Fig. 8, subject RAA, the ventilatory rates at control, mid-test and recovery were 9.9, 11.6 and 7.6 liters/minute respectively.

If one assumes that the data indicate a greater respiratory demand for subject ARD than that for subject RAA, this would account for the absence of subjective comments on respiratory involvement by subject RAA and the presence of comments from subject ARD. Regardless, there is insufficient evidence from these two tests to provide a definitive answer whether exercise or the heat produced a greater stimulus to respiration. From the limited data that can be provided, there is a likelihood that Bazett's conclusion is somewhat supported here. However, the so-called air hunger might better be explained on the basis of the type of respiratory apparatus used. It is possible that the "low resistance" canisters for the MK V mask were not sufficiently low to avoid a severe respiratory load under the thermal conditions.

It has been shown by Daily and Harrison's (1948) review of literature and experimental studies that the most serious complication is circulatory collapse. The blood pressure and cardiac output responses, with acute and increasing pyrexia in dogs, were similar to those observed and estimated in these experiments. They pointed out that the mechanism of vascular collapse has not been established; however, the available data suggested several mechanisms:

a) Shock due to extravasation of plasma, with a reduction of circulating blood volume. They cite the work of Kopp and Solomon as indicating patients in therapeutic hyperpyrexia were all found to have a reduction of blood volume of 10 to 32 per cent.

b) Shock that may be related to chemical changes in the blood. Blood pH fell markedly and a marked accumulation of lactic acid was noted in the blood. In early stages of hyperpyrexia in dogs they claim it is reasonable to expect an alkalosis due to hyperventilation and acapnia. However, they believe that latter stages might be overbalanced by the accumulation of fixed acids (e.g., lactic) to produce acidosis.

c) The vascular collapse may be due to heart failure; and,

d) Shock may be due to a generalized dilation and atony of arterioles and capillaries. This would be representative of the familiar mechanism of peripheral circulatory failure.

The experimental data from this study do not indicate that a state of hyperpyrexia existed. The internal body temperatures did not exceed 103.5°F in any experiment. Also, by gross examination there were no changes in venous micro-hematocrits which were not within experimental error of 1.5 per cent. There was no information relative to the blood pH or lactic acid levels. Furthermore, the ECG records of the two subjects did not show any changes in wave forms other than a marked increase in rate only. Therefore, the feasible explanation may be related to a generalized peripheral dilatation and splanchnic vasoconstriction.

Bazett (1924) presented reasons for believing that in acute exposures to excessive heat a cutaneous vasodilatation must be compensated by a splanchnic vasoconstriction. There has been some evidence in support of Bazett's belief. Daily and Harrison (1948) cite their own results, whereas Korozenidis, Shepherd and Marshall (1961) refer to the evidence from three sources plus themselves.

The works of these various authors indicate that there is a likelihood of splanchnic vasodilatation prior to circulatory collapse. This seems to support the subjective remarks that there was a "burning sensation in the lower stomach region" just prior to the marked depression of diastolic blood pressure. After the experiments, both subjects described the circumstances as "like hot charcoals were dumped into my stomach, and that the extreme discomfort lasted only a few minutes." In this light, the rationalization of Daily and Harrison may be correct. They assumed that this later splanchnic dilatation was the result of either thermal injury to regulatory centers in the brain or the accumulation of metabolites in the abdominal viscera. As in the case of their dog experiments, "once the state of visceral vasodilatation supervened the blood pressure declined sharply, cutaneous flow diminished, and death soon followed."

The loss of sensation in the limbs, progressing from the finger tips to the shoulders and toes to upper thighs, appears to be associated with the circulatory responses when tolerance is exceeded. No literature has been found to support this observation, but the sequence of events seem to indicate circulatory involvement.

The determination of cardiac output by the method described by Starr et al. (1954), Starr (1954) and Jackson (1955) has been employed soley as an indication of trends. No significance is laid upon the possibilities of absolute values. Kissen and Hall (1963) indicate that their data, with Starr's method, indicated a statistically significant correlation with the dye-dilution technique, but, the indirect blood pressure method values were almost always lower. The unpublished findings of Dr. Paul Webb's heat stress experiments indicate that the Starr approach yielded consistently lower values than those he obtained with radioiodinated serum albumen (RISA). Therefore the cardiac output values in Figs. 7 and 8 may be an underestimation of true outputs.

Dye-dilution and direct Fick principle methods for cardiac output show increases from 30 to 400 per cent during a variety of heat stress experiments (Grollman, 1930; Asmussen, 1940; Burch and Hayman, 1957; Koroxenidis, Shepherd and Marshall, 1961; Burch and DePasquale, 1962). Koroxenidis, Shepherd and Marshall (1961) were unable to provide a ready explanation for the differences in the diversity of results.

Kissen and Hall (1963), using the Starr method, have shown a 75 per cent increase in cardiac output during less severe heat stress conditions than in this study. Fig. 7 shows a 240 per cent increase prior to circulatory failure, and Fig. 8 shows a 433 per cent increase. Therefore, the data from this study are in agreement with findings of Asmussen (1940). He noted that circulatory failure during work develops rather fast in humid heat owing to the fact that the heat dissipation is made difficult. A larger amount of blood is demanded for the skin circulation, making maintenance of an adequate cardiac output increasingly difficult.

The effects of a hot and humid environment on the circulatory system must include a marked increase of cardiac output, primarily due to increased heart rate; peripheral resistance decreased greatly; peripheral venous pressure increased; and, right arterial pressure increased slightly (Burch and DePasquale, 1962). Therefore with considerable shifts in circulation a degree of instability must ensue. The more severe the heat stress, the greater instability and more pronounced disability, especially when a test subject is standing upright (Machle and Hatch, 1947).

Fortunately, the two experiments, where a "safe" tolerance limit was exceeded, were reversible. The results of these situations confirm the belief that all other experiments in this study were within a "safe" limit, which was frequently greater than that described by Veghte and Webb (1957).

A brief descriptive comment from the data log is; "This one is a bitch!" (RAA, 4-10-64).

In view of the results obtained in these experiments, together with observations in the many subjects run under less stressful conditions, it is concluded that under the specified conditions the upper limit of "safe" tolerance can be defined as body temperature not exceeding 39^{o}C (102.2^{o}F), heart rate not exceeding 180 beats per minute, and blood pressure not less than 90/40 mm Hg.

Internal Body and Skin Temperatures

Data published by Copman, Minard and Dasler (1963) and Minard, Copman and Dasler (1964) have clearly demonstrated the cyclic patterns of esophageal (t_o) and tympanic membrane (t_e) temperatures in their preliminary study with impermeable clothing. The rectal temperature (t_r) was non-cyclic in these transient heat load conditions. Fig. 9 illustrates the cyclic t_o, t_e and mean skin (t_s) temperatures, and essentially non-cyclic t_r observed in all work-rest experiments of the current study. Fig. 9 is a photographic reduction of a large direct tracing of an original record. Mean t_s was converted from its unamplified presentation of the record to correspond with the same temperature scale as that used for internal temperature sites. Heart

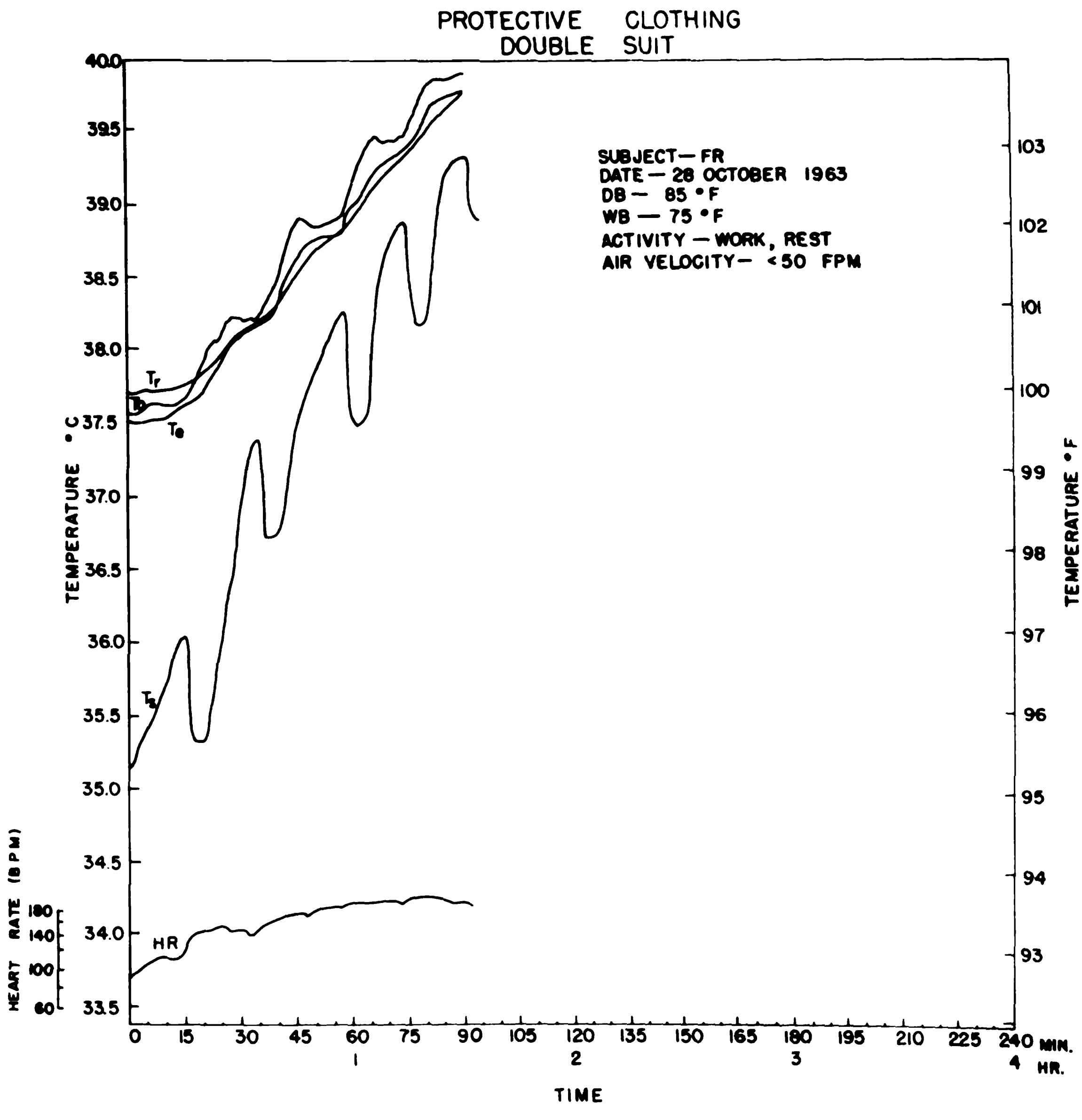


Figure 9. T_r = rectal temperature; T_o = esophageal temperature; T_e = tympanic membrane temperature; T_s = mean skin temperature; HR = heart rate.

rate (HR) was taken as a direct tracing and the appropriate scale indicated.

The cyclic appearance of the internal temperature is due to the alteration of work and rest. Greater amplitudes of the cycles are seen in the esophagus. The cycles in t_e are lower in amplitude and the onset of rise lags behind t_o. The cyclic pattern is hardly apparent in t_r and its lag between onset of work and initial rise is the longest of the three internal temperatures.

From studies in which the entire resting heat production was stored in the body, it has been suggested that the lesser responsiveness of t_r depends in part upon a diversion of blood away from the abdominal viscera during severe heat stress, and in part upon the heat capacity of the relatively avascular pelvic structure itself (Minard and Copman, 1963b; Copman, Minard and Dasler, 1963; Minard, Copman and Dasler, 1964). Blood flow is maximal, on the other hand, through tissues which are the major site of heat production and through the skin, subcutaneous tissue and muscle. Therefore, t_o and t_e appear to measure the temperatures of highly perfused tissues, which accounts for a greater responsiveness of t_o and t_e, and least response from t_r. Furthermore, the fact that t_o rises faster than t_e, in cases of maximum heat storage as well as with the impermeable suit, is believed to be due to the closer proximity of t_o to the heart and great vessels.

The mean t_s also shows a marked cyclic pattern; however, during work t_s fell abruptly and at rest t_s increased markedly. From Fig. 9 it can be seen that the magnitude of decrease and increase of mean t_s is considerable. Examination of all of the temperature records from this study, and a number of others from various experiments in the Thermal Stress Laboratory, clearly show that this response is restricted to the work-rest activities. The cyclic patterns are of varying degrees, dependent upon the severity of environmental conditions; the greater the heat stress and work the greater the amplitude.

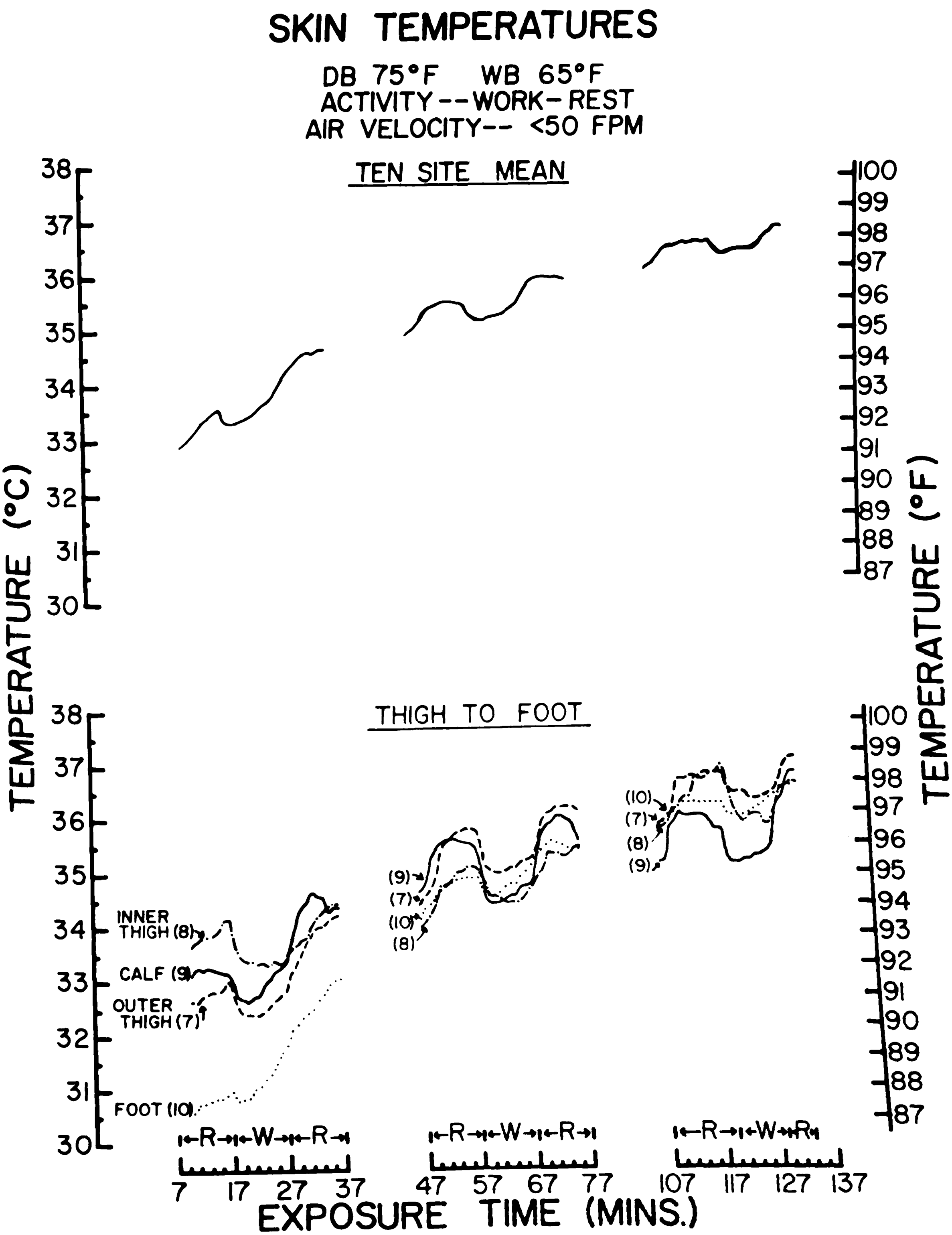
Less than 26 seconds after the onset of work the mean t_s had decreased in an obvious manner. The mean t_s began to rise as the exercise continued, and increased markedly upon onset of rest. This pattern was inverse to that of the internal body temperatures. When rest commenced there was a partial reversal of the skin and internal body temperatures. This reversal was not complete; both skin and internal sites continued to climb in a stepwise fashion although out of phase with each other.

A detailed examination of the individual skin temperatures was undertaken to determine possible reasons for this inverse relationship. Recordings from the 10 individual skin sites, taken during application of a moderately severe environment condition, were grouped so as to provide data on temperature changes of different anatomical regions.

Temperatures at one minute intervals were plotted as shown in Figs. 10 and 11.

It is apparent that the anatomical region from thigh to foot contributes a major portion of the decrease in mean t_s upon onset of work and rest. But, the lumbar region of the back is also a major site of considerable temperature change. The lesser reduction of skin temperatures of the biceps and hand may well be related to the subject's use of his arms as a guide on railings while climbing up and down the exercise steps.

Complete records were available from five other test subjects submitted to this moderately severe condition. The data from all six records were pooled for statistical analysis. Table 4 indicates the mean and standard error for each of the 10 skin sites during the mid-points of work and rest periods early, middle and late in the experiments. In turn, the most powerful two-way analysis of variance was applied to detect similarities and/or differences between all possible combinations of time and activity periods as well as the 10 individual skin sites throughout the experimental condition. Table 5 summarizes the results of the analysis of variance. In addition, the New Multiple Range Test was applied to the pooled data, the results of which are diagrammed in Figs. 12, 13 and 14.



SKIN TEMPERATURES
DB 75°F WB 65°F
ACTIVITY--WORK-REST
AIR VELOCITY-- <50 FPM
TEN SITE MEAN
THIGH TO FOOT
INNER THIGH (8)
CALF (9)
OUTER THIGH (7)
FOOT (10)
(9)
(7)
(10)
(8)
R
W
R
TEMPERATURE (°C)
TEMPERATURE (°F)
38
37
36
35
34
33
32
31
30
100
99
98
97
96
95
94
93
92
91
90
89
88
87
7
17
27
37
47
57
67
77
107
117
127
137
EXPOSURE TIME (MINS.)

Figure 10

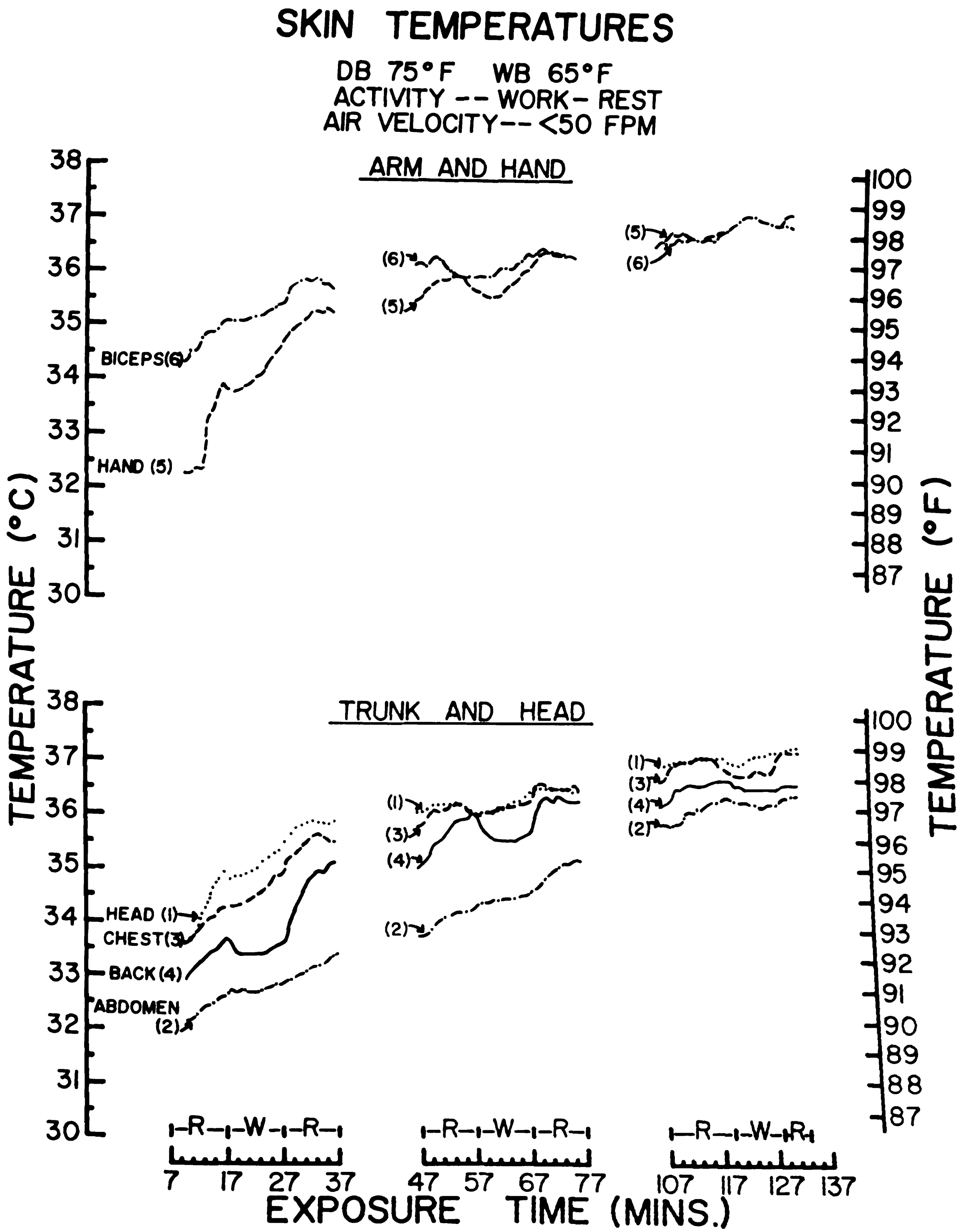

SKIN TEMPERATURES
DB 75°F WB 65°F
ACTIVITY -- WORK- REST
AIR VELOCITY-- <50 FPM
ARM AND HAND
BICEPS(6)
HAND (5)
(6)
(5)
TRUNK AND HEAD
HEAD (1)
CHEST(3)
BACK (4)
ABDOMEN (2)
(1)
(3)
(4)
(2)
TEMPERATURE (°C)
TEMPERATURE (°F)
R W R
7 17 27 37 47 57 67 77 107 117 127 137
EXPOSURE TIME (MINS.)

Figure 11

TABLE 4

CYCLING OF TEN INDIVIDUAL SKIN TEMPERATURES DURING WORK AND REST PERIODS (^{o}C)

(Means ± Standard Errors For 6 Subjects)

Anatomical Site		Phase of Experiment and Physical Activity					
		Early		Middle		Late	
No.	Position	Work	Rest	Work	Rest	Work	Rest
1	Head (Ext. occipital protuberance)	34.51 ± 0.45	35.59 ± 0.40	36.09 ± 0.46	36.72 ± 0.43	37.09 ± 0.35	37.79 ± 0.31
2	Abdomen (Linea alba)	33.43 ± 0.61	34.13 ± 0.65	35.35 ± 0.61	36.13 ± 0.10	36.70 ± 0.28	37.30 ± 0.36
3	Chest (M. pectoralis major)	34.05 ± 0.34	35.14 ± 0.32	36.08 ± 0.33	36.77 ± 0.28	37.20 ± 0.27	37.54 ± 0.25
4	Back (M. latissimus dorsi)	33.67 ± 0.13	34.66 ± 0.36	35.81 ± 0.38	36.77 ± 0.34	36.85 ± 0.41	37.56 ± 0.43
5	Hand (dorsal surface)	33.47 ± 0.27	34.52 ± 0.41	35.55 ± 0.39	36.51 ± 0.41	36.64 ± 0.51	36.86 ± 0.37
6	Biceps (M. biceps brachii)	33.70 ± 0.49	34.47 ± 0.50	35.73 ± 0.29	36.63 ± 0.32	37.00 ± 0.38	37.19 ± 0.31
7	Outer Thigh (M. vastus lateralis)	33.10 ± 0.37	34.48 ± 0.56	35.38 ± 0.26	36.32 ± 0.15	36.49 ± 0.13	36.84 ± 0.18
8	Inner Thigh (M. gracilis)	32.72 ± 0.51	33.51 ± 0.63	34.87 ± 0.48	35.84 ± 0.48	36.12 ± 0.28	36.78 ± 0.29
9	Calf (M. gastrocnemius)	32.64 ± 0.35	33.88 ± 0.42	34.03 ± 0.40	35.60 ± 0.28	35.32 ± 0.29	36.27 ± 0.31
10	Foot (dorsal surface)	31.81 ± 0.40	32.98 ± 0.29	35.19 ± 0.46	36.08 ± 0.40	35.96 ± 0.25	37.03 ± 0.38

TABLE 5

TWO-WAY ANALYSIS OF VARIANCE WITH REPLICATION AND EQUAL SAMPLE SIZES

(WITH SINGLE DEGREES OF FREEDOM AND ORTHOGONAL DISTRIBUTION)

Source	df	Mean SS	F
Work-Rest Activity (Early, Middle, Late)	5	126.46	137.01***
$W_{E,M,L}$ vs. $R_{E,M,L}$	1	64.38	69.75***
W_E vs. $\overline{W_M W_L}$	1	283.52	306.88***
W_M vs. W_L	1	38.24	41.43***
R_E vs. $\overline{R_M R_L}$	1	228.01	247.03***
R_M vs. R_L	1	18.17	19.69**
Ten Skin Sites (Early, Middle, Late)	9	11.04	11.96**
Interaction	45	0.52	0.57*
Error	300	0.92	

* = No significant interaction at the .001 level
** = Very significant at the .001 level
*** = Highly significant at the .001 level
W = Work period
R = Rest period
E = Early in tests (Second work period and third rest period)
M = Middle in tests (Fourth work period and fifth rest period)
L = Late in tests (Seventh work period and eighth rest period)

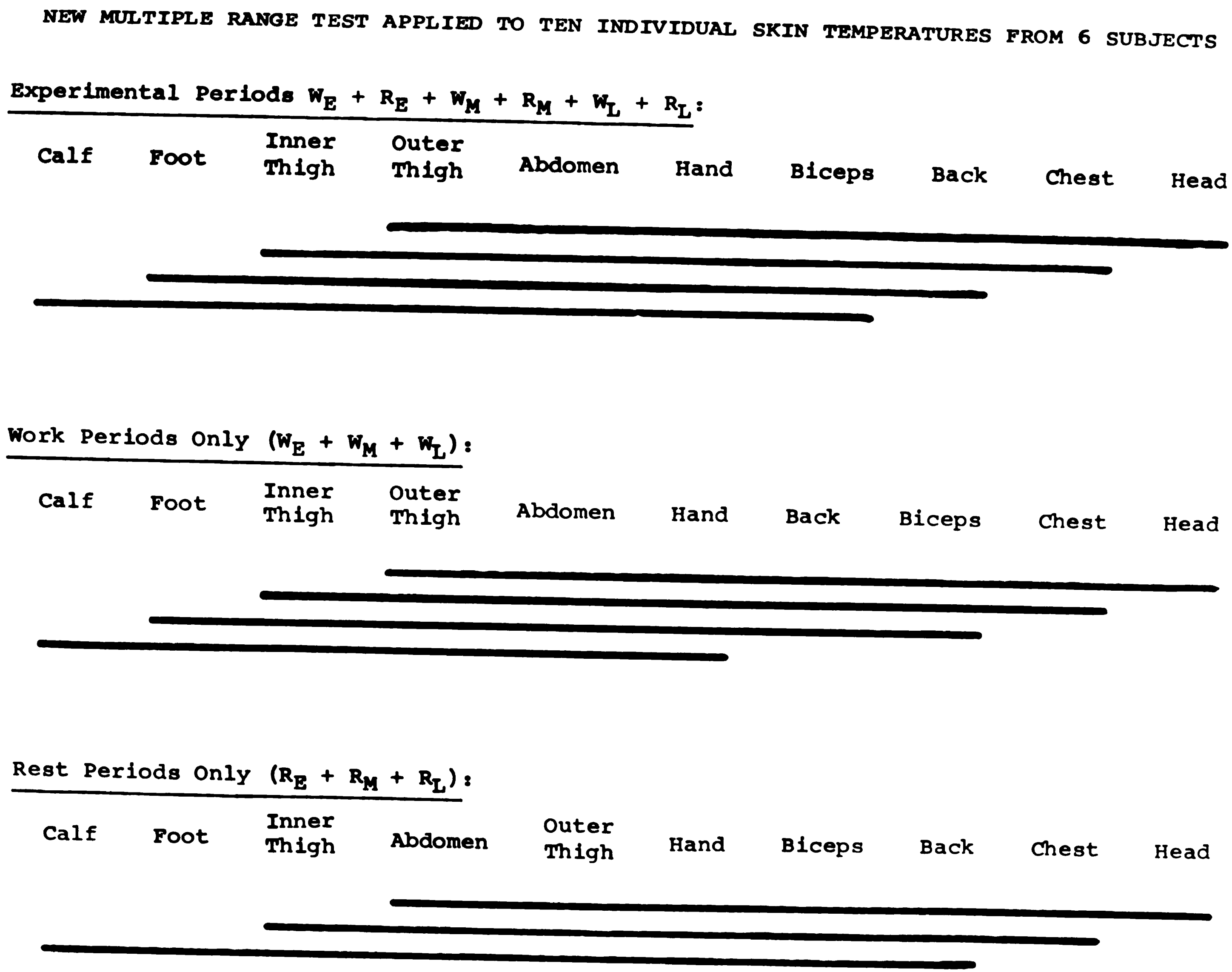

NEW MULTIPLE RANGE TEST APPLIED TO TEN INDIVIDUAL SKIN TEMPERATURES FROM 6 SUBJECTS
Experimental Periods $W_E + R_E + W_M + R_M + W_L + R_L$:
Calf
Foot
Inner Thigh
Outer Thigh
Abdomen
Hand
Biceps
Back
Chest
Head
Work Periods Only ($W_E + W_M + W_L$):
Calf
Foot
Inner Thigh
Outer Thigh
Abdomen
Hand
Back
Biceps
Chest
Head
Rest Periods Only ($R_E + R_M + R_L$):
Calf
Foot
Inner Thigh
Abdomen
Outer Thigh
Hand
Biceps
Back
Chest
Head

Figure 12

BREAKDOWN OF WORK PERIODS FROM NEW MULTIPLE RANGE TEST FOR THE TEN INDIVIDUAL SKIN TEMPERATURES

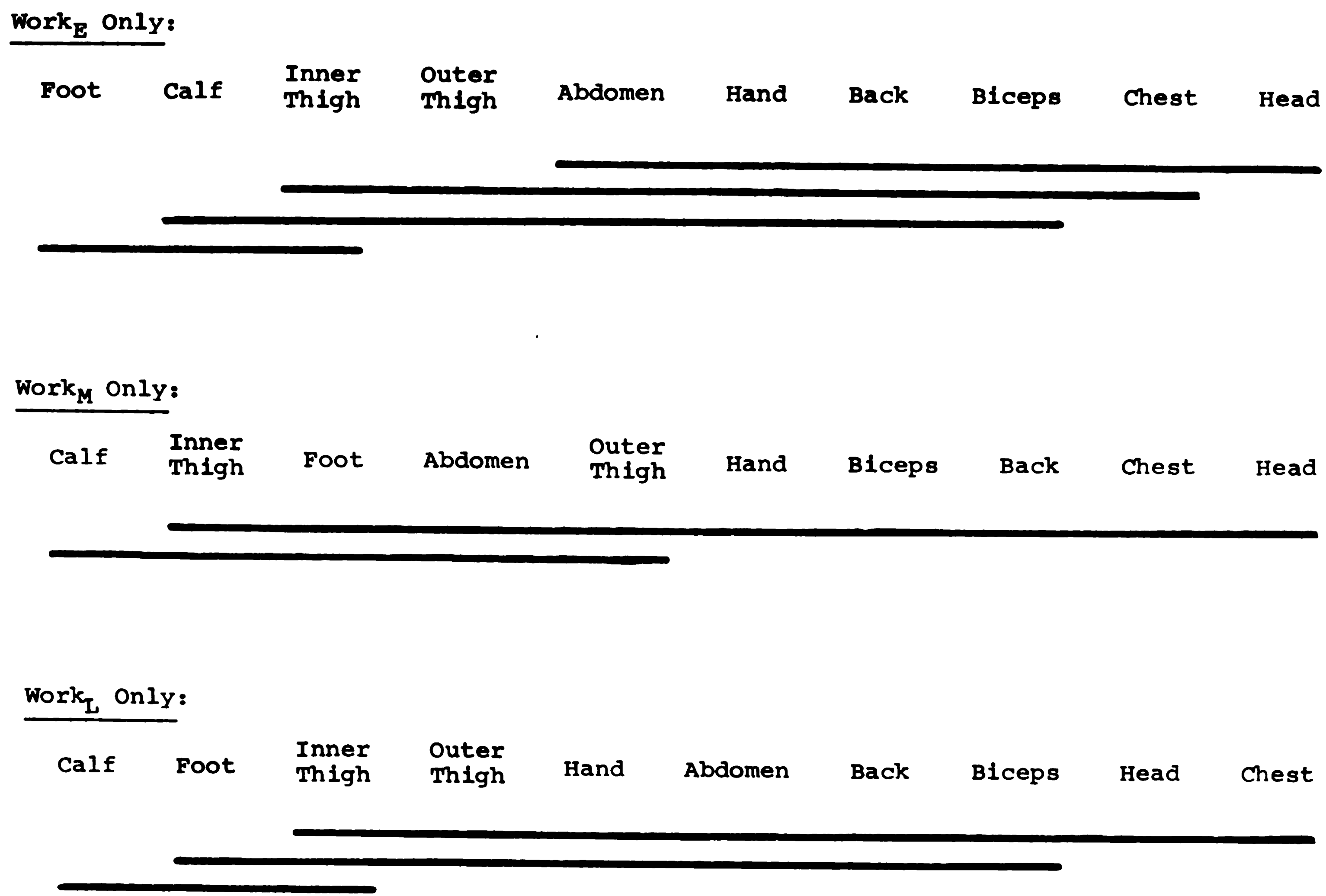


Figure 13

BREAKDOWN OF REST PERIODS FROM NEW MULTIPLE RANGE TEST FOR THE TEN INDIVIDUAL SKIN TEMPERATURES

$Rest_E$ Only:

BREAKDOWN OF REST PERIODS FROM NEW MULTIPLE RANGE TEST FOR THE TEN INDIVIDUAL SKIN TEMPERATURES

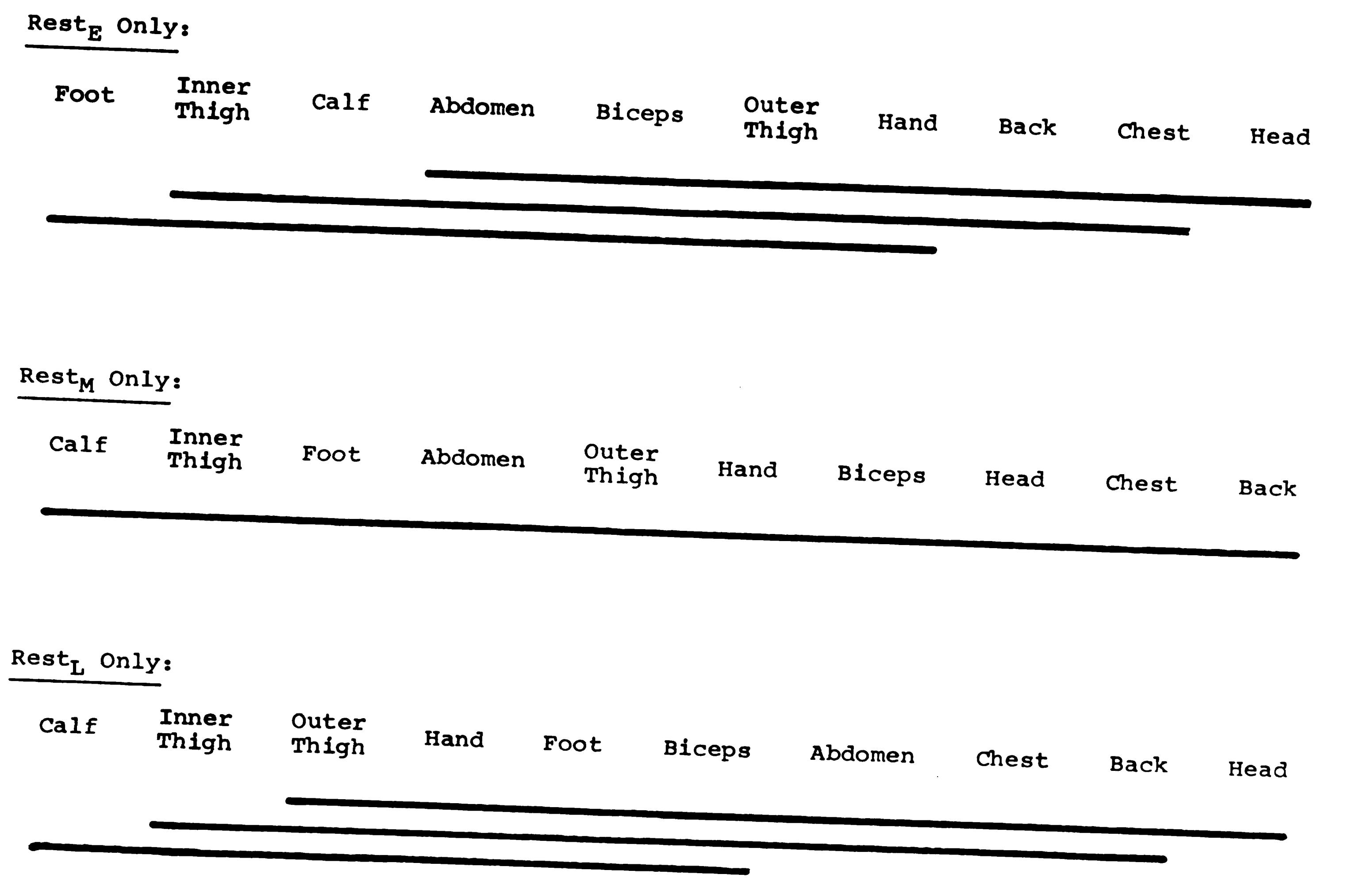


Figure 14

An evaluation of the skin temperature data and statistical analysis indicates:

a) According to the two-way analysis of variance, Table 5, there is a highly significant difference ($p < .001$) between periods of work and rest, and very significant difference ($p < .001$) between skin sites.

b) Whether one considers either work or rest periods, the early phases are more different than the middle and late phases together. There was a greater difference between the work periods than between the rest periods.

c) There is a trend toward greater differences earlier than later in the experiments, this applies to both the work and rest activity. This supports the observations of Hardy and DuBois (1938) of a tendency toward convergence of various body temperatures at an elevated level.

d) The skin site overlying the least active muscle group had the highest temperature. In this case, the external occipital protuberance region was hotter and logically the least active in the performance of required work; and,

e) The skin site overlying the most active muscle group had the lowest temperature. In this case, the skin overlying the M. gastrocnemius region was coolest and logically the area involved with greatest physical activity.

The internal body temperature responses, when the resting heat production was completely stored in the body, led to the conclusion that t_e and t_o represented the temperature of over 80 per cent of the body mass, whereas t_r represented less than 20 per cent (Minard and Copman, 1963b; Copman, Minard and Dasler, 1963; Minard, Copman and Dasler, 1964). There is evidence from a series of studies in hot-humid shipboard working spaces that the lag in t_r, while wearing normal working clothes, must introduce errors in application of t_r as an index of heat strain (Dasler, 1964). Furthermore, although the lag in t_r is not pronounced in this study as in others cited above, the data from this study indicate that a lag in t_r cannot be overlooked when attempting to determine heat storage (Dasler and Reineke, 1965).

In turn, when man is not in a steady thermal state, three widely known equations for mean body temperature will be in error since they employ heavy weighting of t_r. A recent modification of the accepted equations introduced a correction term for transient changes in t_s, but no changes were taken into consideration for the response to t_r. For the purposes of continuity, the four equations are as follows:

a) $$t_b = 0.65\ t_r + 0.35\ t_s \qquad (8)$$

where; t_b = mean body temperature

t_r = rectal temperature

t_s = mean skin temperature.

(Burton, 1935)

b) $$t_b = 0.8\ t_r + 0.2\ t_s \qquad (9)$$

where; t_b = mean body temperature

t_r = rectal temperature

t_s = mean skin temperature

(Hardy and DuBois, 1938)

c) $$t_b = 0.67\ t_r + 0.33\ t_s \qquad (10)$$

where; t_b = mean body temperature

t_r = rectal temperature

t_s = mean skin temperature

(Burton and Edholm, 1955)

d) $$T_B = 0.8\ T_R + (0.2 - \beta\, dTs/dt)\ T_S \qquad (11)$$

where; T_B = mean body temperature (in transient states)

T_R = rectal temperature

β = a reduction coefficient for transient states

dTs = change in skin temperature

dt = change in time

T_S = mean skin temperature

(Stolwik and Hardy, 1963)

Consideration of earlier studies and the present work has led to eight possible forms of an equation for mean body temperature in transient thermal states:

a) $$t_b = (a \cdot t_r) \qquad (12)$$

where; a = a constant

b) $$t_b = (b \cdot t_e) \qquad (13)$$

where; b = a constant

c) $$t_b = (c \cdot t_o) \qquad (14)$$

where; c = a constant

d) $$t_b = (d \cdot t_r) + \left[(1 - d)\ t_s\right] \qquad (15)$$

where; d and (1 - d) are constants

e) $$t_b = (e \cdot t_e) + \left[(1 - e)\ t_s\right] \qquad (16)$$

where; e and (1 - e) are constants

f) $$t_b = (f \cdot t_o) + \left[(1 - f)\ t_s\right] \quad (17)$$

where; f and (1 - f) are constants

g) $$t_b = \left[(1 - g)\ t_o\right] + \left[\big(1 - (g + h)\big)\ t_e\right] + \left[\big(1 - (g + h + i)\big)\ t_r\right] \quad (18)$$

where; g, h and i are constants

h) $$t_b = \left[(1 - j)\ t_o\right] + \left[\big(1 - (j + k)\big)\ t_e\right] + \left[\big(1 - (j + k + m)\big)\ t_r\right] + \left[\big(1 - (j + k + m + n)\big)\ t_s\right] \quad (19)$$

where; j, k, m and n are constants.

In view of preceding evidence, equation (19) should provide a more meaningful approximation of mean body temperatures; however, as the purpose of known equations is to provide an empirical guide with simplicity of computation and involve easily obtainable measurements, it is believed that equation (16) would provide a reasonable approximation of mean body temperature when the body of man is in a transient state.

The need for an empirical equation to describe mean body temperature in a transient state is apparent. However, none of these general equations can be applied and validated until the correct constants have been determined with more experimental data. It was hoped that it would be possible to derive many of the constants from data presented in this paper, but there were no direct calorimetry values available to determine the reliability of derived constants. Therefore the problem of a descriptive general equation for mean body temperature of man in a transient state remains unanswered.

Three factors should be considered in attempting to explain the decrease of skin temperatures during exercise and the increase during rest:

a) Evaporation of sweat from the skin.

b) Convective heat exchange; and,

c) Reduced cutaneous blood flow.

If evaporation occurred at the skin, the skin temperature would decrease and the water vapors would condense on the inner surface of the suit. In the process of condensation the suit would show a rise in temperature. To check for this phenomenon a duplicate set of thermocouples was attached on the outside of the suit, directly over the skin site locations. The external surface of the suit was found to be about 0.5 to 1.0°C (0.9 to 1.8°F) cooler than the body surface temperatures. During work the skin temperatures fell and the external surface temperature of the suit fell; conversely, during rest the skin temperatures increased and the external surface of the suit increased. In addition, DB and WB temperatures were determined inside the clothing at about mid-thigh. The DB and WB temperatures were essentially the same. Therefore, these observations do not confirm the likelihood of evaporation from the skin producing the dramatic changes in skin temperature.

Convective heat exchange, in the condition shown in Figs. 10 and 11, was calculated to be between 15.3 and 23.6 $KCal/m^2/hr$. As will be seen later, this quantity of convective heat loss was very small. With such low convective heat loss it does not seem likely that convection would have produced the changes found for the skin temperatures.

Changes in blood flow may have produced the observed responses. Four hypotheses were considered relative to the work-rest changes:

a) Muscle temperature and blood flow increased and the skin blood flow decreased. In turn, the skin temperature would decrease until tissue conductance and/or sufficient blood flow returned to the skin.

b) Muscle temperature and blood flow increased with no change in skin blood flow. This would produce an increase in skin temperature due to heat conductance through tissues between the muscle and skin.

c) Muscle temperature increased and blood flow decreased and skin blood flow was either unchanged or increased. Such a situation would most likely result in an increase in skin temperature; and,

d) <u>Muscle temperature increased, blood flow was unchanged and skin blood flow was decreased</u>. One might expect a decrease in skin temperature until tissue conductance would transfer heat from the muscle to the skin.

The results of the present work can be explained by either hypothesis *a* or *d*, or a combination of both. Hypothesis *b* and *c* are obviously untenable because they do not account for the results. These findings are in accord with Burton's (1965) discussion of blood flow in the human calf muscle, and also the report of Cooper, Randall and Hertzman (1959).

In the present study it was necessary to rely upon physical and physiological heat transfer principles to estimate changes in peripheral blood flow. Based upon Newton's law of cooling, Burton (1934) pointed out that the ratio of the internal thermal gradient ("core" to skin) to the external gradient (skin to air) may be used as an index of peripheral blood flow. Burton termed this ratio the "Thermal Circulation Index (TCI)."

Sheard (1944), in comments on the TCI, referred to Poiseuille's law of flow of liquids through a tube of small diameter. According to this law, the flow varies as the fourth power of the vessel diameter. Therefore, small changes in blood vessel size produce marked changes in blood flow, which results in marked changes in heat exchange. Therefore, when skin, internal body and air temperatures are measured, one obtains an indirect estimate of peripheral blood flow.

Equation (7) for TCI employs t_r as the deep internal body temperature. Although it has been shown that t_r lags behind responsive and more appropriate sites (e.g., deep esophageal) in a transient thermal state, no modifications of the TCI equation were made. It was believed that consistency of using data from the mid-point of the selected work and rest periods would serve the purpose in comparing adjacent rest-work and work-rest periods. Table 6 indicates the trends in TCI values for the head and calf sites, using pooled data from six test subjects.

It is not possible to attempt a relationship between head and calf TCI values. This is due to the fact that the TCI depends upon the length of path (thickness of tissue) which the heat must traverse from the interior of the body to the chosen skin site, on the blood supply to the site in question and upon the amount of superficial fat at the site. However, the comparison of trends between different activity states for a given site indicates that TCI values generally are decreased during work following rest, and the values all increase in the rest phase following work. The only exception to this pattern was found in the comparison between the first early rest period and the succeeding work period,

TABLE 6

THERMAL CIRCULATION INDEX (TCI)*

(Using Means For 6 Subjects)

Head
(Ext. occipital protuberance)

Phase of Experiment and Physical Activity

Item	Early			Middle			Late		
	Rest	Work	Rest	Rest	Work	Rest	Rest	Work	Rest
TCI	2.6	3.5	5.7	6.8	6.6	9.7	9.3	7.2	12.2
Δ TCI		+0.9	+2.2		-0.2	+3.1		-2.1	+5.0

Calf
(M. gastrocnemius)

Phase of Experiment and Physical Activity

Item	Early			Middle			Late		
	Rest	Work	Rest	Rest	Work	Rest	Rest	Work	Rest
TCI	1.3	1.8	2.7	3.7	2.6	4.2	5.1	3.5	4.7
Δ TCI		+0.5	+0.9		-1.1	+1.6		-1.6	+1.2

* $TCI = \frac{T_S - T_A}{T_R - T_S} = \frac{\text{External drop of temperature}}{\text{Internal drop of temperature}}$ (Burton, 1934)

which is believed to be the result of the body beginning to warm up while there was still an ample volume of blood in splanchnic regions that could be shifted peripherally for heat dissipation.

Benedict and Parmenter (1928) observed decreases of skin temperatures in working regions of the body during five minute exercise periods where metabolism was increased five- to sixfold. They hypothesized that during work there may be a peripheral vasoconstriction, resulting in a temporary transport of blood from the periphery to the muscles. In contrast, Cooper, Randall and Hertzman (1959) reported the heating of skin overlying a working muscle and attributed this to direct vertical vascular convection of heat from muscle to the skin. McCook, Wurster and Randall (1965) pointed out that the functional control of this response remains unknown.

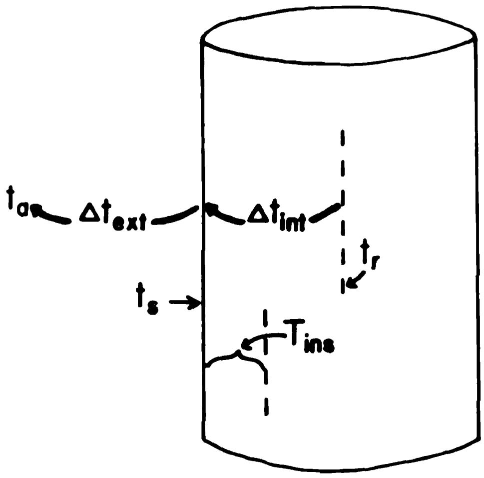
This author believes that both the findings of Benedict and Parmenter and Cooper, Randall and Hertzman are correct, but, the experimental conditions were such for each group of researchers that their findings describe two different physiological responses. The combination of clothing and marked elevation of heat production in Benedict and Parmenter's study resulted in a generalized hyperthermia. It is possible that a sizable portion of normothermic splanchnic blood volume was in cutaneous regions during the no-exercise state, and during exercise the muscle demand for blood resulted in restricting a considerable quantity of blood from reaching the skin because of increased demands by the muscle. When a reduced volume of hot blood was supplied to the skin, the skin temperature fell. The study of Cooper, Randall and Hertzman was conducted at environmental temperatures varying from 20 to 33°C (68 to 91°F), with relative humidity varying between 40 and 60 per cent. Their subjects were very lightly clothed with shorts and with or without undershirts. Based upon the brief description of the type of exercise used, the metabolic rate of their subjects was apparently much less than in the study by Benedict and Parmenter. Therefore, in consideration of the experimental design and findings it is possible that there were sufficient reserves of blood in internal body regions to provide an adequate supply to meet working muscle demands without restricting blood flow to the skin.

Uvnäs (1960) suggested a number of factors that may be interrelated to explain the phenomenon of decreased skin temperature during muscular work. He indicated that the increase in cardiac output during exercise is distributed chiefly to the muscles by shifts of tone in the peripheral vessels. Eliasson and co-workers (Uvnäs, 1960) were able to localize hypothalamic areas which when stimulated activated the sympathetic vasodilator outflow to skeletal muscle and simultaneously produced cutaneous and visceral vasoconstriction. Also, adrenals were activated and epinephrine was selectively liberated. Uvnäs believed that even though the quantities of epinephrine were not sufficient to produce vasomotor reactions in the muscles and skin, the amount was sufficient to increase the metabolic processes in the muscles, heart and other organs. From this form of reasoning, Uvnäs stated "one is tempted to assume that the sympathetic vasodilatory nerves are activated in circumstances which require optimal conditions for muscular effort."

Shepherd (1963) has indicated the same physiological responses as cited by Uvnäs (1960), but Shepherd describes the effect of epinephrine on skin and muscle blood vessels in terms which aid in additional clarification of data from this study. He presented evidence that epinephrine produces vasoconstriction in skin vessels, whereas vasodilatation results in muscle vessels. The effects of epinephrine are such that muscle blood flow is increased, skin blood flow is decreased, heart rate shows a transient increase, systolic blood pressure rises, diastolic blood pressure decreases, and pulmonary ventilation rate increases (Cobbold, Ginsburg and Paton, 1960). These responses are like those observed in this study.

The relationship between internal and skin temperatures is graphically summarized in Fig. 15. The decrease in TCI values during work and rise during rest demonstrates that under these experimental conditions the skin blood flow was decreased during work and increased during rest. The

THERMAL CIRCULATION INDEX (TCI)*

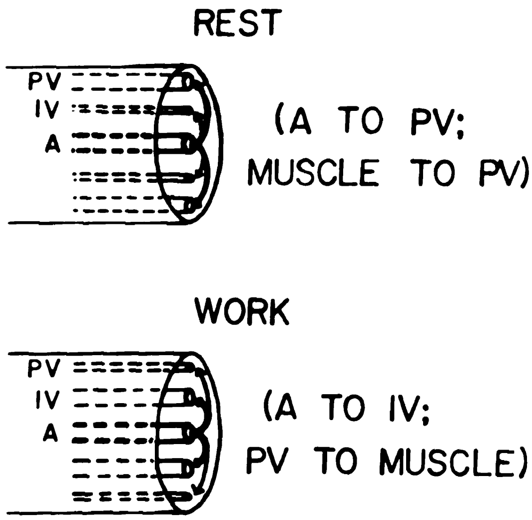


t_r = RECTAL TEMPERATURE
t_s = SKIN TEMPERATURE
t_a = AIR TEMPERATURE
Δt_{int} = INTERNAL GRADIENT $(t_r - t_s)$
Δt_{ext} = EXTERNAL GRADIENT $(t_s - t_a)$
T_{ins} = TISSUE INSULATION

$$^{*}TCI = \frac{t_s - t_a}{t_r - t_s} = \frac{\text{EXTERNAL DROP}}{\text{INTERNAL DROP}},$$

(BURTON, 1934)

HYPOTHETICAL BLOOD FLOW SHIFT



A = ARTERY
PV = PERIPHERAL VEIN
IV = INTERNAL VEIN

AFTER SCHMIDT-NIELSEN, 1961 (MODIFIED)

Figure 15

hypothetical blood flow shift is shown in the diagram modified from Schmidt-Nielsen (1961). As illustrated by this diagram, when heat production was increased during work blood was shunted to internal vessels resulting in heat retention in deep body tissues and active muscles. This caused a rapid spiraling of internal body temperatures.

Partitional Calorimetry

Research conducted prior to commencement of the present study clearly indicated that heat stress with the complete clothing assembly was extremely restrictive under ambient conditions that were normal for men in usual work clothes. It was concluded in the initial research (Dr. David Minard, unpublished data) that tolerance time of the subjects was directly related to the rate of body heat storage. Furthermore, a limited number of experiments demonstrated that tolerance time could be extended by increasing the air velocity over the external surface of the suit.

The experimental conditions in the present study were based upon control of air velocity while using three pre-established upper levels of ambient temperatures and two physical activity levels. "Control" conditions for the different activity levels were selected by the subjective judgment of comfort in the suit, and objective observation of relatively constant internal body temperatures. The 10 experimental conditions utilized throughout this study are given in Table 7, along with the effects of air velocity on tolerance time.

Table 7 clearly supports the concept that air movement can increase tolerance time in the heat, provided a critical air speed is not exceeded. The tolerable exposure time was found to be a function of dry bulb temperature, physical activity and air velocity. Since tolerance time was extended from 26 per cent to 93 per cent, depending on the conditions, the logical explanation had to be either increased convective heat loss or increased evaporative cooling. As has been shown, evaporative cooling within or on the surface of the suit was not possible under the experimental conditions. However, the relationship between convection and air velocity will be shown more clearly from the results of the first order partitional calorimetry.

The most commonly used methods to determine body heat storage, those of Burton (1935) and Blockley, McCutchan and Taylor (1954), have mean body temperature (t_b) as a key element of their equations. As has been shown, the calculation of t_b by available equations is not appropriate in transient thermal states. To avoid the underestimation of heat storage during rapid storage and an overestimation during rapid loss by using equations dependent upon t_r, the data were applied to the general expression for heat balance, equation (1). Substitution of radiation from equation (2),

TABLE 7

EFFECTS OF AIR VELOCITY ON TOLERANCE TIME

Conditions*	Number Subjects	Exposure Time (hrs.) (Mean)	(S.E.)	Difference From Control** (%)	Other Differences** (%)
STANDING (No Exercise):					
62/54, <50 (Control)	8	3.96	± 0.12	-----	-----
90/80, <50	8	1.79	± 0.11	- 55	-----
90/80, 250	7	2.29	± 0.29	- 42	+ 28 > (90/80, <50)
90/80, 1000	8	2.92	± 0.36	- 26	+ 63 > (90/80, <50); + 28 > (90/80, 250)
MODERATE EXERCISE:					
62/54, <50 (Control)	7	3.52	± 0.23	-----	-----
75/65, <50	8	1.88	± 0.11	- 47	-----
75/65, 250	8	2.88	± 0.23	- 18	+ 53 > (75/65, <50)
75/65, 1000	8	3.63	± 0.26	+ 3	+ 93 > (75/65, <50); + 26 > (75/65, 250)
85/75, <50	3	1.61	± 0.15	- 54	-----
85/75, 1000	2	2.50	± 0.50	- 29	+ 55 > (85/75, <50)

* = DB (^{o}F)/WB (^{o}F), Air Velocity (fpm)

** - = Loss, + = Gain

convection from equation (3), respiratory evaporation from equation (4) and metabolism into equation (1) yielded the estimated partitional calorimetry of body heat as shown in Figs. 16-21.

It is usually believed that evaporation from the respiratory tract is an important avenue of heat loss. Under the conditions of these experiments however, respiratory heat loss was negligible in every instance. It is also of interest that radiative heat loss showed comparatively little change in contrast to the substantial changes observed in heat storage and convection. It is shown most clearly in Figs. 16-18, at DB 75°F and WB 65°F, that there is an inverse relationship between heat storage and convective heat loss. A similar relationship can be deduced from the data in Figs. 19-21. However, the comparison is complicated by the fact that several different variables were included in these experiments.

The values for radiation and convection given in Figs. 16-21 are plotted versus air velocity in Fig. 22. It is apparent that radiation is relatively unaffected by air velocity, whereas convection is directly related to but nonlinear with air velocity. At <50 fpm air velocity, radiation is two times greater than convection, at 250 fpm convection exceeds radiation, and at 1000 fpm convection is about two and one-half times greater than radiation. Leithead and Lind (1964) point out that a gradual increase in air movement

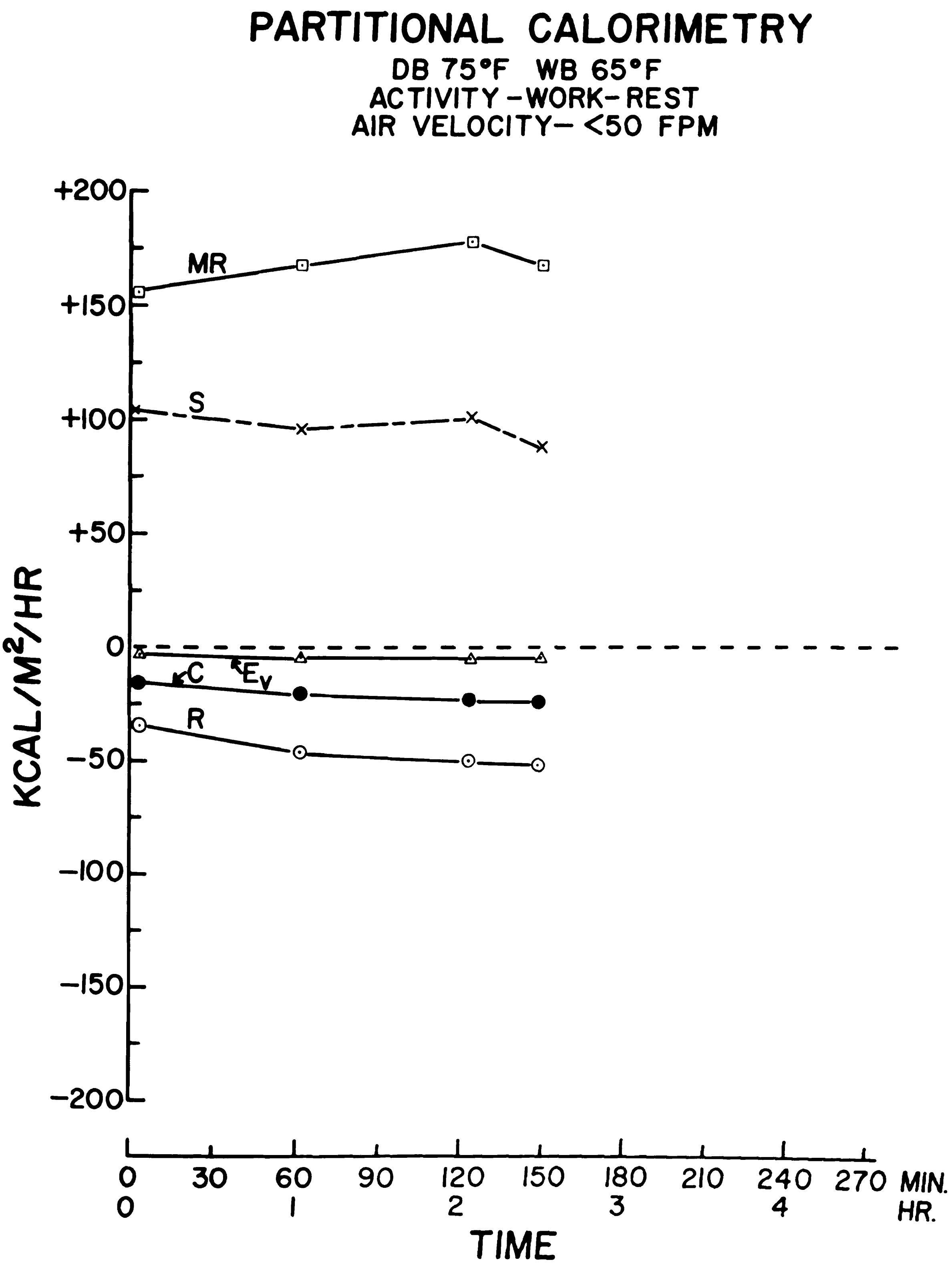


Figure 16. MR = metabolic rate; S = heat storage; C = convection; R = radiation; and E_V = respiratory evaporation.

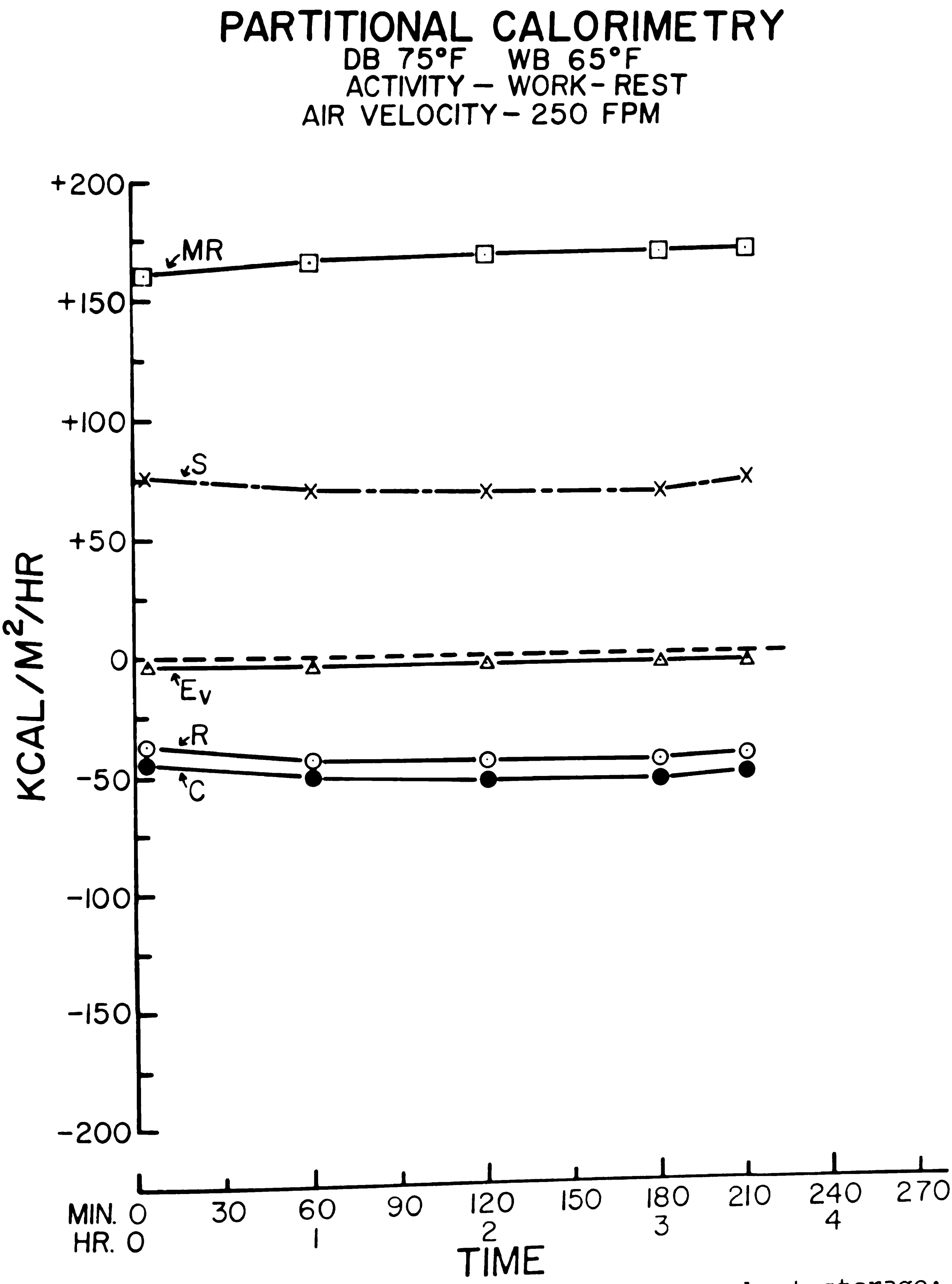


Figure 17. MR = metabolic rate; S = heat storage; C = convection; R = radiation; and E_v = respiratory evaporation.

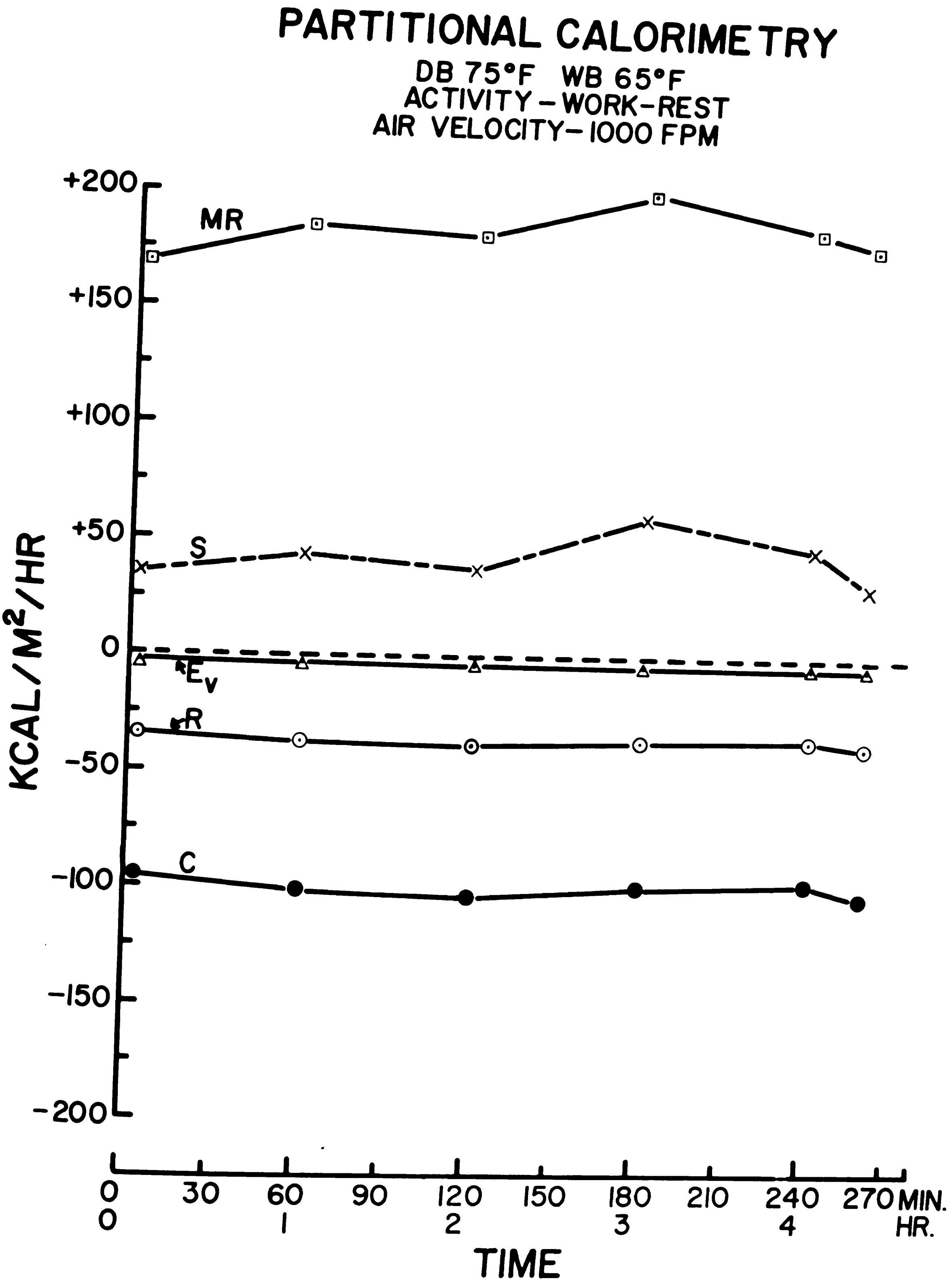


Figure 18. MR = metabolic rate; S = heat storage; C = convection; R = radiation; and E_V = respiratory evaporation.

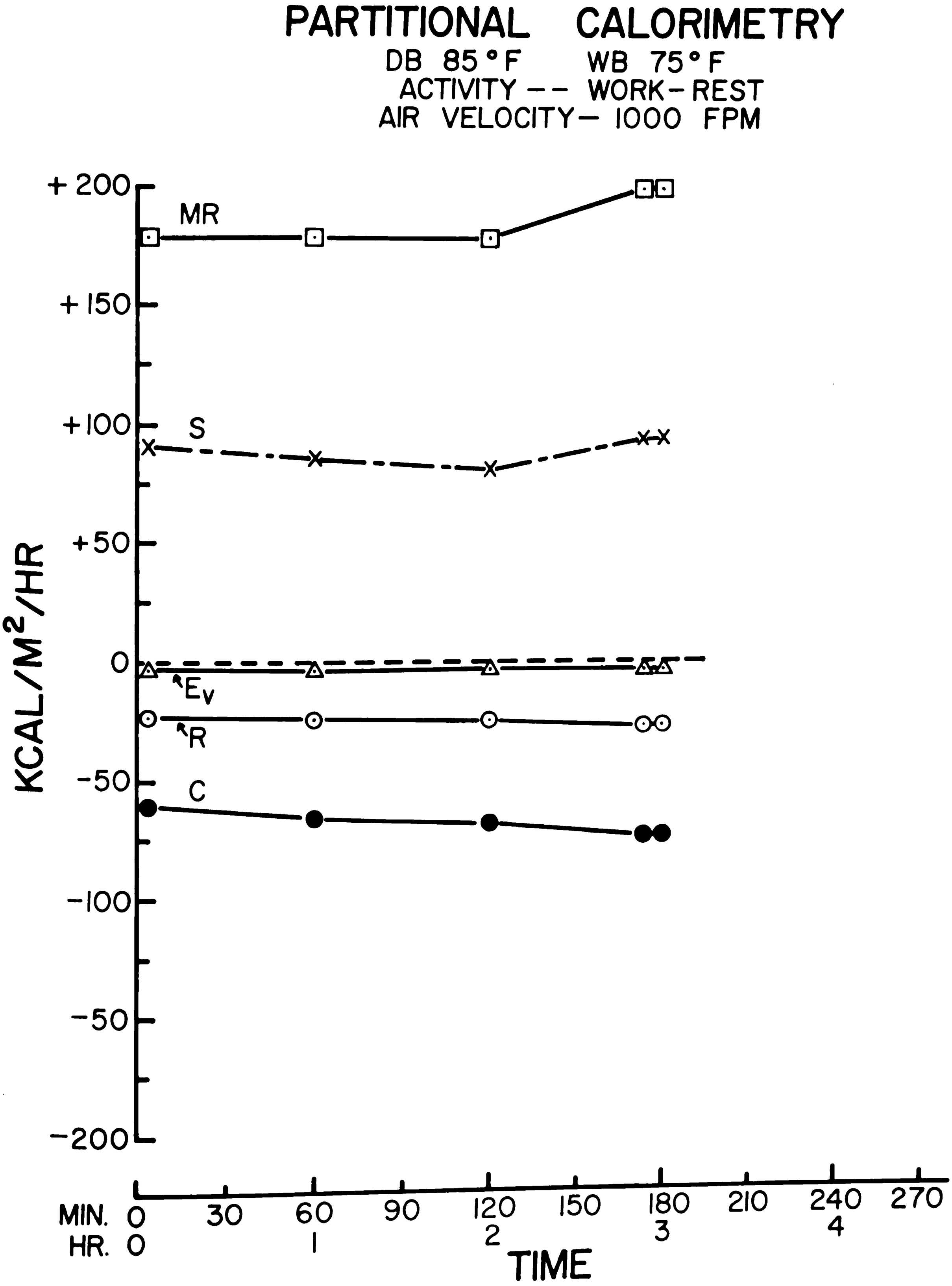


Figure 19. MR = metabolic rate; S = heat storage; C = convection; R = radiation; and E_V = respiratory evaporation.

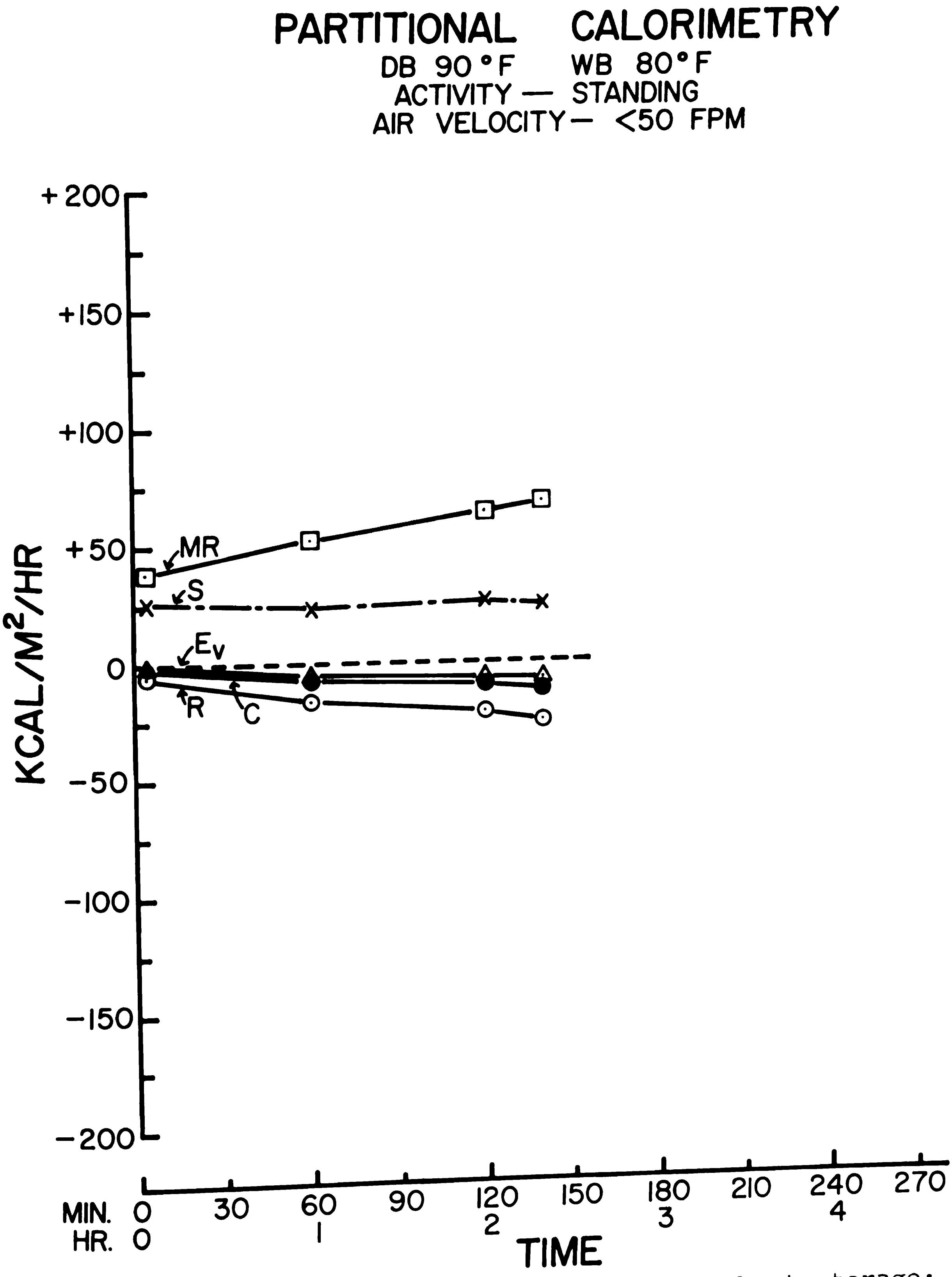


Figure 20. MR = metabolic rate; S = heat storage; C = convection; R = radiation; and E_v = respiratory evaporation.

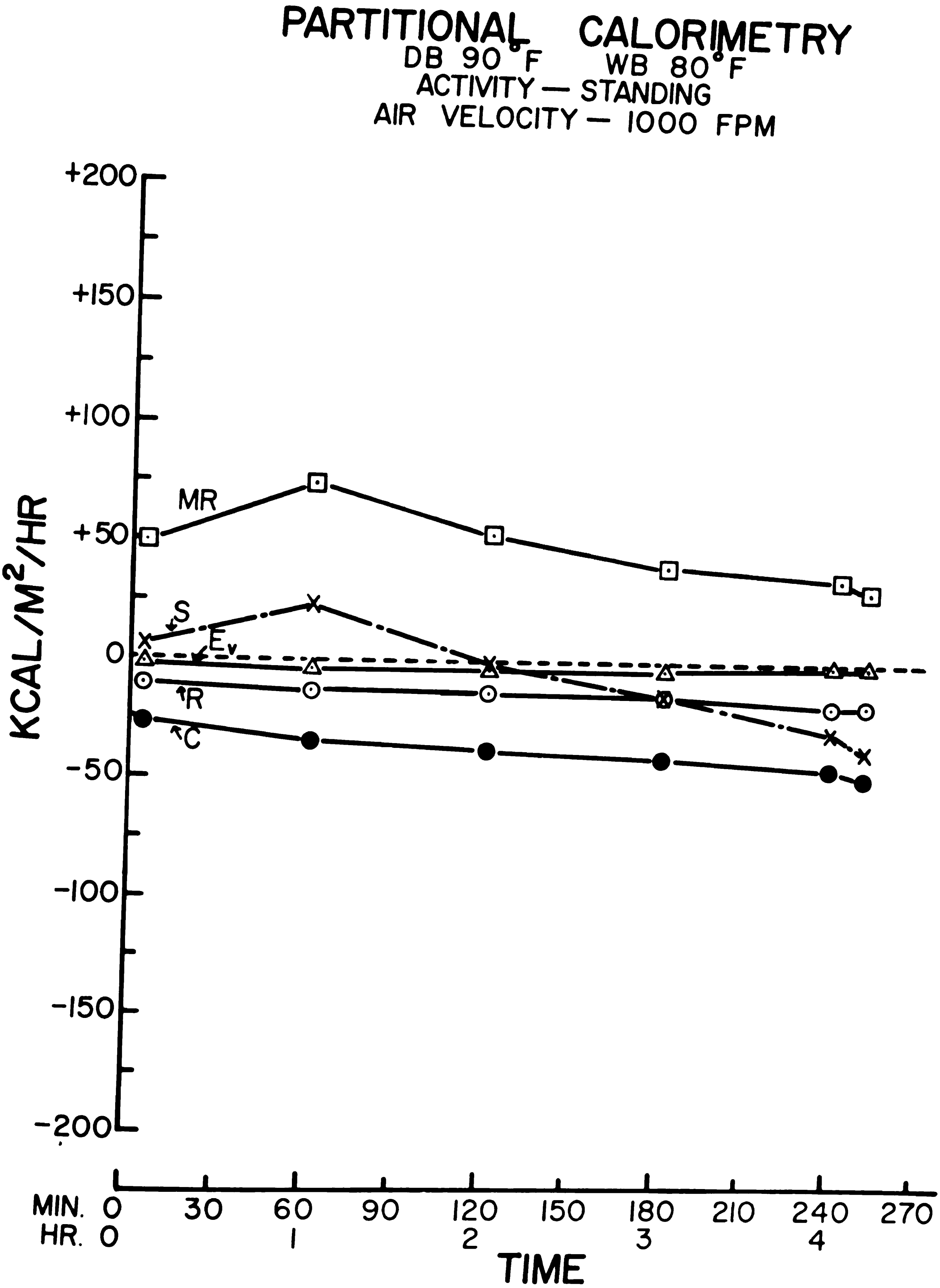


Figure 21. MR = metabolic rate; S = heat storage; C = convection; R = radiation; and E_V = respiratory evaporation.

RADIATION

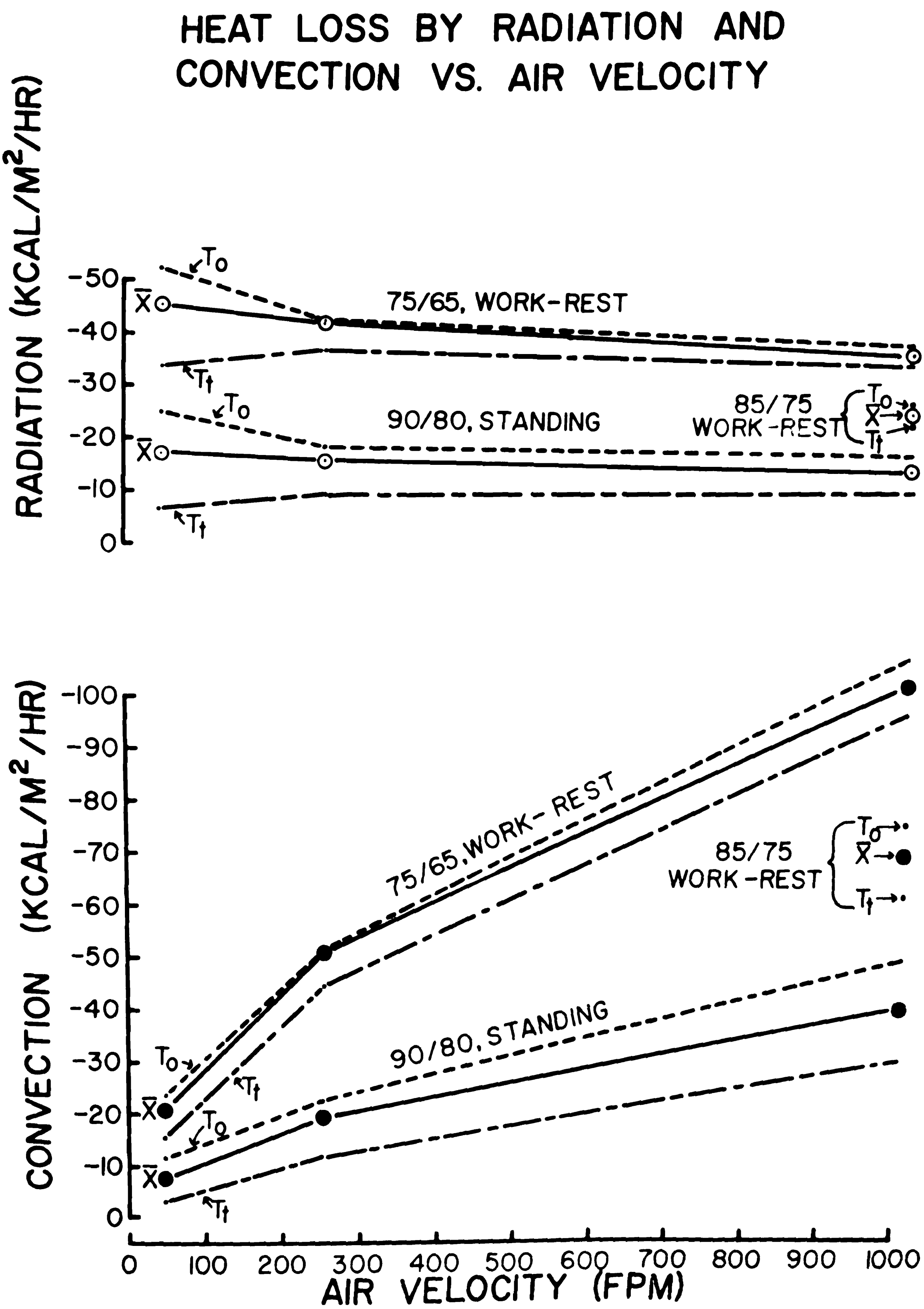


Figure 22. T_o = time zero; T_t = time terminal; and $\overline{X}$ = mean.

in warm to hot air temperatures will be beneficial at first, but above some critical speed it will become detrimental. The data in Fig. 22 shows the non-linearity between convection and air movement, where increasing the air speed four times greater than 250 fpm produced only a twofold increase in convective heat loss. Therefore, to greatly exceed 1000 fpm would yield less convective loss per unit of velccity until the critical air speed would be reached, at which time the friction of air movement would impose a heat load on the test subject.

The practical advantage of employing first order partitional calorimetry has been demonstrated. This approach appears to provide a reasonable way of estimating heat storage for this study, and at the same time to provide an opportunity to evaluate the various avenues of heat loss in a rational fashion. Among the experimental variables tested, the only one which shows promise in reducing the heat load under the experimental conditions is convection. Parallel experiments, not reported herein, showed that substantial improvements in tolerance time could be obtained by using an evaporative cooling garment and water spray on the external surface of the suit (Dr. David Minard, unpublished data). A logical sequence for these experiments would be to combine convection and evaporative cooling in a future study conducted under controlled conditions.

SUMMARY AND CONCLUSIONS

Heat tolerance was studied in volunteer human test subjects clothed in an impermeable, unventilated bacteriological-chemical warfare protective assembly that barred evaporative heat loss. Data are presented to show conditions needed to approach the upper limit of heat tolerance in man. The physiological consequences of exceeding the heat tolerance limit are also described.

The ambient environmental temperatures ranged from DB 18.3^{o}C and WB 12.2^{o}C (65 and 54^{o}F) to DB 32.2^{o}C and WB 26.6^{o}C (90 and 80^{o}F). Air velocity over the surface of the impermeable suit was controlled at $<$50, 250 and 1000 fpm. Physical activity was limited to standing at rest and working by climbing two 6" high steps and then stepping back down at a rate of 10 round trips per minute.

The parameters measured included temperatures of the rectum, tympanic membrane, deep esophagus, 10 individual skin sites and mean skin temperature. In addition, metabolic rate, heart rate and blood pressure were determined. Computations and data were presented for first order partitional calorimetry, estimated cardiac output, and peripheral blood flow by use of the Thermal Circulation Index.

Theoretical equations were developed for mean body temperature in a transient thermal state.

It is concluded that:

1. Under the specific conditions of this study the upper limit of "safe" tolerance can be defined as body temperature not exceeding 39°C, heart rate not exceeding 180 beats per minute, and/or blood pressure not less than 90/40 mm Hg.

2. Circulatory instability was observed when the heat tolerance limit was exceeded, resulting in imminent circulatory failure.

3. When heat storage is rapid and continuous, rectal temperature is not a reliable index of body temperature; whereas deep esophageal and/or tympanic membrane temperatures do reflect sudden changes in internal body temperature.

4. When man is in a transient thermal state the widely used equations for mean body temperature cannot accurately predict mean body temperature or heat storage.

5. During work, deep body temperatures rise and skin temperatures fall; conversely, during rest skin temperatures rise and deep body temperatures fall.

6. Based upon physical principles of heat transfer, the decrease in skin temperature during work and rise during rest was not the result of evaporation or convection, but the result of changes in peripheral blood flow.

7. Tolerance to severe heat stress, with unchanged air temperatures, was increased with increasing air velocity.

8. Convection heat exchange is the most practical avenue of heat loss when evaporative cooling is not possible.

REFERENCES

Adams, T. 1959. Environmental factors influencing thermal exchange. Arctic Aeromedical Lab. Rept. no. AAL TR 59-22, 54 pp. ASTIA AD-251 856.

Asmussen, E. 1940. The cardiac output in rest and work in humid heat. Am. J. Physiol. 131:54-59.

Barber, N. 1966. The Black Hole of Calcutta. Houghton Mifflin Co., Boston.

Bazett, H. C. 1924. Studies on the effects of baths on man. I. Relationship between the effects produced and the temperature of the bath. Am. J. Physiol. 70:412-429.

Bazett, H. C. 1927. Physiological responses to heat. Physiol. Revs. 7:531-599.

Belding, H. S. and T. F. Hatch. 1955. Index for evaluating heat stress in terms of resulting physiological strains. Heating, Piping and Air-Conditioning, ASHAE Journal Section, pp. 129-136. August.

Bellet, S., S. Deliyiannis and M. Eliakim. 1961. The electrocardiogram during exercise as recorded by radio-electrocardiography. Comparison with the postexercise electrocardiogram (Master Two-Step Test). Am. Jour. Cardiology 8:385-400.

Bellet, S., M. Eliakim, S. Deliyiannis and E. M. Figallo. 1962. Radioelectrocardiographic changes during strenuous exercise in normal subjects. Circulation 25:686-694.

Benedict, F. G. and H. S. Parmenter. 1928. Human skin temperature as affected by muscular activity, exposure to cold and wind movement. Am. J. Physiol. 87:633-653.

Benjamin, F. B. and L. Peyser. 1964. Physiological effects of active and passive exercise. J. Appl. Physiol. 19:1212-1214.

Benzinger, T. H. and G. W. Taylor. 1963. Cranial measurements of internal temperature in man. Chapter 10 In Temperature: Its measurement and control in science and industry. 3:111-120. Reinhold Publishing Corp., New York.

Bergmann, C. 1845. Nichtchemischer Beitrag zur Kritik der Lehre von Caler animalis. Müller's Arch. Anat. Physiol. Lpz., pp. 300-319.

Bernard, C. 1876. Leçons sur la Chaleur Animale, sur les Effets de la Chaleur, et sur la Fievre. J-B. Bailliere et fils. Paris, France.

Blockley, W. V., J. W. McCutchan and C. L. Taylor. 1954. Prediction of human tolerance for heat in aircraft: a design guide. WADC Tech. Report 53-346. Wright Air Development Center.

Bockley, W. V. and C. L. Taylor. 1948. Studies of human tolerance for extreme heat. Memo. Rept. MCREXD-696-1113A. Wright-Patterson AFB.

Burch, G. E. and N. P. DePasquale. 1962. Hot Climates, Man and His Heart. C. C. Thomas, Springfield, Ill.

Burch, G. E. and A. Hyman. 1957. Influence of a hot and humid environment upon cardiac output and work in normal man and in patients with chronic congestive heart failure at rest. Am. Heart J. 53:665-679.

Burton, A. C. 1934. The application of the theory of heat flow to the study of energy metabolism. J. Nutrition 7:497-533.

Burton, A. C. 1935. Human calorimetry. II. The average temperature of the tissues of the body. J. Nutrition 9:261-280.

Burton, A. C. 1948. III. Temperature of skin: Measurement and use as index of peripheral blood flow. Methods in Medical Research 1:146-166.

Burton, A. C. 1965. Physiology and Biophysics of the Circulation. Year Book Medical Publishers, Inc., Chicago.

Burton, A. C. and O. G. Edholm. 1955. Man in a cold environment--Physiological and pathological effects of exposure to low temperatures. Edward Arnold Ltd., London.

Clanton, B. R. 1953. The physiological effects of permeable impregnated clothing on troops performing routine duties in tropical conditions. Medical Laboratories Research Report No. 167. Chem. Corps. Army Chem. Center. (Declassified.)

Cobbold, A. F., J. Ginsburg and A. Paton. 1960. Circulatory, respiratory and metabolic responses to isopropylnoradrenaline in man. J. Physiol. 151:539-550.

Consolazio, C. F., R. E. Johnson and L. J. Pecora. 1963. Physiological Measurements of Metabolic Functions in Man. McGraw-Hill Book Co., Inc., New York.

Cooper, K. E. 1965. Personal communication (at the NRC meeting in Chicago, Feb. 20-22, 1965).

Cooper, K. E., W. I. Cranston and E. S. Snell. 1964. Temperature in the external auditory meatus as an index of central temperature changes. J. Appl. Physiol. 19:1032-1035.

Cooper, T., W. C. Randall and A. B. Hertzman. 1959. Vascular convection of heat from active muscle to overlying skin. J. Appl. Physiol. 14:207-211.

Copman, L., D. Minard and A. R. Dasler. 1963. Elevation of internal body temperatures during transient heat loads and at thermal equilibrium. Project MR 005.01-0001.02, Rept. No. 1, 17 June. Nav. Med. Res. Inst.

Cotes, J. E. 1955. The role of body temperature in controlling ventilation during exercise in one normal subject breathing oxygen. J. Physiol., London 129: 544-563.

Craig, F. N. 1950a. Ventilation requirements of an impermeable protective suit. The influence of temperature, humidity, and flow of ventilating air on the physiological strain. Medical Division Research Report No. 5. Chem. Corps Army Chem. Center.

Craig, F. N. 1950b. Preliminary observations on the physiological strain of wearing a polyvinyl alcohol suit. Medical Division Research Report No. 10. Chem. Corps Army Chem. Center. (Declassified.)

Craig, F. N., H. Frankel and W. V. Blevins. 1952. The heat balance of men wearing protective clothing. Medical Laboratories Research Report No. 132. Chem. Corps Army Chem. Center. (Declassified.)

Crawford, A. 1788. Experiments and Observations on Animal Heat and the Inflammation of Combustible Bodies. 2nd ed., London.

Daily, W. M. and T. R. Harrison. 1948. A study of the mechanism and treatment of experimental heat pyrexia. Am. J. Med. Sci. 125:42-55.

Dasler, A. R. 1964. BuMed Final Report on Shipboard Toxicological Operational Protective Systems (STOPS)(U) Phase No. 2, Evaluation During Sea Trials. Nav. Med. Res. Inst., NMRI-0130aw, 3900, Ser: 09, 27 July. (CONFIDENTIAL.)

Dasler, A. R. 1965. Heat stress in military operations. United States Navy Medical News Letter (NAVMED P-5088), 46(8):6-7, 22 October.

Dasler, A. R. and D. Minard. 1966a. Inverse temperatures during hyperthermia in man. Fed. Proc. 25:part I, No. 1559, p. 468.

Dasler, A. R. and D. Minard. 1966b. Inverse temperatures during hyperthermia in man. United States Navy Medical News Letter (NAVMED P-5088), 47(10):23-25, 27 May.

Dasler, A. R. and E. P. Reineke. 1965. Thermal responses in man wearing impermeable clothing. Fed. Proc. 24: No. 834, p. 281.

DuBois, E. F. 1927. Basal Metabolism in Health and Disease. 1st ed. Lea and Febiger, Philadelphia.

DuBois, E. F. 1951. The many different temperatures of the human body and its parts. West. J. Surg. 59:476-490.

Fielding, G. H. 1964. Shipboard BW/CW Defense and Countermeasures. U.S. Naval Research Laboratory NRL Report 5969, 28 January. (For Official Use Only.)

Fiske, C. N. 1913. The effects of exposure to intense heat on the working organism. Am. J. Med. Sci. 145: 565-585.

Frankel, H. M., W. V. Blevins, H. W. Garren and F. N. Craig. 1953. The influence of design on the physiological effects of wearing semipermeable protective clothing. Med. Lab. Res. Rept. No. 226. Chem. Corps Army Chem. Center. (Declassified.)

Gagge, A. P. 1936. The linearity criterion as applied to partitional calorimetry. Am. J. Physiol. 116:656-668.

Gagge, A. P., C. E. A. Winslow and L. P. Herrington. 1938. Influence of clothing on the physiological reactions of the human body to varying environmental temperatures. Am. J. Physiol. 124:30-50.

Garren, H. W., H. M. Drupieski, H. Frankel, W. V. Blevins and F. N. Craig. 1953. The influence of the physical properties of fabrics on the physiological effects of impermeable, semipermeable, and permeable protective clothing. Med. Lab. Res. Rept. No. 188. Chem. Corps Army Chem. Center. (Declassified.)

Grollman, A. 1930. Physiological variations of the cardiac output in man. X. The effect of variations in the environmental temperature on the pulse rate, blood pressure, oxygen consumption, arterio-venous oxygen difference, and cardiac output of normal individuals. Am. J. Physiol. 95:263-273.

Hall, J. F., Jr. 1952. Heat stress imposed by permeable versus impermeable clothing. Technical Note WCRD 52-112. Wright-Patterson AFB.

Hall, W. W. and E. G. Wakefield. 1927. A study of experimental heat-stroke. J.A.M.A. 89(3):177-182.

Hardy, J. D. 1961. Physiology of temperature regulation. Physiol. Revs. 41:521-606.

Hardy, J. D. and E. F. DuBois. 1938. Basal metabolism, radiation, convection and vaporization at temperatures of 22 to 35°C. J. Nutrition 15:477-497.

Hasseb, M. A. and A. Fayiz. 1958. Fatal effects of heat on man. J. Trop. Med. Hyg. 61:280-281.

Hertig, B. A. and H. S. Belding. 1963. Evaluation and control of heat hazards. Chapter 32 In Temperature: Its measurement and control in science and industry. Vol 3, Part 3. Reinhold Publishing Corp., New York.

Jackson, C. E. 1955. Nomogram for simple calculation of cardiac output. Circulation 11:635-637.

Kissen, T. T. and J. F. Hall, Jr. 1963. Physiologic response to transient heat stress in reflective versus nonreflective clothing. Technical Documentary Report No. AMRL-TDR-63-79. Wright-Patterson AFB.

Koroxenidis, G. T., J. T. Shepherd and R. J. Marshall. 1961. Cardiovascular response to acute heat stress. J. Appl. Physiol. 16:869-872.

Leithead, C. S. and A. R. Lind. 1964. Heat Stress and Heat Disorders. F. A. Davis, Philadelphia.

Li, J. C. R. 1964. Statistical Inference. Edwards Brothers, Inc., Ann Arbor.

Machle, W. and T. F. Hatch. 1947. Heat: Man's exchanges and physiological responses. Physiol. Rev. 27:200-227.

Macpherson, R. K. 1960. Physiological Responses to Hot Environments. Med. Red. Coun. Spec. Rep. No. 298. Her Majesty's Stationery Office, London.

McCook, R. D., R. D. Wurster and W. C. Randall. 1965. Sudomotor and vasomotor responses to changing environmental temperature. J. Appl. Physiol. 20:371-378.

McDowell, R. E., B. T. McDaniel, M. S. Barrada and D. H. K. Lee. 1961. Rate of surface evaporation from the normal body surface and sweat glands inactivated under hot conditions. J. Animal Sci. 20:380-385.

Minard, D. 1961. Heat stress in navy and marine corps operations. Navy Technical Forum, Spring 1961, NavExos P-2193, pp. 31-53. (Declassified.)

Minard, D. and L. Copman. 1963a. Elevation of body temperature in desease. In Temperature: Its measurement and control in science and industry. 3:253-273. Reinhold Publishing Corp., New York.

Minard, D. and L. Copman. 1963b. Elevation of body temperature in health. In Temperature: Its measurement and control in science and industry. 3:527-543. Reinhold Publishing Corp., New York.

Minard, D., L. Copman and A. R. Dasler. 1964. Elevation of body temperature in health. Ann. N. Y. Acad. Sci. 121: 12-25.

Minard, D., L. Copman and A. R. Dasler. 1966. Sweat rate during work and rest at elevated internal temperatures. (In Press.)

Minard, D. and R. L. O'Brien. 1964. Heat casualties in the Navy and Marine Corps 1959-1962 with appendices on the field use of the wet bulb - globe temperature index. Nav. Med. Res. Inst. Research Rept. MR 005.01-0001.01, Rept. No. 7, 12 March.

Mortensen, K. G. 1957. Heat transfer and the clothing of man. Textile College, Gordon Inst. of Technology Publication No. 12. Gordon Inst. of Tech., Geelong, Victoria, Australia.

Press, J. J. 1959. Textile Research: A Challenge. Ann. N. Y. Acad. Sci. 82:Art. 3, pp. 645-796. Conference on radiation and high temperature behavior of textiles. Oct. 9.

Robinson, S. 1965. Mechanism of sweating in work. Arch. Environ. Health. 11:454-459.

Robinson, S., F. N. Marzulli and E. McFadden. 1950. The effects of impermeable and ventilated gas protective clothing on men working in summer heat. Med. Division Research Report No. 12 Chem. Corps Army Chem. Center. (Declassified.)

Schmidt-Nielsen, K. 1961. Animal physiology. Second ed. Foundations of Modern Biology Series. Prentice-Hall Inc., Englewood Cliffs, N. J.

Sheard, C. 1944. Temperature of skin and thermal regulation of the body. In Medical Physics. Year Book Publishers, Inc., Chicago.

Shepherd, J. T. 1963. Physiology of the Circulation in Human Limbs in Health and Disease. W. B. Saunders, Philadelphia.

Starr, I. 1954. Clinical tests of simple method of estimating cardiac stroke volume from blood pressure and age. Circulation 9:664-681.

Starr, I., T. G. Schnakel Jr., S. I. Askowitz and A. Schild. 1954. Studies made by stimulating systole at necropsy: IV. On relation between pulse pressure and cardiac stroke volume, leading to clinical method of estimating cardiac output from blood pressure and age. Circulation 9:648-663.

Stolwik, J. A. J. and J. D. Hardy. 1963. Estimation of body temperature during sudden changes in environmental temperature. Fed. Proc. 22:Part I, No. 97, p. 176.

Teichner, W. H. 1958. Assessment of mean body surface temperature. J. Appl. Physiol. 12:169-176.

Uvnäs, B. 1960. Central cardiovascular control. In Handbook of Physiology, vol. 2, Neurophysiology, pp. 1131-1162. Williams and Wilkins, Baltimore.

Veghte, J. H. and P. Webb. 1957. Clothing and tolerance to heat. WADC Technical Report 57-759. Wright-Patterson AFB.

von Euler, C. 1961. Physiology and pharmacology of temperature regulation. Pharmacol. Rev. 13:361-398.

Wakefield, E. G. and W. W. Hall. 1927. Heat injuries. A preparatory study for experimental heat-stroke. J.A.M.A. 89:92-95.

Weir, J. B. De V. 1949. New methods for calculating metabolic rate with special reference to protein metabolism. J. Physiol. 109:1-9.

Whayne, T. F. 1951. History of heat trauma as a war experience, military medicine notes 2: Section 5. Problems of hot and cold climates, Army Medical Service Graduate School.

Winslow, C. E. A., A. P. Gagge and L. P. Herrington. 1940. Heat exchange and regulation in radiant environments above and below body temp. Am. J. Physiol. 131:79-92.

Winslow, C. E. A., L. P. Herrington and A. P. Gagge. 1936a. A new method of partitional calorimetry. Am. J. Physiol. 116:641-655.

Winslow, C. E. A., L. P. Herrington and A. P. Gagge. 1936b. The determination of radiation and convection exchanges by partitional calorimetry. Am. J. Physiol. 116:669-684.

Winslow, C. E. A., L. P. Herrington and A. P. Gagge. 1937. Physiological reactions of the human body to varying environmental temperatures. Am. J. Physiol. 120:1-22.

Winslow, C. E. A., L. P. Herrington and A. P. Gagge. 1938. The relative influence of radiation and convection upon the temperature regulation of the clothed body. Am. J. Physiol. 124:51-61.

Yaglou, C. P. and D. Minard. 1952. Human endurance to high levels of heat and humidity. Nav. Med. Res. Inst. Research Rept. Project X-205, Rept. No. 9, 9 July.

APPENDICES

APPENDIX I

SUMMARY OF INTERNAL BODY AND MEAN SKIN TEMPERATURES AND HEART RATES OF THE SUBJECTS INDICATED IN TABLE 7

(Note that the code letters A-H at the bottom of each figure, correspond with the respective subject indicated in Table 1.)

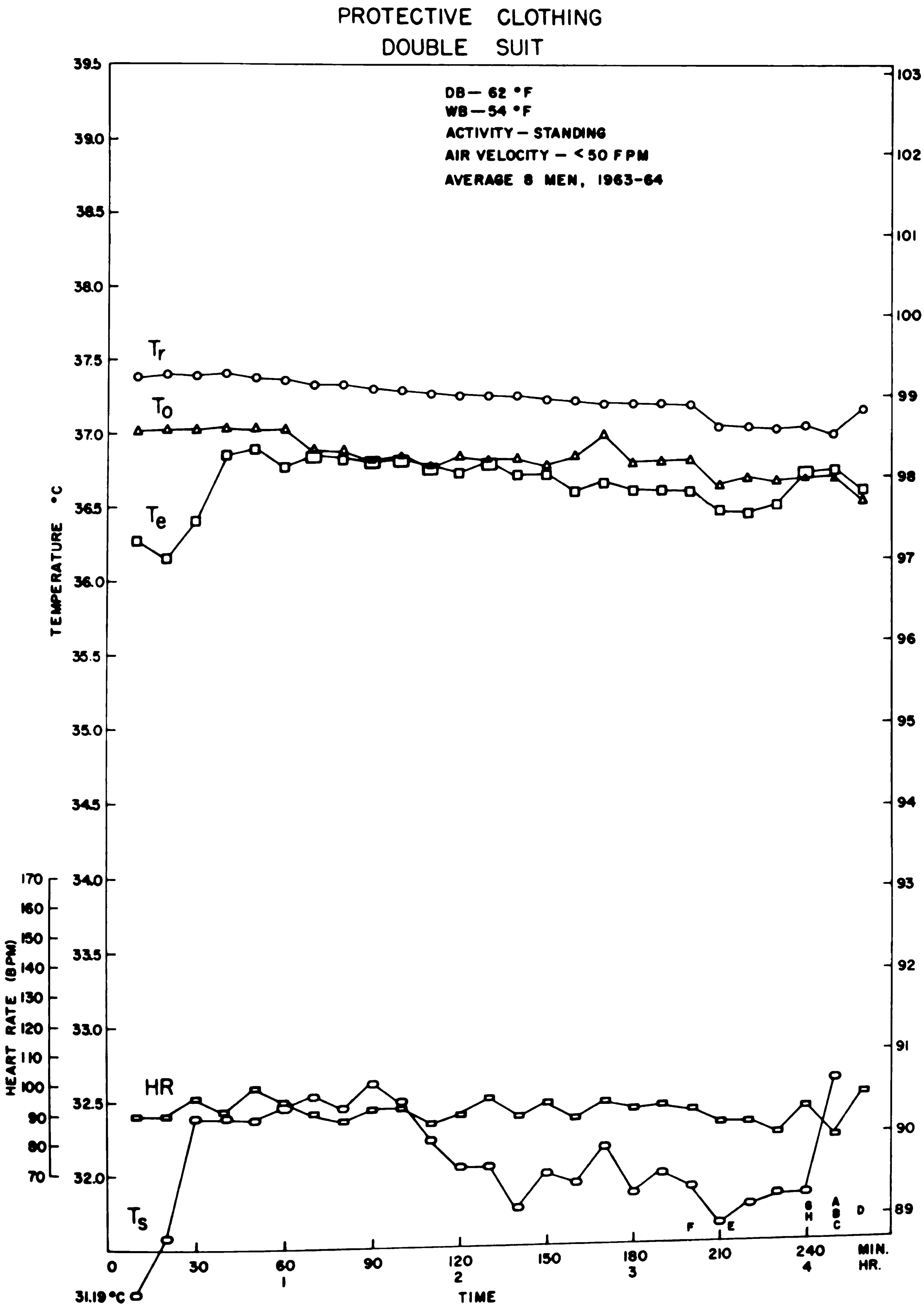

PROTECTIVE CLOTHING
DOUBLE SUIT
DB— 62 °F
WB—54 °F
ACTIVITY — STANDING
AIR VELOCITY — <50 FPM
AVERAGE 8 MEN, 1963-64
Tr
To
Te
HR
Ts
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
TIME
MIN.
HR.
31.19 °C
F
E
G H
A B C
D

Figure 1

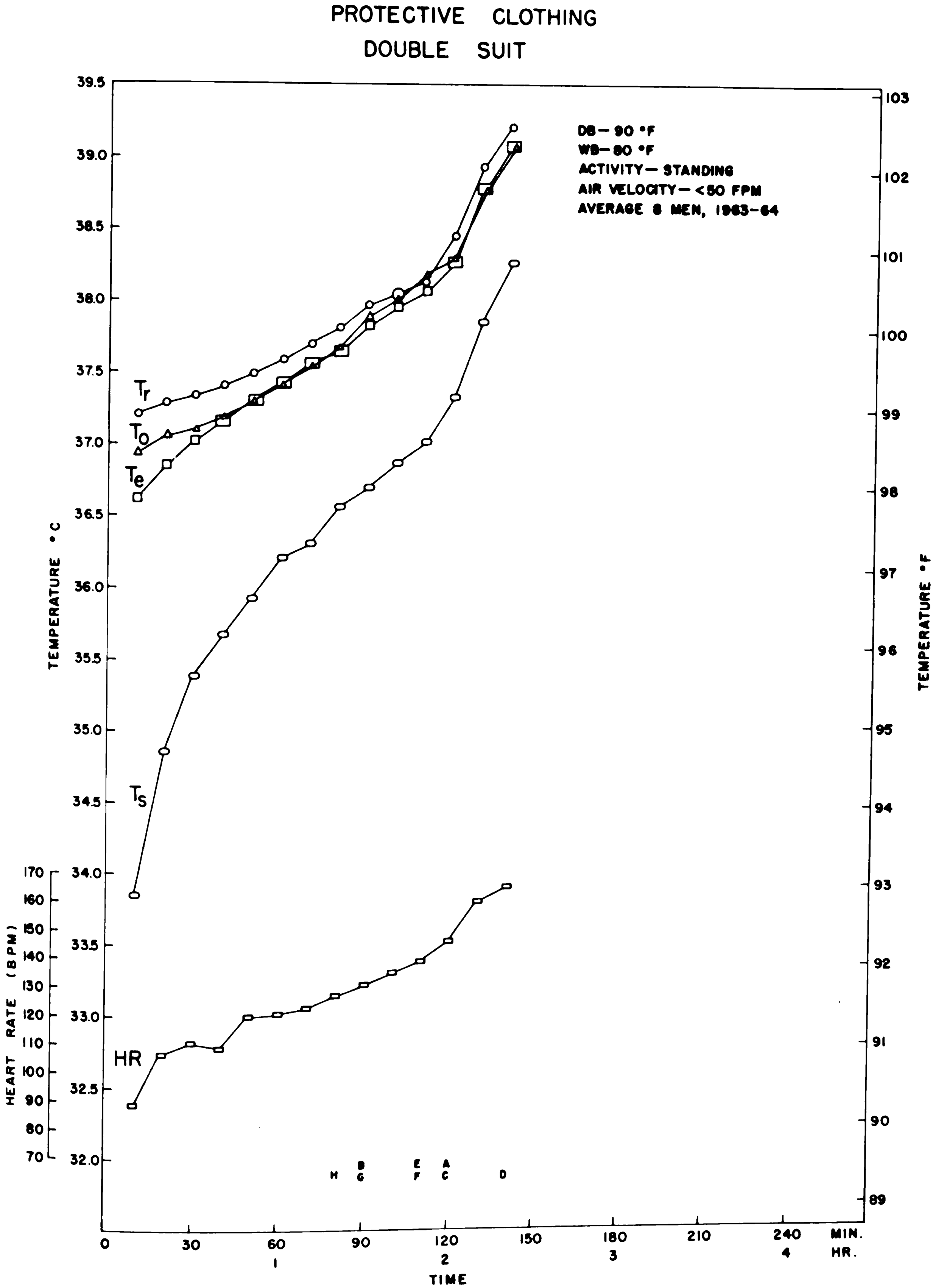

PROTECTIVE CLOTHING
DOUBLE SUIT
DB — 90 °F
WB — 80 °F
ACTIVITY — STANDING
AIR VELOCITY — <50 FPM
AVERAGE 8 MEN, 1963-64
Tr
To
Te
Ts
HR
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
TIME
MIN.
HR.

Figure 2

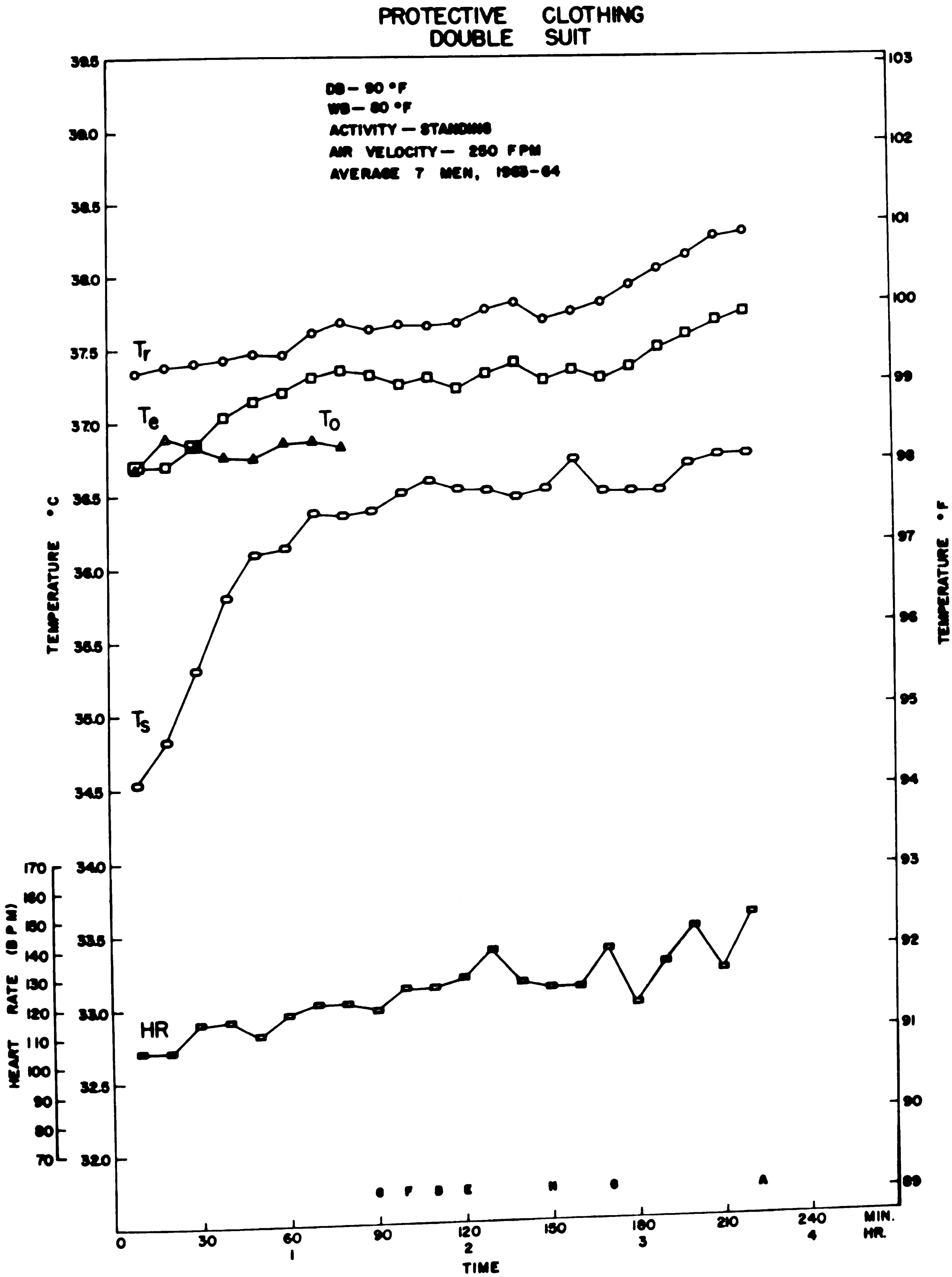
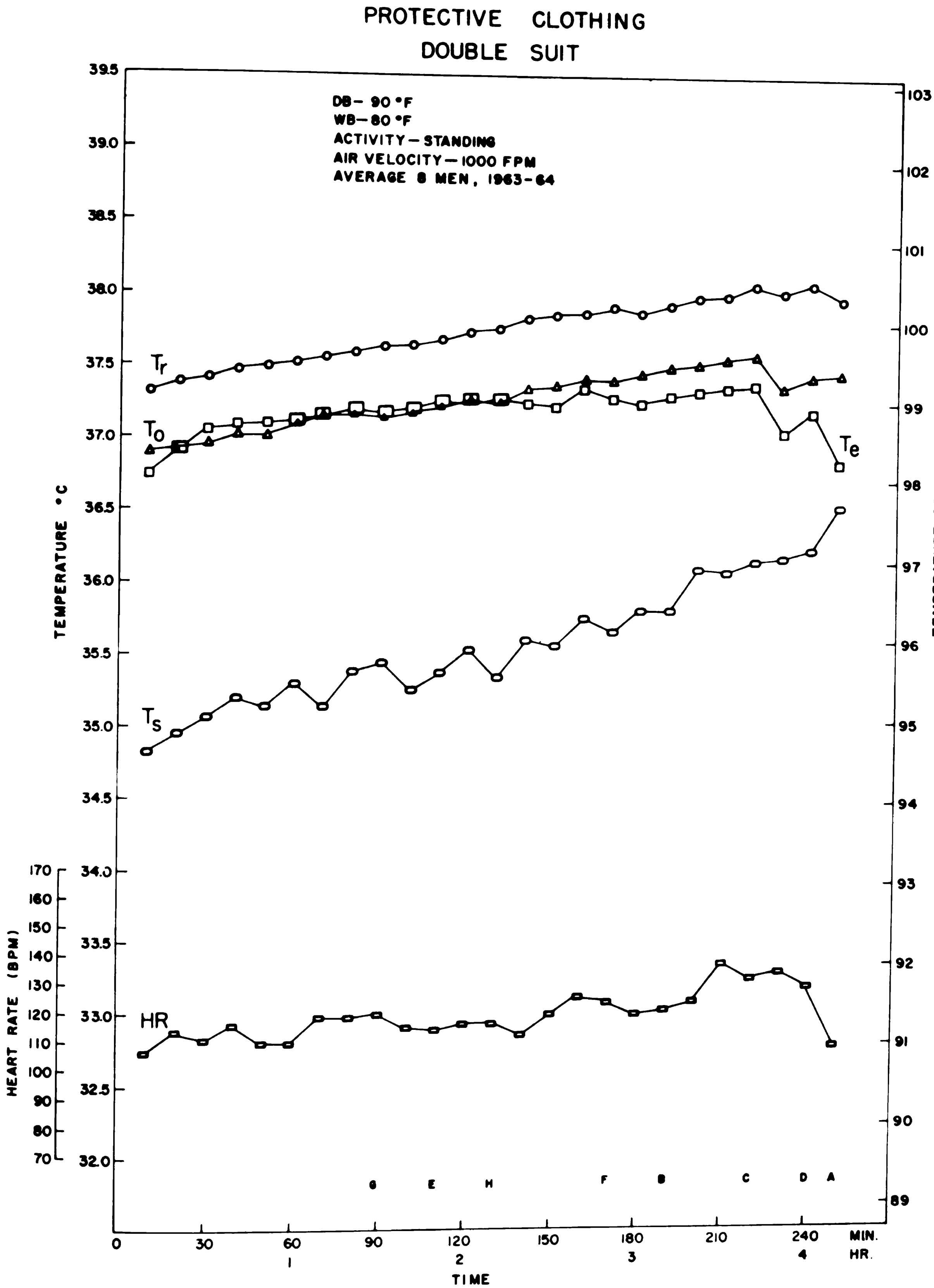
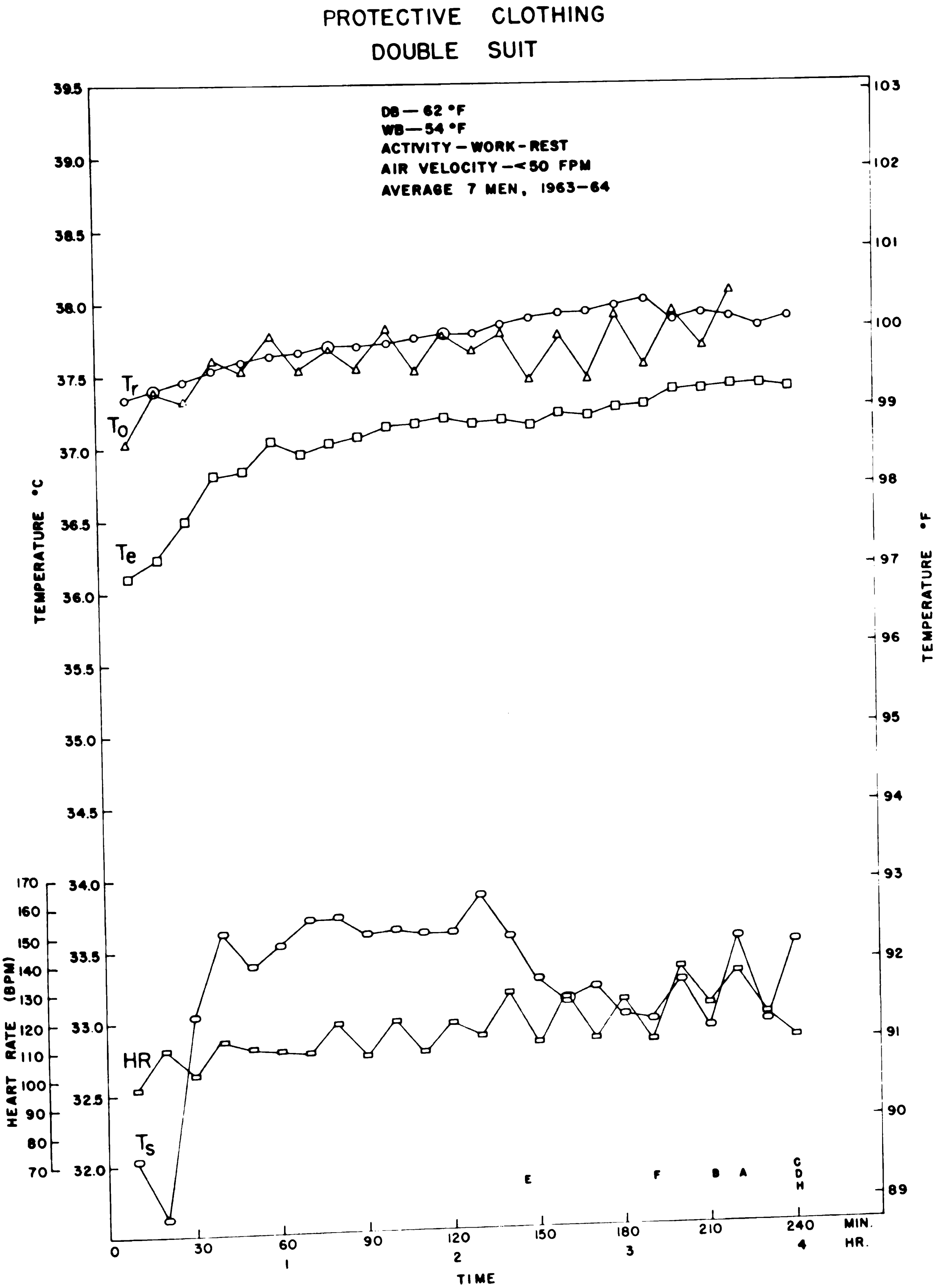

PROTECTIVE CLOTHING
DOUBLE SUIT
DB – 90 °F
WB – 80 °F
ACTIVITY — STANDING
AIR VELOCITY — 250 FPM
AVERAGE 7 MEN, 1963-64
Tr
Te
To
Ts
HR
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (B P M)
TIME
MIN.
HR.
0
30
60
90
120
150
180
210
240
1
2
3
4

Figure 3



PROTECTIVE CLOTHING
DOUBLE SUIT
DB- 90 °F
WB-80 °F
ACTIVITY-STANDING
AIR VELOCITY-1000 FPM
AVERAGE 8 MEN, 1963-64
Tr
To
Te
Ts
HR
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
170
160
150
140
130
120
110
100
90
80
70
G E H F B C D A
0 30 60 90 120 150 180 210 240 MIN.
1 2 3 4 HR.
TIME

Figure 4


PROTECTIVE CLOTHING
DOUBLE SUIT
DB — 62 °F
WB — 54 °F
ACTIVITY — WORK - REST
AIR VELOCITY — <50 FPM
AVERAGE 7 MEN, 1963-64
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
Tr
To
Te
HR
Ts
E
F
B
A
C
D
H
MIN.
HR.
TIME
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
170
160
150
140
130
120
110
100
90
80
70
103
102
101
100
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95
94
93
92
91
90
89
0
30
60
90
120
150
180
210
240
1
2
3
4

Figure 5

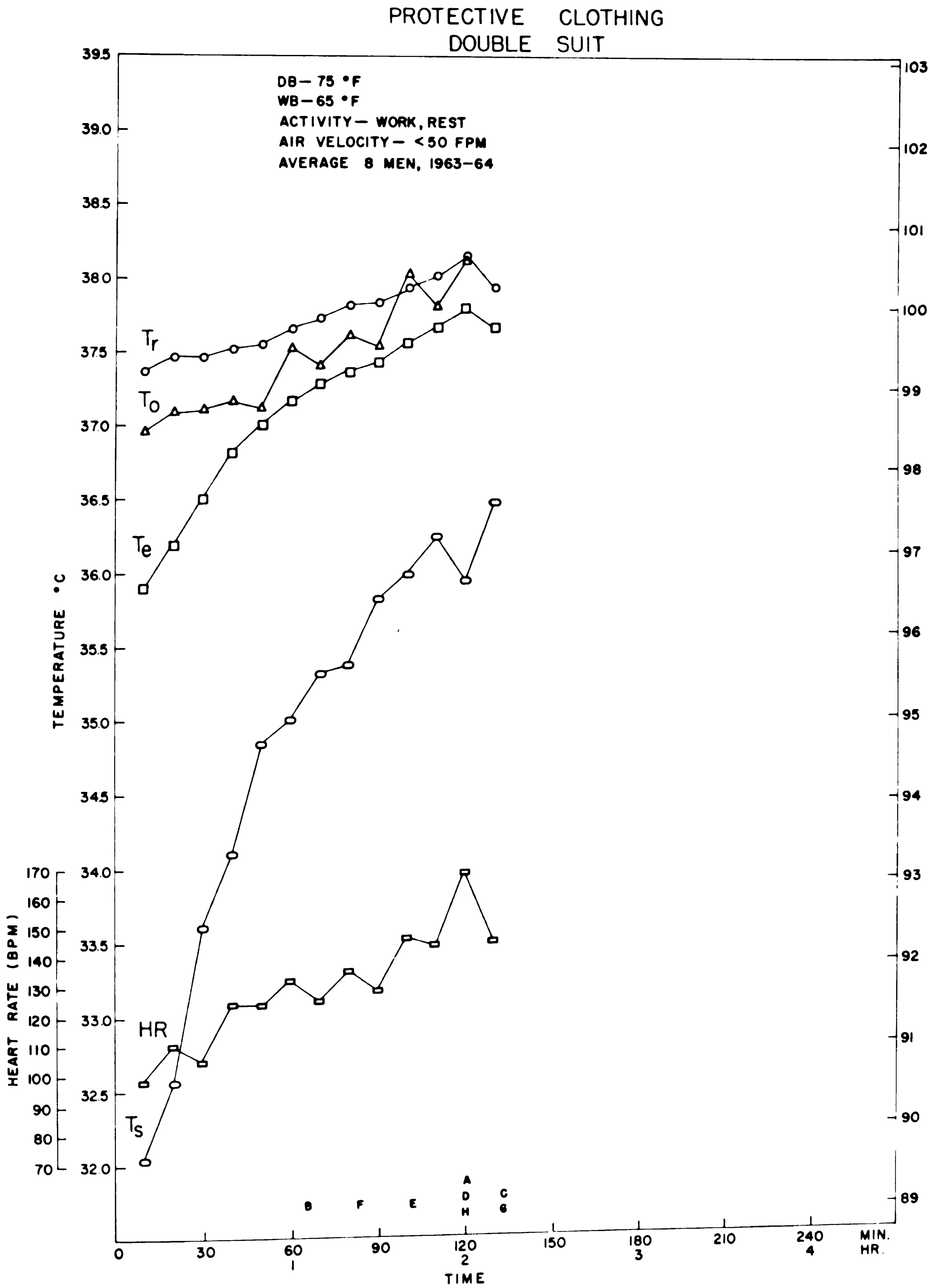

PROTECTIVE CLOTHING
DOUBLE SUIT
DB— 75 °F
WB—65 °F
ACTIVITY— WORK, REST
AIR VELOCITY— <50 FPM
AVERAGE 8 MEN, 1963-64
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
T_r
T_o
T_e
T_s
HR
TIME
MIN.
HR.
A
B
C
D
E
F
G
H

Figure 6

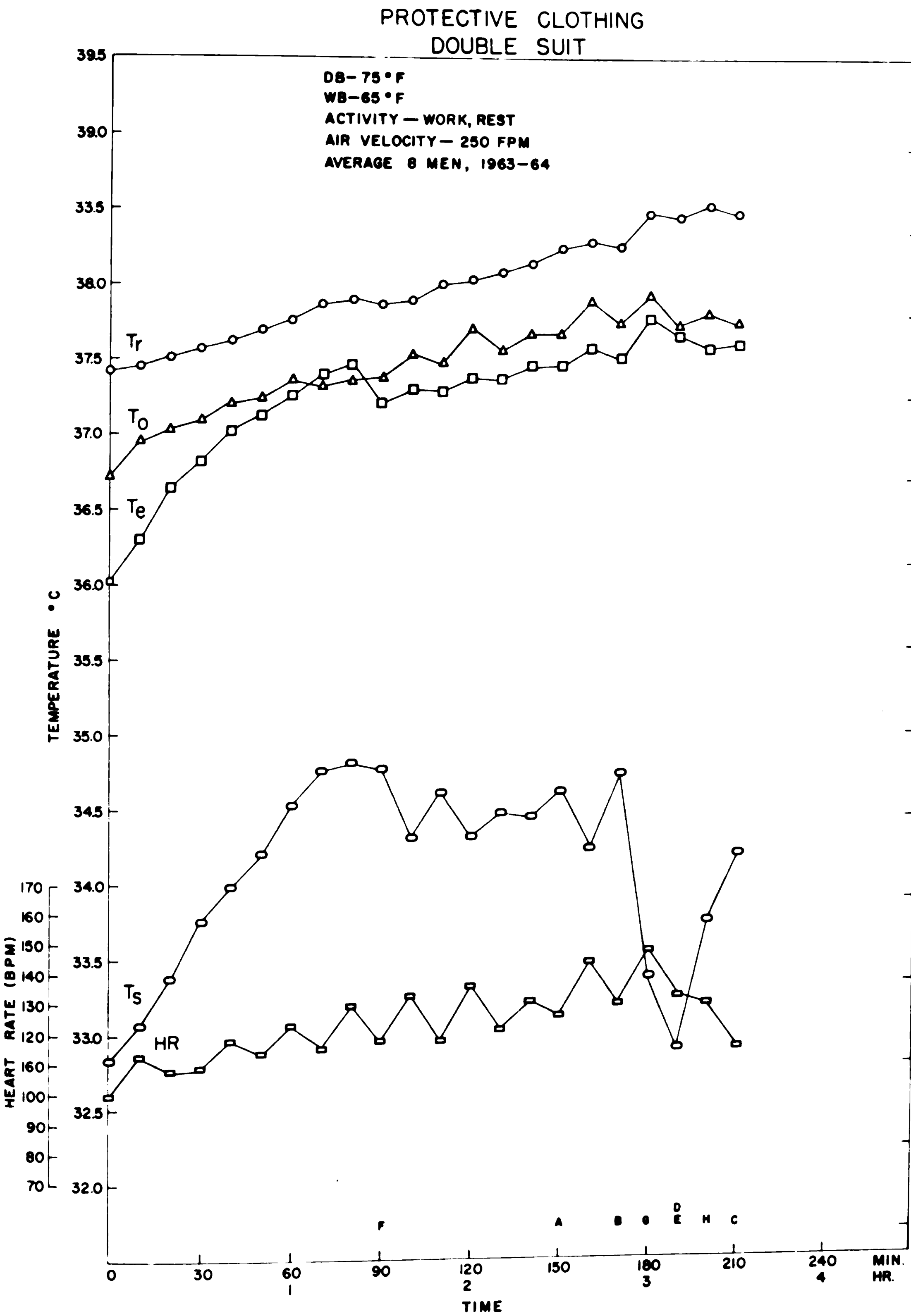

PROTECTIVE CLOTHING
DOUBLE SUIT
DB-75°F
WB-65°F
ACTIVITY — WORK, REST
AIR VELOCITY — 250 FPM
AVERAGE 8 MEN, 1963-64
Tr
To
Te
Ts
HR
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
TIME
MIN.
HR.
F
A
B
G
D
E
H
C

Figure 7

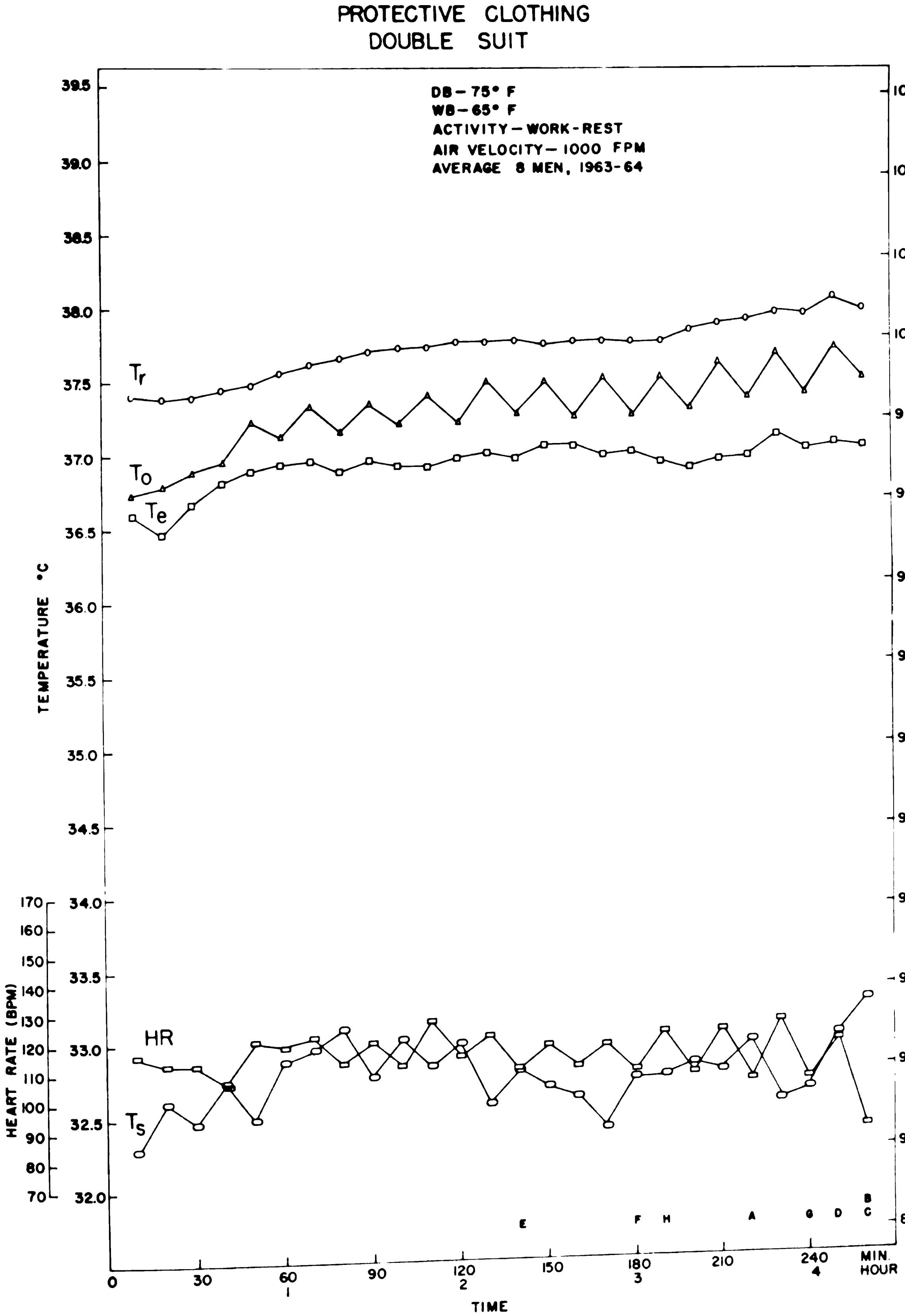

PROTECTIVE CLOTHING
DOUBLE SUIT
DB - 75° F
WB - 65° F
ACTIVITY - WORK - REST
AIR VELOCITY - 1000 FPM
AVERAGE 8 MEN, 1963-64
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
Tr
To
Te
HR
Ts
E
F
H
A
G
D
B
C
TIME
MIN.
HOUR
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
170
160
150
140
130
120
110
100
90
80
70
0
30
60
1
90
120
2
150
180
3
210
240
4

Figure 8

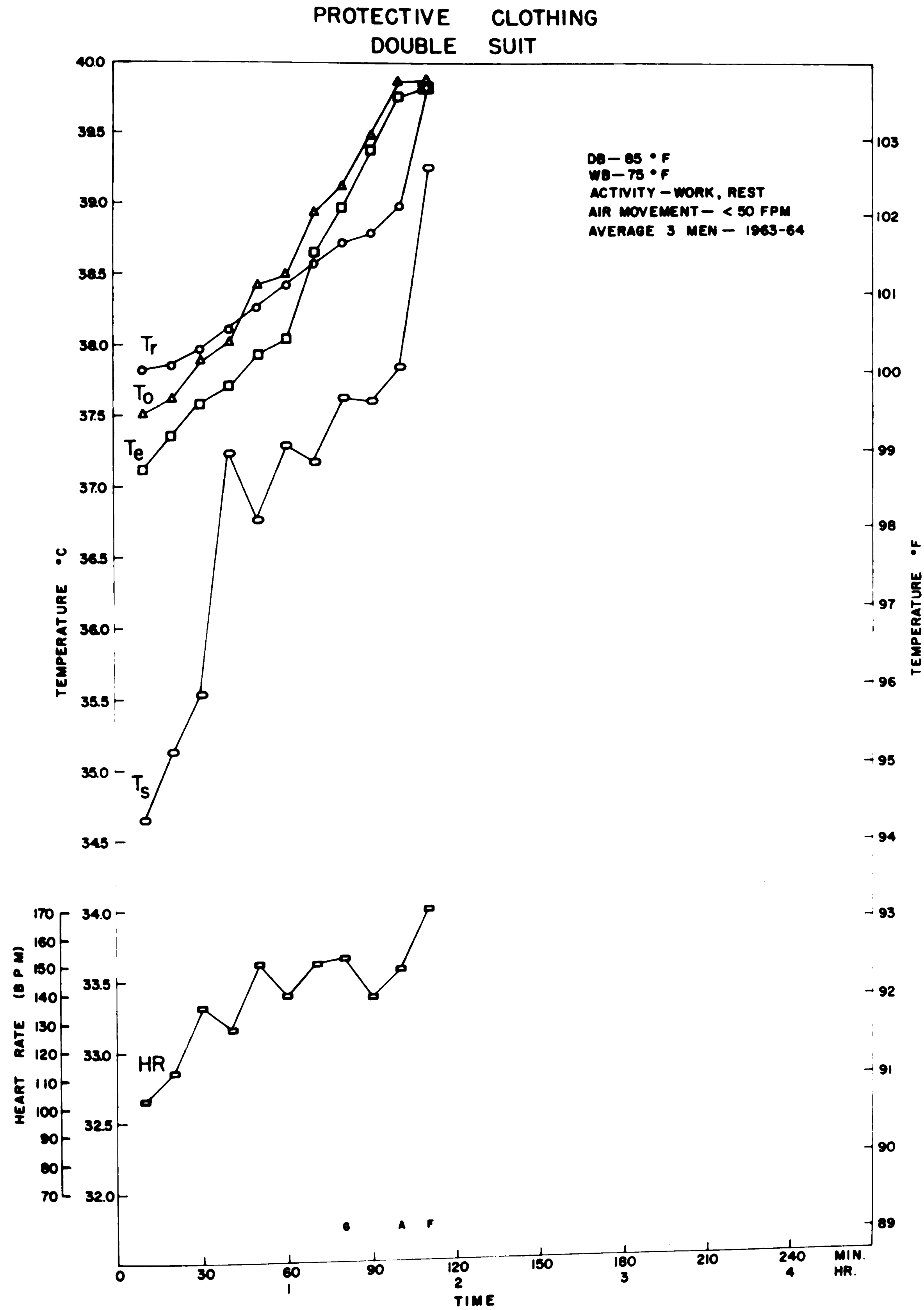
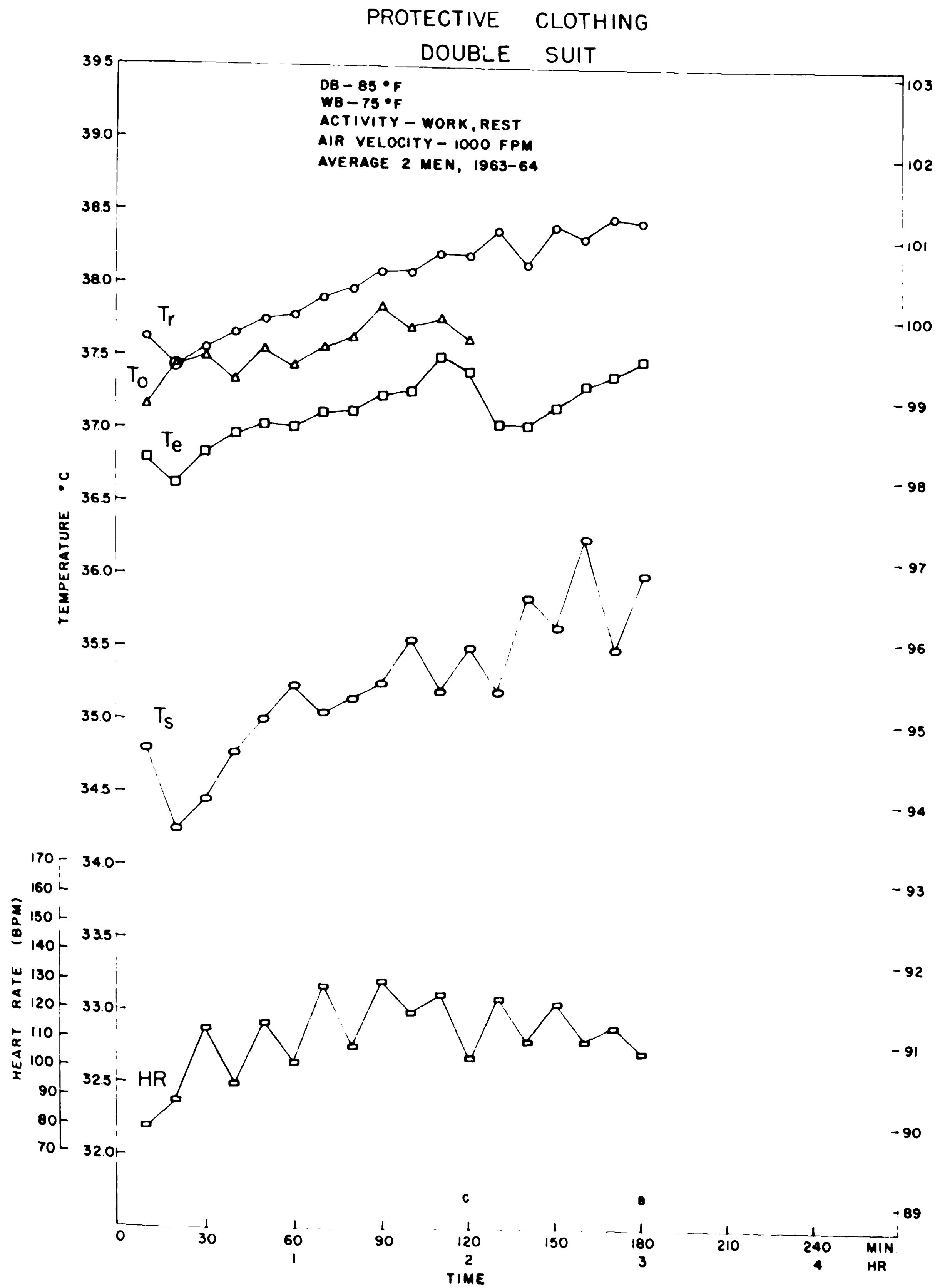

PROTECTIVE CLOTHING
DOUBLE SUIT
DB — 85 °F
WB — 75 °F
ACTIVITY — WORK, REST
AIR MOVEMENT — < 50 FPM
AVERAGE 3 MEN — 1963-64
Tr
To
Te
Ts
HR
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (B P M)
TIME
MIN.
HR.
G
A
F
40.0
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
170
160
150
140
130
120
110
100
90
80
70
0
30
60
90
120
150
180
210
240
1
2
3
4

Figure 9


PROTECTIVE CLOTHING
DOUBLE SUIT
DB - 85 °F
WB - 75 °F
ACTIVITY - WORK, REST
AIR VELOCITY - 1000 FPM
AVERAGE 2 MEN, 1963-64
Tr
To
Te
Ts
HR
TEMPERATURE °C
TEMPERATURE °F
HEART RATE (BPM)
39.5
39.0
38.5
38.0
37.5
37.0
36.5
36.0
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
103
102
101
100
99
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97
96
95
94
93
92
91
90
89
170
160
150
140
130
120
110
100
90
80
70
C
B
0
30
60
90
120
150
180
210
240
MIN
1
2
3
4
HR
TIME

Figure 10

APPENDIX II

STIMULUS PRESENTATION DEVICE

Stimulus Presentation Device

By

Mr. M. Eicher

Head, Medical Instrumentation Laboratory
Naval Medical Research Institute

An instrument was constructed to measure and record reactions of thermal stress subjects under varying temperature conditions, while the subjects were wearing BW/CW protective clothing being evaluated for the Bureau of Ships. The basic objective of the stimulus presentation device was established by Dunlap and Associates, Inc., who are experts in the field of assessing mental performance of subjects submitted to heat stress.

The stimulus selected was a reading on a standard three (03) inch panel meter. This stimulus remained in position on the meter for a fixed interval of time and then changed to another reading, proceeding through a random sequence of fifty (50) readings of twenty (20) different values, then repeating the cycle. The subject responded to the stimulus by depressing one (1) of twenty (20) buttons which correspond to the stimulus presented. A twenty-pen operations strip chart recorder indicated the stimulus presented as well as the button which was depressed in response to the stimulus. Figures 1, 2 and 3 illustrate the device and how a subject uses the device.

A rate of presentation of stimuli of 30 per minute was used for the testing procedure, although an optional slower rate of 15 per minute was available when needed for teaching a new subject. The reading of the panel meter, mounted at eye level (Fig. 1), represented a typical task required of shipboard personnel. The meter face was marked with twenty (20) numerical divisions, 0 to 4.0 in 0.2 increments. The meter needle read coincident with the divisions, requiring no interpolations or estimating. The twenty (20) response buttons were one inch in diameter with the numbers engraved on the faces of the buttons. They were arrayed on an 8" X 10 5/8" sloping panel in four (04) rows and five (05) columns. The numerical order was left to right, top to bottom, starting with 0 and ending with 3.8. In all tests the top of the meter was at a 10 per cent depression from a straight line (horizontal) sight of the subject, which minimized the physical strain of the subject.

The record obtained on the Esterline-Angus event recorder was twenty printed parallel lines each showing a deflection when its corresponding stimulus was presented (Fig. 2). At a paper speed of six (06) inches per minute, a two (02) second stimulus was 1/5 inch long. Depressing a response button caused its corresponding pen to deflect with a distinctive oscillating mark which was superimposed on the stimulus deflection for a "correct" response. In this way, correct and incorrect responses would be distinguished as well as response time relative to the time of the stimulus presentation. Also, this method immediately gave a permanent record of the test result, which could be summarized later.

Construction of the pulser and stepping switch is shown in Fig. 3 and a block diagram of the basic flow scheme is illustrated in Fig. 4. The indicating timed pulses were produced at fifteen (15) to thirty (30) per minute by a synchronous motor driven cam and switch. These pulses operated a six-level 10-position stepping switch. Five (05) levels were used with minor switch to transfer the signal to the succeeding level. This permitted fifty (50) stimulus presentations before the pattern was repeated.

Each of the stepping switch contacts operated one of twenty relays whose contacts passed a signal to the panel meter and also made the corresponding pen on the recorder deflect. Since there were only twenty (20) different stimuli, the stimuli were all presented twice and ten of them three times in the pattern of fifty.

Figure 1

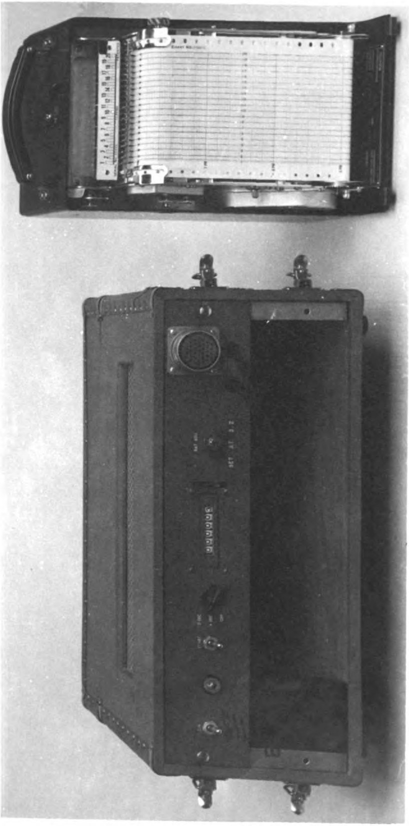

Figure 2

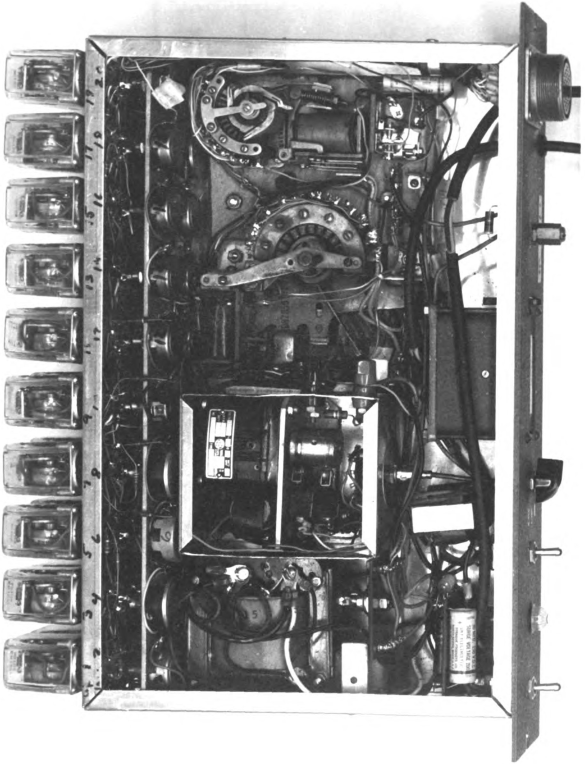

Figure 3

BASIC FLOW SCHEME FOR STIMULUS PRESENTATION DEVICE

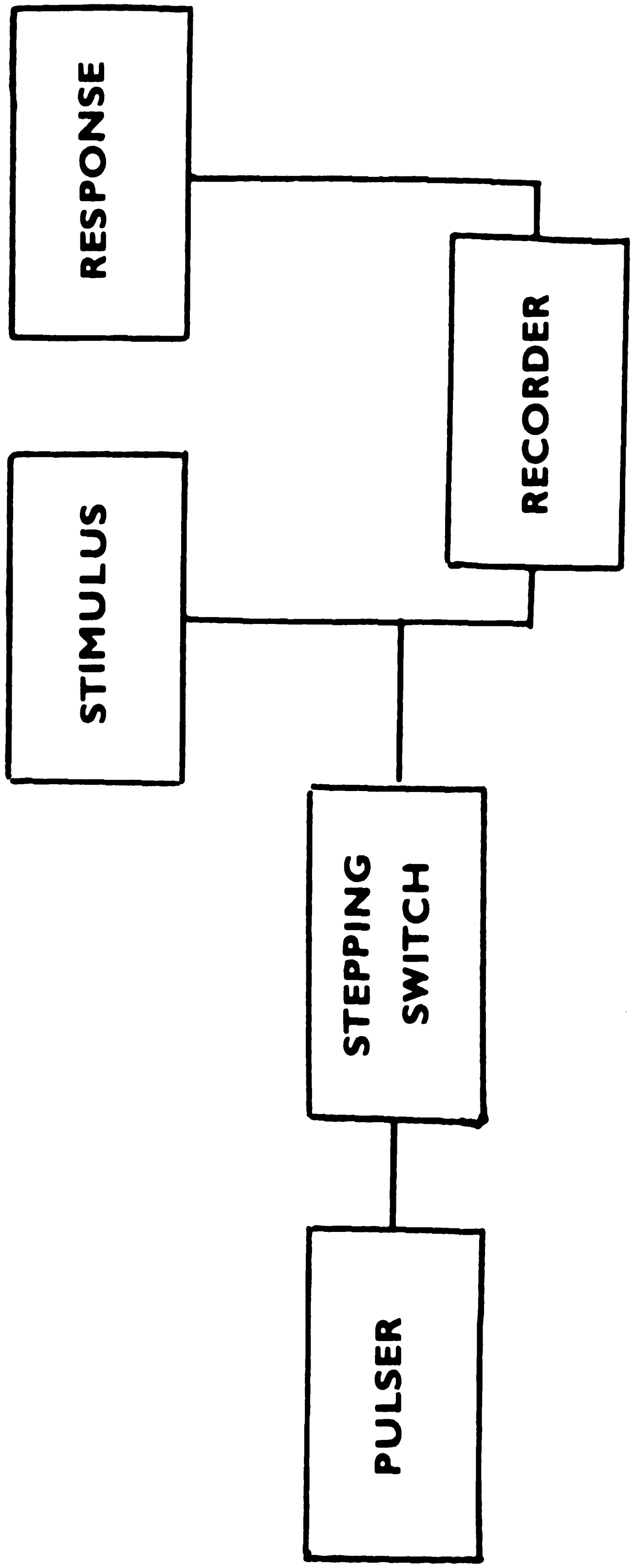

Figure 4

APPENDIX III

Conclusions From:

ACCURACY OF METER READING UNDER THERMAL STRESS INDUCED BY WEARING AN IMPERMEABLE PROTECTIVE SUIT

(Dunlap and Associates, Inc., Report DRD-64-109)
By Dr. R. D. Pepler

Conclusions

1. Subjects wearing an impermeable protective suit were generally able to maintain a reasonably high level of accuracy in reading the meter values under all conditions of work, ambient temperature and air movement.

2. Heat and work reduced the consistency with which the more motivated subjects read the meter accurately. These conditions appeared also to reduce the average levels of accuracy of the more motivated subjects, but these latter trends in performance were not statistically significant.

3. Increases in speed of air movement from 50 to 250 fpm and from 250 to 1000 fpm resulted in approximately equal improvements in the consistency with which the more motivated subjects read the meter accurately.

4. The more motivated subjects were almost as consistenly accurate at reading the meter under the most stressful set of conditions (stepping and standing at $85^{o}/75^{o}F$ with 50 fpm) as under the cool conditions of $62^{o}/54^{o}F$. This finding demonstrates that well motivated men wearing an impermeable suit are able to sustain a high degree of accuracy in reading a meter under conditions of severe thermal stress, even until the time the suit becomes intolerable and is removed.

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