A SYSTEMATIC STUDY OF THE HUMAN SWEAT RESPONSE TO ACTIVITY AND ENVIRONMENT IN THE COMPENSABLE ZONE OF THERMAL STRESS

by

W. V. Blockley

with the technical assistance of
J. F. Crocker and J. L. Annis

Prepared under Contract No. NAS 9-3356

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

N 66 20935

WEBB ASSOCIATES

Yellow Springs, Ohio and Malibu, California

SUMMARY

This research study explores the interrelationships between several physiological variables involved in thermal regulation and their effect on performance reserve, in environments varying from cool to oppressively warm. Three levels of activity and five temperatures for each activity level were selected to form a matrix of test conditions calculated to produce skin temperatures ranging from below 30 to above 36 degrees Centigrade. The vapor pressure of the test environments was kept below 15 mm Hg, that is, in the zone where skin temperature is essentially independent of humidity, and skin wettedness is distinctly less than 100%. Six healthy male subjects were studied, ranging in age from 25 to 37, and from 150 to 189 lbs in weight; they were not acclimatized to heat when the experiments began and the order of presentation of experimental conditions was designed to minimize acclimatization effects. At each activity level (nominally 100, 250, and 400 Kcal/hr metabolic rate), the five environments were selected to have a P4SR index of 0, 0.5, 1, 2, and 3.

The skin temperature at the sweating threshold is inversely proportional to metabolic rate. At rest, the threshold skin temperature ranged from 33.5 to 34.9°C; at a mild exercise level of approx. 250 Kcal/hr, the threshold ranged from 31.2 to 33.0. For the moderate exercise level, nominal metabolism 400 Kcal/hr, the inter-individual variation in threshold t_s was sharply increased; for five subjects the range was 26.5 to 30.8, but the sixth man had a threshold estimated to be 21.3°C or lower. The major element in this extreme discrepancy appears to be subcutaneous fat, as indicated by skin-fold thickness.

Sweat rate is a linear function of skin temperature at each metabolism. At low levels of activity, a slight change in t_s is associated with a large change in sweat rate; in high activity a larger increase in t_s was required to achieve the same increment in sweat rate for most subjects. An intensive analysis indicates that all the results can be explained in terms of a single common relationship between sweat rate and deep skin temperature. This latter parameter is computed from skin heat flow and thermal resistance of the most superficial layer of the skin, and is conceived to represent an integrated mean temperature of the blood in the skin. The threshold value of this parameter is approx. 35.5C for all subjects, and the sensitivity coefficient for sweating, or slope, is approx. 290 grams/hr, °C.

Large changes in the core-skin gradient occur above a P4SR of 1, suggesting that this may mark an upper level of desirability for sweating during activity. The cardiac cost of activity in this study was minimized through the use of intermittent work but there were strong signs of increased cost between P4SR 1 and 2.

The discussion includes an analysis of the problem of voluntary dehydration and its effects, the need for an index of physiological strain comparable to the P4SR stress index system, and the factors involved in measuring Performance Reserve.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

General Background

The maintenance of thermal equilibrium requires that all of the heat generated within the body by metabolism be delivered to the environment; the maintenance of "comfort" requires that delivery of this metabolic heat be achieved without significant loading of the physiological mechanisms available for thermal regulation. The general task undertaken in this study was to inquire what constitutes a significant loading.

Heat may be removed from the skin by convection to the surrounding fluid, by radiation to the surrounding surfaces or to space, by conduction to materials in contact with the skin, or by evaporation. Of all these, the last has, under most conditions, the greatest capacity for removing large quantities of heat at a rapid rate. So effective is this means for heat dissipation that it can compensate for a reversal in the direction of action of all the other modes of heat transfer (from their normal role of removing heat from the body) at the same time that it disposes of the internally generated metabolic heat.

This effectiveness of the sweat production system of the body, which is basically a consequence of the high value of the latent heat of vaporization of water, led to the adoption of sweat evaporation as the major element in the heat transfer system of all early ventilating garments, including those designed for space suits. Pioneering work at the I.A.M. at Farnborough (Ref. 1, 2, 3) showed that it was feasible to do a superior heat removal job for the seated man in a ventilated suit without relying on the sweating mechanism of the body, but the technique required extremely large quantities of very cold air, which is impractical in the context of space operations. Subsequently, the Farnborough group developed a second and more economical means of replacing evaporation for micro-climate control, the liquid cooling garment (Ref. 4) which has been adopted as the basis for current developments in space-suit heat transport systems.

The development of "ventilated suits", or thermal control garments, to use a more general term, both in England and the U.S.A., originated in the requirements of aircraft pilots, whose metabolic rates seldom exceed 150 Kcal/hour (600 Btu/hour). For these seated men, the virtue of eliminating the need to sweat was self-evident and needed no justification beyond the simple logic that thermal discomfort could interfere with the skilled performance of critical tasks.

In the space context we are dealing with potential metabolic rates up to the maximum capacity of the individual, when we consider extra-vehicular and lunar exploration tasks. Under such conditions of significant exercise and work, the value, or even the desirability, of eliminating sweating as a thermoregulatory response is much less obvious than in the case of resting man. (Indeed, we were unable to find in the literature unequivocal evidence that it is possible to eliminate the production of sweat at all levels of prolonged work.) One of the reasons for this uncertainty, of course, is the fact that under the normal conditions of temperate zone room temperatures where the vast bulk of the exercise research and the indoor real work is carried on, even moderate activity results in sweat production. The classical procedure, which has been followed by scientists and by industry efficiency experts alike, is to improve the conditions for removal of vapor from the skin so that the apparent wetness of the exposed skin areas is minimized. This usually entails removal of clothing, or increase in the velocity of air motion, or both. As we have discovered in the present study, to actually eliminate sweating altogether as a means of heat dissipation in a normal convective environment involves the use of air temperature which raises problems of cold discomfort as soon as the work is interrupted, or possibly even during the work.

A similar situation exists in the context of ordinary every-day outdoor work or exercise. In the Arctic, considerable skill and ingenuity is required to control (that is, to minimize) the production of sweat during periods of activity while simultaneously avoiding frostbite and preserving sufficient insulation capacity to conserve body heat during inactivity. Perhaps the bikini-clad skiers of Sun Valley press-agents' releases are the best examples of a nonsweating clothing-exercise-environment combination, though one of limited practicality as a fall into a snowbank will readily demonstrate.

Even if it should turn out to be true that the facts of every-day life make the elimination of sweating during work impractical in most earth-bound situations, it is nonetheless proper to question whether an artificially controlled microclimate such as the interior of a space suit should depend on or provide for sweat evaporation. In the event that some degree of sweat production is found to be a "natural" concomitant of physical work, it will remain to be determined what the upper limit of output should be for any particular level of activity. Such a determination presupposes the adoption of a set of criteria as to the acceptability of physiological strain evoked by thermal stress, whether of internal or external origin or both.

Problem Statement

The question which is central to this research is: "To what extent, if any, is there a penalty associated with the utilization of sweat production and evaporation to preserve thermal equilibrium during rest and long-term work?" Before attempting an answer to this question, the following points had to be established by means of a systematic examination of the interrelationships between metabolic heat production, skin and rectal temperature, and sweat output:

1) physiological threshold conditions for the initiation of sweating as a function of metabolic rate.

2) sensitivity of the sweating control system to increase in body temperature.

3) cardiac response to increased body temperatures associated with rise in sweat output and the consequent reduction in core-to-surface temperature gradient.

Underlying the overall plan of attack on these questions are the complications introduced into any thermal or exercise study by problems of individual variation and training factors. In the present case, the problems are doubled by the fact that both exercise and thermal stress are under simultaneous investigation; any material change in the characteristics of one of our subjects between the start and finish of a series of experiments could obscure the relationships we are seeking to uncover. As has been recently pointed out by Piwonka et al (Ref. 5), since these experiments were concluded, the process of exercise training in the absence of externally imposed heat can markedly improve the resistance to heat stress. On the other hand, even a single exposure to combined heat stress and work can make a big improvement in the response pattern of an individual to a subsequent exposure to similar conditions.

Rationale for the Experimental Design

The strategy which was adopted in the present work to counteract the effect of these factors was made up of three elements:

(a) The metabolic rates above the resting level were produced by intermittent work in which rest periods of 60 seconds duration were interspersed with work periods of 30 or 40 seconds length. This type of cyclic activity has been shown to minimize fatigue and lactic acid build-up, and it was reasoned that any training effect would complete its course most rapidly under these conditions.

(b) Subjects were exposed to the coolest environments at each activity level first, then to the second environment in each activity, and so on, so that the last experiment for each subject would be the most severe environment at the highest metabolism. This order of presentation is considered to have the lowest possible probability of heat acclimatization effects within the limitations of the time duration available for the study.

(c) As far as circumstances would permit, each subject was exposed to each of 15 combinations of activity level and environment, so that he served as his own control. Experiment duration was 3 hours in almost all cases to permit the attainment of a stable equilibrium. Environments were selected for each activity level which would cover the same range of physiological strain, so that the comparison of metabolic rates could be made at the same levels of sweat output. All these steps were taken with the aim of minimizing the scatter of the final data.

As has been indicated earlier, the eventual application of the conclusions from this study is expected to be in the improvement of space-suit thermal control systems. The design of these experiments was therefore focussed on body parameters rather than environmental ones, to facilitate cross reference. The most accessible body thermal parameter is the skin temperature, and it is a convenient reference point for comparing diverse thermal situations. As has been pointed out by Woodcock and Breckenridge (Ref. 8) and by Hatch (Ref. 9) in a slightly different context, the universe of environmental combinations in which a nude man can maintain equilibrium is divisible into two zones on the basis of humidity. Below some critical vapor pressure whose value varies with the temperature, wind velocity, and radiation conditions, further decreases in humidity have no detectable effect on mean skin temperature when air temperature is held constant, while above the dividing line, small increases in humidity causes large jumps in skin temperature.

Environments were selected for this study to fall as far below the critical vapor pressure line as was achievable in practice under the conditions of heavy sweat production which were planned for the most severe conditions at each activity level. In general, we were able to hold vapor pressure below 15 mm Hg. Several special experiments were made at high vapor pressures to explore in a preliminary way the effect of humidity on the response pattern at constant sweat output.

One explanation for the insensitivity of skin temperature to humidity when metabolism, radiation and convection are held constant is that the area covered by the sweat gland output increases in proportion to the reduction in potential vapor pressure gradient as ambient vapor pressure rises, so that the rate of evaporation remains unchanged and heat balance is maintained at the same surface temperature. Thus the term "wetted area fraction" introduced by Gagge in 1937 (Ref. 10) has been used to express the degree to which the effective vapor pressure over the total body surface approaches the theoretical maximum achievable at the same skin temperature. Gagge's "wetted area" can equally well be thought of as the "relative humidity" of the skin, as has been suggested by Woodcock and others.

A detailed analysis of the interaction between sweat production, heat transfer coefficients and skin temperature was made for the purpose of estimating the probable minimum value for "wetted area" or "skin relative humidity" which could be obtained under the experimental conditions of high sweat rate. This theoretical analysis demonstrated that it is not possible to achieve sweat rates of 750 grams/hour under reasonable air movement conditions without reaching wetted area levels of the order of 50 to 75%. This conclusion was in agreement with the calculations of Woodcock (Ref. 8) for a metabolic rate of 250 Kcal/hour and typical indoor conditions of heat transfer, which predict a skin humidity of 40% when sweating is slight and skin temperature a comfortable 33.5°C, and 55% when the environmental temperature is 45°C, corresponding to our most severe test environment for this level of activity.

Psychological Effects and Performance

One object of the study was to develop a measurement technique by which changes in the capacity for mental performance could be detected and quantified. It has been shown by Kalsbeek (Ref. 11) that when a person is required to perform a simple binary choice task perfectly, the pace which can be accepted is inversely proportional to the difficulty of a second task which is imposed simultaneously. For a relatively straightforward second task such as spontaneous written composition, the character of the output passes through successive changes, from creative to banal, to repetition of name and date, and the handwriting changes from normal to illegible, as the imposed pace of the primary binary choice task is increased toward the maximum which the subject is capable of when no secondary task is imposed.

I.D. Brown, at Cambridge, has used the dual task idea as a means of assessing the difficulty of a standardized automobile driving problem (Ref. 12). While his subjects drive along a planned route involving both city and country road conditions, they are presented with number-matching or mental arithmetic problems by means of tape recorder carried in the car. The score on this secondary task is taken as a reflection of the amount of effort or attention which the driving requires at any particular time.

Extension of these concepts to the realm of environmental stress and its influence on performance is based on the central idea of the "effort" required to perform a specific task. A task which is easy for one person may be hard for another, yet under most circumstances both will complete the task satisfactorily. It is one of the discouraging facts of behavioral research that, speaking very generally, the differences in the actual performance of most tasks between such individuals are subtle, unreliable or nonexistent. Analogously, in the same individual a set task may be easy when the environment is pleasant or comfortable, and very difficult or "demanding" when the environment is a stressful one. The literature is full of unsuccessful attempts to measure decrement in performance under the influence of excessive heat, cold, noise or other unpleasant environmental conditions. The subjective reports of individuals exposed to stressful environmental conditions support the assumption that the relative effort required to achieve the customary level of performance (whether it be in terms of quality, quantity, accuracy or variability) is greatly increased in the presence of environmental stress.

In a study of the effects of extreme heat on the ability of pilots to maintain proficiency in flying a precise 4-minute pattern "on instruments" in a modified electro-mechanical Link Trainer, Blockley and Lyman (Ref. 13) demonstrated that performance remained unaffected until about three-quarters of the endurance time ("time to incipient collapse") had elapsed and symptoms of heat exhaustion were beginning to be noticed. Once deterioration had begun, the number of errors seemed to multiply and grow exponentially until the men were removed from the heat on the point of collapse, whereupon recovery was rapid. This picture was believed to fit the concept of an increasing effort and determination to meet the criteria of perfection which had been set up for the test flight problem, culminating in an essentially abrupt collapse of capability when the maximum capacity for effort ("channel capacity", in information theory terminology) was reached. Stated in another way, it appeared that a reserve of capacity for performing under stress was progressively dipped into as the physiological strain induced by the severe external heat load grew larger and larger; when the reserve was used up, the outward performance began to deteriorate, and the deterioration then compounded itself until the physiological collapse point was reached.

Reasoning that such a borrowing from a reserve capacity for performance might be a common feature of all stressful heat exposures and not uniquely associated with storage-limited exposures to non-compensable heat, a way was sought of measuring the magnitude of the performance reserve during work under warm conditions.

It was decided early in the pre-contract planning stages of the investigation that the binary choice task of Kalsbeek, with an auditory stimulus and a manual or pedal response, would be used as the primary task. This task has the following desirable attributes; simplicity, involves decision-making, minimal training or practice effects, simple score, requires continuous attention, amenable to wireless remote actuation during work, universally applicable (field, laboratory, vehicle or simulator). The potential for direct comparison of results with the original studies of "spare mental capacity" was a further attraction.

A special study was initiated to help decide on the design of a secondary task. In reviewing the whole subject of reserve capacity measurement, Brown (Ref. 14) presents impressive arguments in favor of using the second task as a subsidiary measuring task, with no errors being permitted on the primary task. In this approach, the combined "perceptual load" (corresponding to the difficulty or effort required) must be greater than the "channel capacity" of the individual, so that errors are inevitable on the subsidiary task. Under these conditions, a change in the reserve capacity for performance is measured by the change in error score on the subsidiary task. The performance reserve which is measured indirectly by this procedure is that which would exist if no second subsidiary task were imposed -- that is, it represents the additional capacity for performance after the demands of the primary task have been met.

It had been our original intention to make some preliminary explorations of the sensitivity to heat stress of several candidate subsidiary tasks before deciding on the detailed technique to be used in the main matrix of experimental heat exposures. When budget and time restrictions made it apparent that there would be no time for such experimentation with alternative methods, a selection was made on the a priori grounds that the peripheral light detection test as used by Bursill was one of the few procedures reported in the literature to show a clearcut decrement under long-term moderate heat exposure. Bursill (Ref. 15) was satisfied that the increase in the number of missed light signals in his experiments was due to "alterations in the central level of attention, and not to local alterations in the eye". Further evidence that the effect was related to overall channel capacity and performance reserve considerations was provided in the fact that <u>no</u> deterioration in detection of peripheral lights occurred when the primary pursuit meter task (which his subjects were performing simultaneously) was reduced in difficulty by a factor of 55 to 35 (perturbations per minute in the target pointer).

Having made the decision to use the detection by peripheral vision of lights placed at three angular displacements on either side of the fixation point, an apparatus was designed and constructed which would permit presentation of these signals in a randomized pattern with respect to time of occurrence and location. Provisions were made for varying at will the pattern of signal presentation, the duration of each signal and for selection of either self-paced or driven pace modes of operation. Performance on the task may be scored either by means of an event recorder which compares signals and responses for each angular location, or by a bank of counters accumulating mined signals at each location. Timing clocks could be added to accumulate the response delay for each light location.

Because of the limitation on time, the necessity of meeting the schedule for completion of the matrix of 90 3-hour experiments, and the desire of the sponsor to include performance reserve measurement in all experiments of the series carried out at low wind velocities, it was not possible to optimize the detailed protocol of the subsidiary task of peripheral light detection. In consequence, the results obtained do not provide a clear-cut and unequivocal picture of performance reserve changes with increasing physiological strain. It will be appreciated that to have discovered the deficiency in the protocol earlier it would have been necessary either to violate the ground rules described earlier for the avoidance of heat acclimatization effects, or to have introduced additional subjects who were not used in the main matrix of experiments. Neither action was feasible under the strict limitations imposed on the project.

When it became apparent that significant changes in the task performance were not likely to be observed with the standard test procedure of the peripheral light task, a new task was introduced as a possible replacement for the subsidiary measuring task.

The new secondary task consisted of simple subtractions of two 2-digit numbers, performed with pencil and paper while maintaining a perfect (or near-perfect) score on the binary choice audio task, (using the non-dominant hand for the manual button-pressing response).

In a later section of this report a discussion is presented of some of the factors influencing the sensitivity and suitability of an experimental task for the purpose of detecting alterations in performance reserve due to environmental stress.

Significance and Relevance of This Work

The primary application of the results of this study will undoubtedly be to the problems of designing effective, economical and safe thermal transport systems for wear by astronauts who may be called upon to perform work over extended periods.

This study should provide insight as to the consequences of adopting mainly convective heat transport as compared with mainly conductive systems (liquid in tubes), and help to establish the minimum capacity for evaporative transfer which mainly conductive systems should have.

In addition to these immediate and practical uses, the results and their discussion constitute a substantial contribution to the understanding of the human thermo-regulatory process. In the controversy which has been raging for the past several years between proponents of the central regulation theory (in which paramount importance is attached to what Wyndham calls the "ear-hole temperature") and those who are convinced that peripherally located sensors bear the primary responsibility for regulating the heat-dissipation mechanisms, there has been a crying need for a systematic body of data on normal men in normal surroundings doing normal work. The nearest approach to meeting this need was made by the data of Robinson et al (Ref. 25), only isolated portions of which have been published, piece-meal, over the past 20 years. The portions which are generally accessible do not include data for mild or comfort-level thermal conditions; the number and identity of subjects varies from one test environment to another, and the state of acclimatization of each subject in any particular experiment is uncertain on the basis of the published information, but appears to have been relatively high in at least some instances.

The work of Benzinger, originally published in 1959, and reinterpreted in a series of subsequent publication (Ref. 36) deals with a very specialized laboratory situation in which a supine subject, lying in a closely confining calorimeter,performed arm and leg work in a unique manner. The significance of the reported results has been debated with great intensity since their publication; most of the human studies which have been undertaken to test the theory advanced by Benzinger in 1959 have failed to yield corroborating data. The originator of the theory has not published any new experimental evidence based on human experiments, so that there has been no basis for the application to practical problems of the theory other than the authors interpretation of his own unique findings.

In the data produced by the present study, a substantial beginning has been made toward the accumulation of a body of systematic multi-parameter information which can be used to test many varieties of thermo-regulation theory, including ones which attempt to explain the basis of individual differences and the mechanisms involved in training and acclimatization. In the long run, this use of the data may turn out to be of greater significance than its immediate use in the guidance of space suit system design.

SECTION I

METHODS AND EXPERIMENTAL CONDITIONS

Environment Selection

In order to use the P4SR index system of equivalence in environmental stress as the basis for selecting experimental environments, it was necessary to develop a series of graphic computation aids. The P4SR nomogram as originally published by McArdle et al (Ref. 16) and reviewed by MacPherson (Ref. 17) does not lend itself to this usage, nor does it permit the quick comparison of environment-work-clothing combinations. The nomogram (Figure 1) has an extremely nonlinear scale, in which the least division is half a unit, or 12.5% of the range of nominally tolerable environments (P4SR values zero to 4). For estimating the stress index rating to be applied to a single particular combination of environment, metabolic load and clothing burden, this degree of precision is adequate, and protects the casual user from being misled as to the reliability of the estimate. For the purpose of constructing a matrix of environments in which the intervals between successive levels of stress are equal for each of three metabolism categories, it is imperative that interpolation to a repeatable precision of one-tenth of a unit (2.5% of the nominal range) be possible.

To achieve this, a tabulation of environment variables was made for each marked value on the B4SR scale of the nomogram between 0 and 4. These tables of dry-bulb or globe temperature versus adjusted wet bulb temperature, read directly from the nomogram, were used to generate a second group of tables, one for each metabolism, listing the combinations of air temperature and actual wet-bulb temperature which have P4SR index values of -0.25, 0, 0.5, 1, 1.5 and so on. Because the adjustment for metabolism greater than resting is a fractional quantity, the P4SR value for each of these sets of wet- and dry-bulb temperatures is an odd fractional quantity, though the interval between them remains one-half a P4SR unit.

When these sets of environments are plotted on a psychrometric chart, as in Figure 2, the result is a family of iso-stress contours. In Figure 2-D the effect of metabolism on P4SR is illustrated by direct comparison of the contours for P4SR 2 for the three activity levels used in this study. The critical feature of these P4SR contours for our present purpose is their tendency to follow a constant-temperature course as the vapor pressure of the environments become progressively lower. The vertical or humidity-independent, portion of each iso-stress contour corresponds to the constant

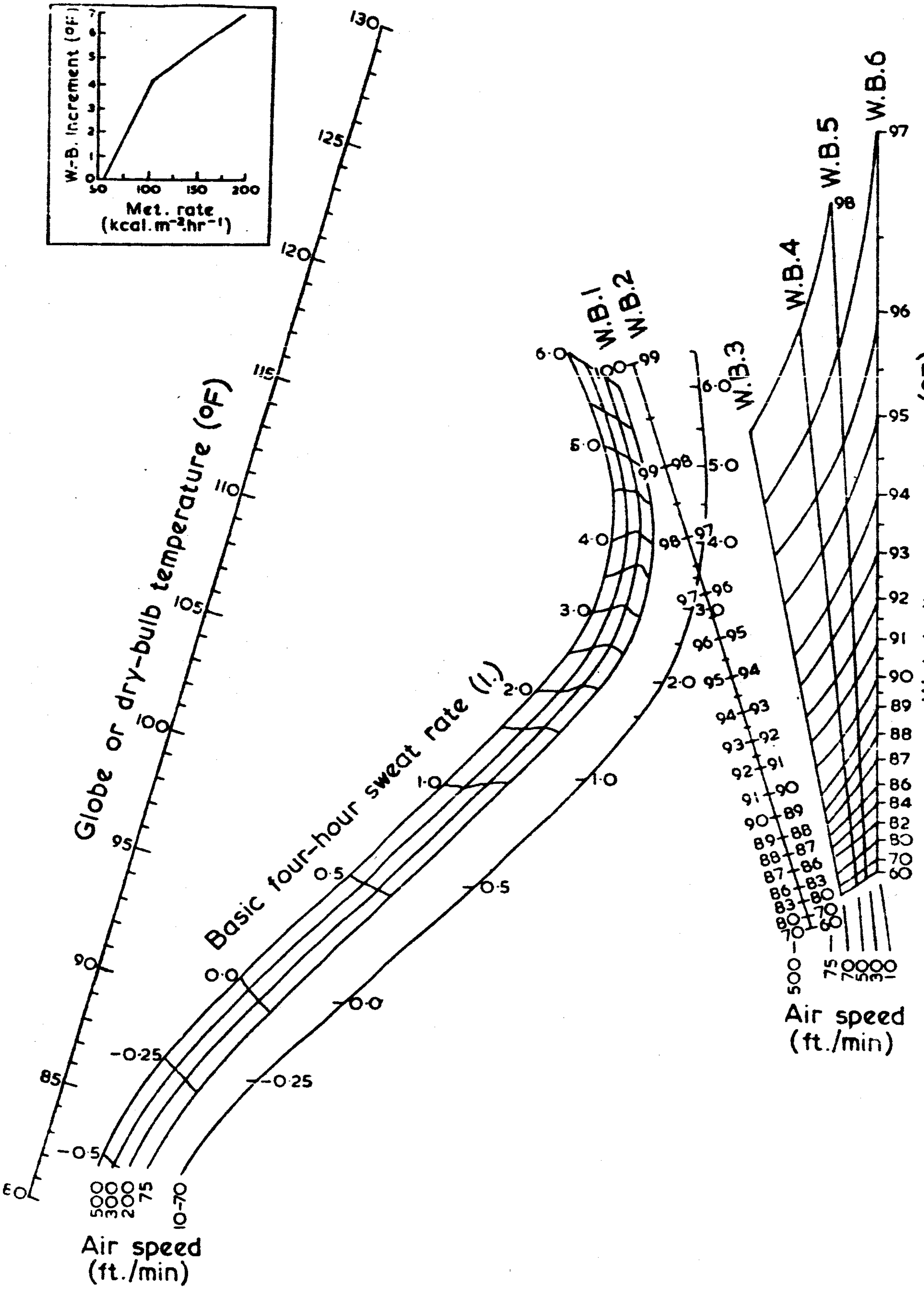


FIGURE 1: NOMOGRAM FOR THE CALCULATION OF THE P4SR. THE INSERT CHART GIVES THE INCREMENT TO BE ADDED TO THE WET-BULB TEMPERATURE FOR METABOLIC RATES BETWEEN 50 AND 200 KCAL. M^{-2}. HR^{-1}.

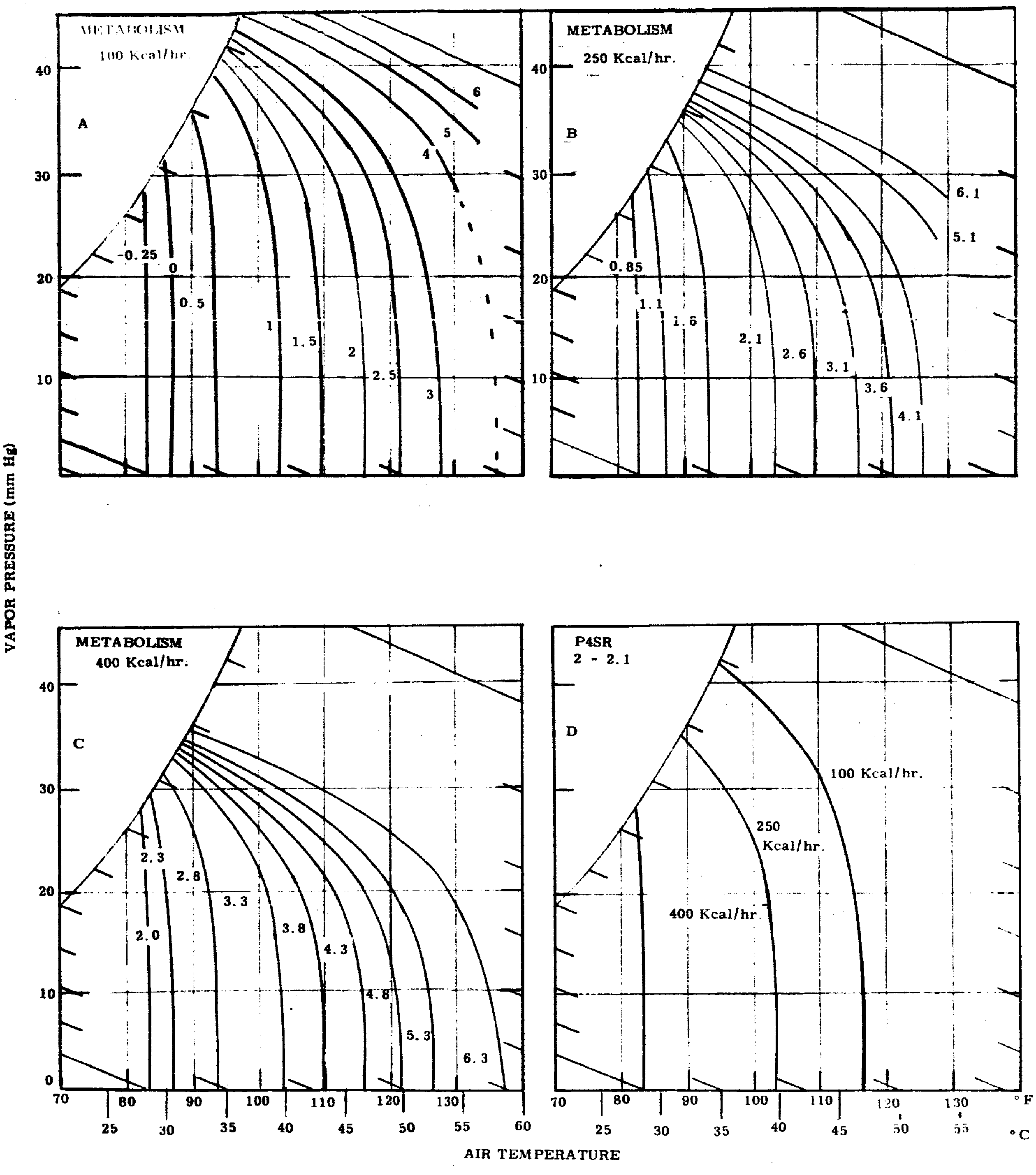


FIGURE 2: LINES OF EQUAL STRESS FOR 3 LEVELS OF ACTIVITY: PASR INDEX FOR MEN DRESSED IN SHORTS, WHEN WALL TEMPERATURE EQUALS AIR TEMPERATURE AND WIND VELOCITY EQUALS 75 FEET/MINUTE

skin temperature zone of Woodcock (Ref. 8) and represents the physiological condition where skin wettedness is substantially less than 100% (mean skin vapor pressure substantially less than the saturation value at mean skin temperature).

In accordance with the rationale discussed in the introduction section of this report, it was decided to select 10 mm Hg as the nominal vapor pressure of all the environments in the primary experiment matrix. Accordingly, a cross-plot was made of P4SR versus air temperature (wall temperature taken as equal to air temperature) by reading off from Figure 2 the points of intersection between P4SR contours and the 10 mm Hg grid line. Figure 3 shows the resulting chart for two levels of air movement. It will be noted that the difference between an air motion of 75 and 200 ft/min. is noticeable only at rest; the higher value is associated with a higher required air temperature to produce a given P4SR index, up to a maximum of 3 F degrees (1.66 C). The nonlinearities seen in Figure 3 are real, though unexplained, and reflect the essentially empirical basis of the P4SR index system, to which it owes much of its practical utility.

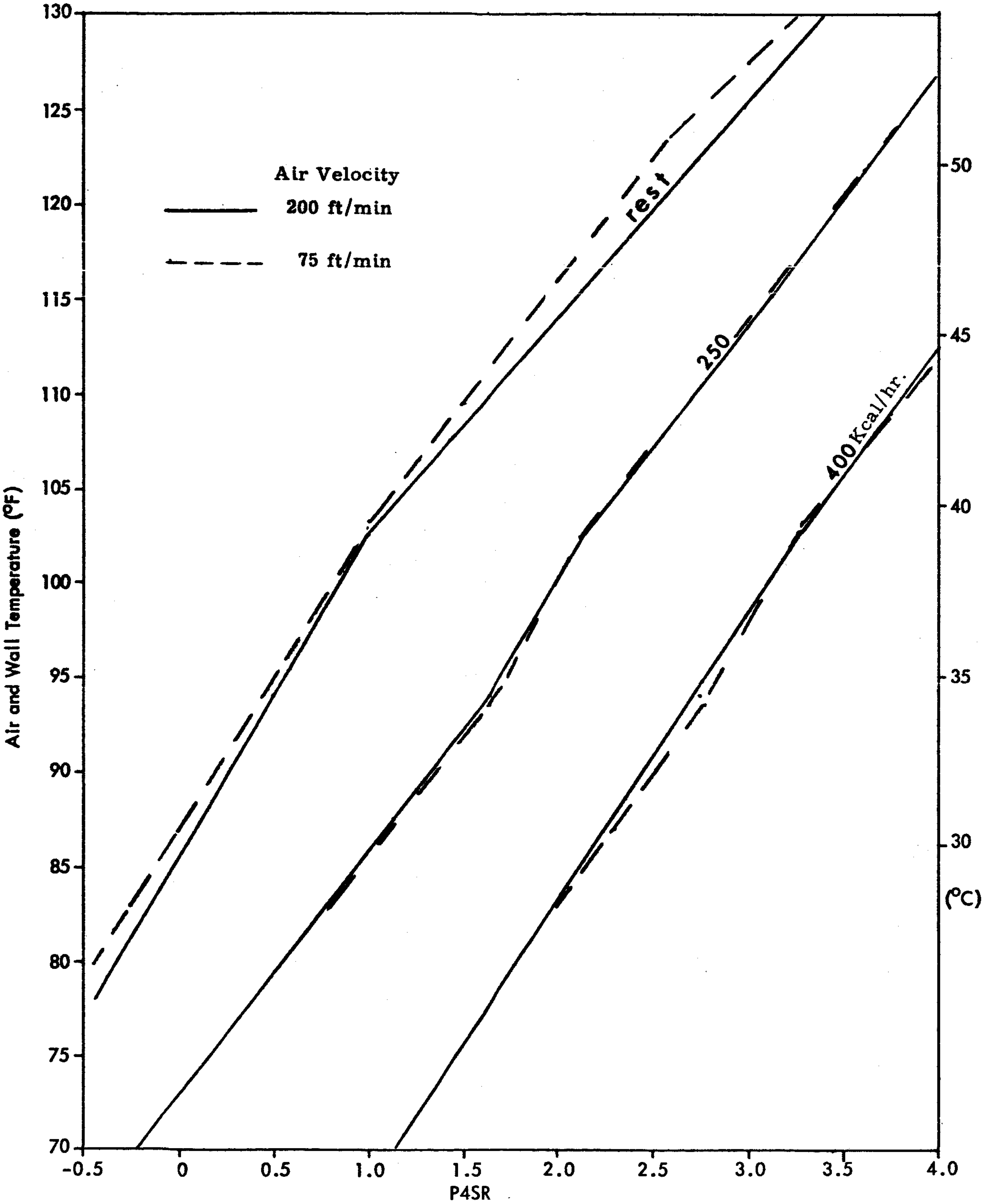
Reading off Figure 3 at even increments of P4SR, the set of nine environments shown in Table 1 was selected for the initial intensive exploration with two subjects. In an effort to achieve the lowest possible degree of skin wettedness, a wind velocity of approximately 200 ft/min. (1 m/sec) was adopted for this first series of experiments.

In the case of the higher metabolic rates, the environments yielding P4SR less than 1 and 2 (for 250 and 400 Kcal/hr respectively) had to be estimated by extrapolation, since the original B4SR nomogram does not extend to air temperatures lower than 80 F (26.6 C). It was intended that the lowest temperature for each metabolism should represent a definite nonsweating condition, and the second environment a very low evaporation requirement.

In addition to the environments listed in Table, 1, the following conditions were investigated once or more.

Air Temperature °C	Air Temperature °F	Vapor Pressure mm Hq	Metabolism Level Kcal/hr	Metabolism Level Btu/hr
11		4	400	1600
21		8	250	1000
29		11.5	100	400
36		28.5	250	1000
36		9.5	400	1600

Figure 3: P4SR at 10 mm Hg Vapor Pressure and Less
for 3 Activity Levels in Shorts



A nominal air velocity of 75 feet/minute (.38m/sec) was adopted for the second series of approximately 60 experiments in the interests of reducing the spread of individual skin temperatures and of more nearly simulating realistic convective environments likely to be encountered in practice. The corresponding air temperatures are shown in Table 1A.

Table 1

Air Temperature of Selected Environments in Series I

°Centigrade (°F)

P4SR Level	Metabolic Rate Level 400 (1600)		250 (1000)		100 (Kcal/hr) 400 (Btu/hr)	
-0.25	13	(55)	20	(68)	27	(81)
0.5	18	(64)	27	(81)	34.5	(94)
1.0	20	(68)	29	(84)	38	(100)
2.0	29	(84)	38	(100)	45.5	(114)
3.0	38	(100)	45.5	(114)	51.5	(125)

Table 1A

Environment Air Temperature in Series II*

P4SR	M=400 Kcal/hr		M=250 Kcal/hr		M=100Kcal/hr	
0	15	(59)	21.5	(71)	30	(86)
0.5	17	(62.5)	25.5	(68)	34	(93)
1	21.5	(61)	30	(86)	38.5	(101)
2	29.5	(85)	38	(100.5)	46.5	(116)
3	36.5	(98)	45	(113)	53.5	(128.5)

* These are the temperatures which, combined with a vapor pressure of 10 mm Hg and a wind speed of 75 ft/min, have the P4SR index values shown when the metabolic heat production is as indicated, the men are wearing only shorts, and air temperature is equal to wall temperature.

Selection of Work/Rest Schedules

The basic plan for the non-rest experiments called for alternating periods of work and rest with two men sharing the treadmill between them. Early experiments indicated that 30 seconds of climbing work followed by 60 seconds of standing still would produce a stable pattern of cardiac response at all but the most severe environmental conditions, and this was adopted as the standard routine for the second series of matrix experiments. Other work/rest patterns investigated during the first series were 30 sec/90 sec, 60 sec/90 sec, 40 sec/60 sec, 9 min/1 min and 29 min/1 min. The last two schedules represent essentially continuous work with occasional pauses for weighing only.

The choice of speed and grade of the treadmill for the "work" portion of the cycle was made initially for each subject by use of the Bobbert equation for predicting metabolic rate from clothed weight (Ref. 18). Final adjustment of the settings was accomplished as necessary on the basis of oxygen consumption measurements made by means of Douglas-bag collections of expired air.

A typical setting for the treadmill in a 30/60 work/rest schedule for a subject weighing 68 Kg (150 lbs) was 4 miles per hour (6.45 km/hr) and 15% grade. This routine had an average mean metabolic cost of 408 Kcal/hr (1632 Btu/hr); the same man marching continuously at 3.5 m.p.h. (5.63 Km/hr) and 3% grade had a metabolic rate of 440 Kcal/hr (1760 Btu/hr).

For the median activity level, nominally 250 Kcal/hr (1000 Btu/hr) the treadmill was usually operated at 3 m.p.h. (4.8 Km/hr) and 6% grade, with the same 30 sec work, 60 sec stand schedule. In the second series of matrix experiments, the highest metabolic rate was obtained with a speed of 4 m.p.h. and grades of from 10% for the heavy subjects early in the series to 14% for the lighter men toward the end of the program.

In general, the prediction made from the Bobbert equation was good when a metabolic cost of 120 Kcal/hr was assumed for standing still between work periods. It is of interest to note, however, that actual oxygen consumption is less during the 30 seconds of work, and more during the 60 seconds of rest, than in the steady state at the respective activity levels. This reflects the relatively slow time constant of the cardio-respiratory control system, and confirms that the fast, a-lactacid components of oxygen debt as described by Margaria (Ref. 19) is utilized in intermittent work regimes of this type.

Such regimes have the advantage of preventing or minimizing the build-up of lactate in the blood, delaying or minimizing fatigue, and providing frequent access to the subject for various purposes such as liquid ingestion, weighing, inspection of the skin, etc. In addition, the intermittent work protocol is more closely imitative of self-paced, unstructured activity than continuous marching would be.

Subject Selection and Evaluation

The selection of test subjects for physiological research obviously demands utilization of techniques and the establishment of requirements not usually evident in employment methods. In recruiting potential subjects for this experimental study, a formidable list of criteria had to be constructed. In order to meet the objective of a subject sample which would provide a reasonable match with a population of astronaut candidates, and insure relative freedom from artefacts of fatigue training, and the like, each man had to meet the following 14 criteria.

1. judged to be in excellent health by medical examination
2. presently possess a level of physical fitness indicating the ability to meet the physical requirements of the experimental program
3. be between the ages of 25 and 42 years
4. demonstrate coordination and timing in physical activity
5. not be presently heat acclimatized
6. have a history of participation in athletics and/or a degree of predilection for physical exertion
7. above average in general intelligence
8. absence of obvious deleterious factors in medical history (esp. where the thermo-regulatory system might be involved)
9. availability for the entire testing period
10. ability to work cooperatively with other people
11. demonstrate a personal interest and understanding of the objectives of the research (motivation)
12. willingness to comply with changes in personal living habits which are considered necessary by the experimentors to support the experiment objectives
13. satisfaction with the remuneration offered
14. willingness to cooperate with procedures required under the overall program.

Since a long training program, during which time the experimentors could get to know each subject was not planned, many of the above criteria which are difficult to quantify had to be determined at the time of the initial interview and examination. During the months of April and May (1965), some 24 persons were interviewed and tested as potential subjects. Senes 1 studies were performed during 1964 using our own technician-subjects, so that only 4 subjects were needed to complete the matrix of experiments. However, ultimately 6 subjects were utilized in this segment of the program with 2 of the subjects participating in only 2 experiments each.

The majority of interviewees were dropped from consideration due to age, or medical condition and fitness. One person, who was seriously considered, was dropped only after a series of "dry-run" training experiments showed he was physically unfit while another promising candidate was dismissed when the medical exam disclosed an enlarged spleen. Even through the 24 persons screened appears to be a sizeable sample from which to select the four subjects needed, we could only conclude that, given the program requirements, the recruitment of test subjects is a difficult matter. In our case the main prohibitive factor was perhaps the age requirement since men of the calibre desired are settled into responsible positions by age 27 and neither need nor wish to take on a temporary, yet demanding, job. For this reason appeal was made to the contribution each could make to space program and science rather than the usual motivational factors such as monetary reward and permanence of employment. Most of the subjects, of necessity, were employed in full time jobs outside and participated in the program because of a personal interest in the work. Only subjects were used after it was decided that their outside activity would not interfere with their performance in the testing. As stated above, two of the participants were, however, in our employ as technician-subjects. Another had gained subject experience in our laboratories under a previous contract.

For convenience, the personal information about the subjects has been compiled into Table 2, which also shows the period for each. The first two subjects on the chart are the experienced men utilized in the baseline experiments of series 1. Subjects R.M. and A.H. served to fill in the gaps created by the early drop-out subjects J.W. and D.J. Although R.M. was younger than the minimum age criterion, he was known to be mature in personality and stable in physiological characteristics, from previous experience.

Table 2

Personal Subject Information

Subject (Initial)	Age	Race	Marital Status	No. of Expts.	Dates of Expts. (from-to)	Usual Occupation	Comments
J.E.	28	Cauc.	S	27	10/15/64-4/27/65	Technician, Test Subject, Student	Smokes, wears contact lenses, sports in season, W.A. employee
B.P.	33	Neg.	M	8	11/24/64-1/19/65	Test Subject, Horse-trainer Maintenance	Smokes, races horses, sports in season, W.A. employee
R.M.	25	Cauc.	M	15	6/15/65-8/ 3/65	Graduate Student, Test Subject	Smokes, sports in season, part-time W.A. employee
B.C.	37	Cauc.	M	17	6/ 1/65-8/ 3/65	Data Processing Supervisor	Smokes, works nights, slight postural defect wears glasses
J.R.	31	Cauc.	S	16	6/ 8/65-8/12/65	Fireman-Rescue Elevator repairman, Import Sales	Nonsmoker, sports in season
A.H.	28	Cauc.	M	11	7/14/65-8/12/65	Data Processor Bomb Disposal Expert (military)	Smokes, asthmatic as youth
J.W.	27	Cauc.	M	3	6/18, 6/10 6/23/65	Press Operator	Smokes, works nights, boxer and wrestler
D.M.	27	Cauc.	M	2	7/ 1/65-7/ 7/65	Student, Recent College Graduate	Smokes, tennis

Physiometric Evaluation and Data

Physical Fitness and Associated Testing

The exercise physiologist have available several methods of estimating the general level of physical fitness in test subjects. Because of its simplicity and effectiveness, the Harvard Step Test was selected for use in the screening of subject candidates. This particular test has been used in the quantification of astronaut fitness levels. It was not necessary for the person in question to obtain a predetermined score in order to be considered, rather his performance was used to provide perspective in the overall evaluation of other aspects of the selection procedure. Subject B.C., for example, scored low on the Harvard; however, an evident high degree of personal motivation and competitiveness convinced us of his value as a test subject. Step Test scores are not available for subjects J.E., B.P., and R.M. due to the fact that our previous experience with these people precluded the necessity of assessing physical fitness at this time since the purpose here was to establish whether each person could, in our opinion, meet the physical demands of the experiments. Where any doubt existed as to the subject's ability to meet the anticipated experimental requirements, several multi-hour treadmill practice sessions were undertaken at the moderate work load.

Because of the importance in the experimental protocol of accurate timing and manual dexterity in the performance task, the coordination of the subjects was examined carefully. At the time of the initial interview, each applicant was observed for balance, timing and coordination both during the Harvard Step Test and during a short treadmill test. The length of time required for each man to adjust to smooth treadmill performance was noted. Most candidates were able to make the necessary adjustments for this new condition in approximately 1 minute. Changes in speed and/or grade of the treadmill in conjunction with accomplishments of assigned tasks such as operating valves and switches were then tried. Again, each man had to demonstrate rapid and effective adjustments to the new conditions.

Insofar as the subjects were available, maximum oxygen intake capacities (MOIC) were determined after the experiment matrix was completed. This test and the results will be discussed at the end of this section.

Anthropometric Data and Considerations

A complete set of anthropometric measurements was not taken; however, in addition to standard height and weight values, skinfold thickness measurements were obtained on the principal subjects. For convenience and clarity this information is given in chart form. This amount of data does not allow us to assign a Sheldonian somatotype classification number, but a general categorization seems reasonable. Table 3 therefore includes a general estimation of the position of the subjects on the ecto-meso-endomorphy scale of Sheldon. For comparison the original Rostan biotypologies are included.

A total of eight skinfold sites were selected for measurement. A Lange constant pressure (10 gm/mm^2) caliper was used. All measurements were made by the same investigator to reduce measurement errors in this notoriously irreproducible procedure. Site selection was based largely on the work of Brozek (Body Measurements and Human Nutrition, 1956) and Pascale, et al (Correlation Between Thickness of Skinfolds and Body Density in 88 Soldiers, Army Med. Nutr. Lab. Report, No. 162, 1955). Basically, it may be said that site selection is based on such factors as accessibility, precision with which the site can be identified and reproduced, relative homogeneity of the layer of subcutaneous fat in a given region, and the validity of skinfold measurements at specified sites as an index of total body fat. Taking into consideration all of these criteria, a clear-cut superiority cannot be claimed for any one site. Combining the work of Brozek and Pascale, at least three sites would appear to have some value in total body fat prediction. These three sites are the mid-triceps, subscapular and the mid-axillary at the level of the xiphoid process.

Without densitometric studies it is doubtful that a meaningful estimation of total body fat can be made from skinfold thickness measurements; however, as the data will indicate these measurements tend to correlate with the observed individual variations in thermoregulatory mechanisms as influenced by the insulatory properties of fat in the skin and subcutaneous tissue.

Table 4 presents the mean data together with an illustration of the sites of measurement.

Environment Measurement and Control

Conditioned air is introduced into the controlled-environment chamber through a porous ceiling, and is exhausted through the floor. Air temperature and wet-bulb temperature are independently controlled by means of a high-precision servo-controller utilizing thermistor sensors. A natural gas furnace is used for heating, with vapor-cycle refrigeration and steam injection for humidity control. This sytem can hold temperature to within $\pm 0.1^{\circ}C$ of the selected set-point, and vapor pressure to ± 1 mm Hg. Deviations of air temperatures from the desired value rarely exceeded $0.3^{\circ}C$.

Table 3:

Physiometrical & Somatological Information for the SWC Subjects

Subj.	Height		Weight		Surface Area (m^2)	Harvard Step-Test Score (PRE)	Average Skinfold Thickness mm.**	Estimation of Psycho-Biotypologies	
	In.	Cm.	Lbs.	Kg				Sheldon	Rostan
J. E.	67.75	172.1	149.5	67.9	1.80	--*	8.0	Ectomorphic mesomorph	Muscular
E. P.	68.75	174.6	168.0	76.4	1.90	--*	16.9	Endomorphic mesomorph	Muscular
R. M.	70.50	179.1	154.5	70.2	1.83	--*	7.5	Mesomorphic ectomorph	Muscular
B. C.	68.50	173.9	159.0	72.3	1.86	20	8.0	Ectomorphic endomorph	Cerebral
J. R.	70.25	178.4	176.7	80.3	1.97	51	12.0	Endomorphic mesomorph	Respiratory
A. H.	68.50	173.9	189.0	85.9	2.00	30	24.25	Moderate endomorph	Digestive
J. W.	69.50	176.5	180.2	81.9	1.97	31	--	Strong mesomorph	Muscular
D. M.	69.50	176.5	158.5	72.0	1.87	88	--	Mesomorphic ectomorph	Muscular
Range	67.75 - 70.50	172.1 - 179.1	149.5 - 189.0	67.9 - 85.9	1.80 - 2.00	20 - 88	7.5 - 24.25		
S. D.	(2.75)	(7)	(48.5)	(18.0)	(0.02)	(68)	(16.75)		

*Not obtained for these subjects due to recent test subject experience

**Average of eight measurements, used here only for comparative purposes

Table 4

Skinfold Measurement (millimeters)

		1	2	3	4	5	6	7	8	Av.
SITE		R. mid-bicep	L. lat. umbilicus	R. subscapular	R. mid-axillary costal	L. chest, pectoral	R. iliac crest	R. mid-triceps	L. sup. patella	
SUBJECTS	J.E.	3	8	12	11	4	12	7	7	8
	B.P.	5	24	18	29	9	22	8	12	16
	B.C.	3	8	10	13	4	13	6	7	8
	A.H.	12	29	29	37	18	30	27	12	24
	J.R.	4	18	11	22	5	16	11	9	12
	R.M.	4	9	10	9	4	11	7	6	7.5

Maintenance of low humidity, in the face of a heavy evaporation load from the two subjects, was occasionally limited during these experiments when the outside air vapor pressure rose above 15 mm Hg. Several increases in refrigeration capacity ameliorated but did not completely eliminate this difficulty.

Physiological Measurements

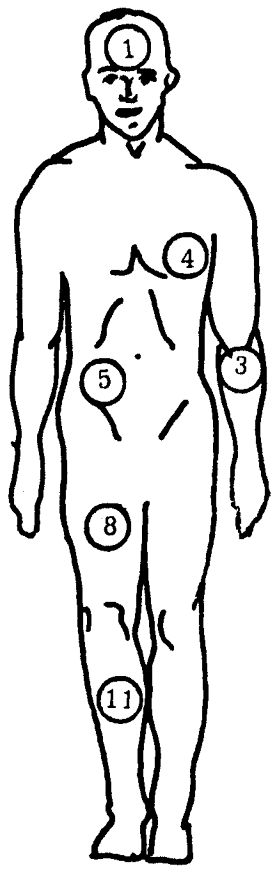
Skin Temperature

Skin temperatures were measured by means of 30-gauge copper-constantan thermocouples mounted in a cruciform arrangement in an open plastic ring about 1-1/2 inches in diameter. On either side of the junction at the center of the ring, the separated, bared thermocouple wires are stretched over projections on the plastic ring which press them, and the junction, into the skin slightly. The excellent thermal contact achieved by this method of attachment ensures that the temperature of the junction is relatively independent of the environmental conditions, and responsive only to the skin temperature itself. The theoretical objection that the pressure of the wire on the skin might interfere with the local temperature gradient or capillary blood flow is more than compensated for by the fact of reproducibility of the contact resistance and the relatively large area along the wire for lateral heat exchange with unloaded skin regions.

Temperatures were read on a 24-point self-balancing potentiometric recorder at the rate of one complete cycle every two minutes. Eleven skin locations were sampled on each man, as illustrated in Figure 4. These were chosen in such a way that each could be assigned an equal share of the total body surface area, so that the simple average of all eleven would equal the area weighted mean skin temperature. The rationale for this procedure is illustrated in Table 5.

Midway through the first series of experiments it was noticed that the forehead temperature was consistently deviant from all the other individual skin temperatures. It was reasoned that the chronically vasodilated state of the scalp and cephalic circulatory system, as demonstrated by Burton (Ref. 19), in conjunction with the unique character of the subcutaneous structure on the forehead, render this location inappropriate for inclusion in a total-body parameter which is to be used in an analysis of thermoregulation control. It was therefore decided to treat the forehead temperature independently, and compute an "effective" mean skin temperature as the simple average of the remaining 10 locations. The resultant segment weighing factors are thus 0.2 for arms, thighs and lower legs, 0.4 for the trunk. In effect, the area contribution of the head is distributed to the trunk (0.05), arms and thighs (0.01 each).

FIGURE 4: LOCATION OF SKIN TEMPERATURE THERMOCOUPLE POSITIONS



1. Forehead
2. R. Upper Arm (Triceps)
3. L. Forearm (Volar)
4. L. Upper Chest
5. R. Abdomen
6. L. Scapula
7. R. Lower Back
8. R. Anterior Thigh
9. L. Posterior Thigh
10. L. Calf
11. R. Shin

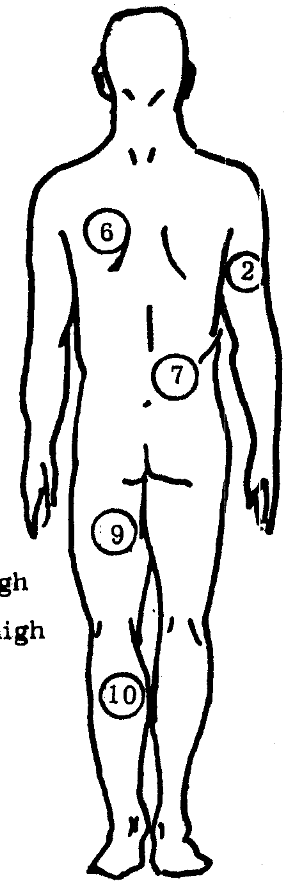


Table 5

Schema for Surface Area Weighting

Location	Fraction of Total Weighting		Body Segment Represented	Du Bois Fractional Area
Forehead	0.091		Head	0.07
Upper Arm Forearm	0.091 0.091	0.182	Arms plus Hands	0.19
Chest Abdomen Scapula Lower Back	0.091 0.091 0.091 0.091	0.364	Trunk	0.35
Anterior thigh Posterior thigh	0.091 0.091	0.182	Upper Legs	0.19
Calf Skin	0.091 0.091	0.182	Lower Legs plus Feet	0.20
Total		1.001		1.00

The skin temperatures were recorded continuously (i.e., at 2-minute intervals for each location) and read from the recorder chart at 10-minute intervals by the experiment data coordinator, who then computed the mean skin temperature. This technique of on-line human data reduction was most valuable as a protection against undetected failures of equipment or any other anomalies in the progress of the experiment.

Rectal Temperature

Flexible thermistor rectal probes (YSI) were used, inserted to a depth of 8 cm. A wrapping of adhesive tape serves to control insertion depth and provides an anchor or purchase for the anal sphimcter. No harness of any kind was used, but the plastic-coated thermistor lead was taped to the skin above the cleft of the buttocks to preclude accidental tension on the probe.

The temperature of the probe was read on a digital-display indicator (Digitec) whose least count is 0.02°C, permitting easy visual interpolation to the nearest hundredth of a Centigrade degree.

Heart Rate

Simple electrodes of the "floating" type were applied to the skin by a simplification of the method introduced in 1959 by Goldberg et al (Ref. 20); a 1-inch square of adhesive-back cork-filled gasketing material, with a 1/2-inch diameter hole cut into it, is applied to a cleaned patch of hairless skin. The pad has stapled to it the insulated stranded-copper lead wire; the bare ends of the strands are fanned out across the open hole in the pad, and the hole is filled with electrode paste. A square of plastic adhesive tape laid over the hole seals in the paste. The stranded copper wire forms its own electrode without contacting the skin and provides a minimal and stable contact resistance.

Electrode locations, chosen to provide minimum muscle noise during marching activity and a maximum R-wave height were as follows:

- just above the sterno-clavicular notch
- center upper back
- lower border of the rib cage in the mid-axillary line.

Lead wire from the electrodes were connected to a pre-amplifier which was attached to the subject's belt. Shielded leads carried the amplified signal outside the chamber to a beat-to-beat cardiotachometer (Gilford). The output of the cardiotachometer and the ECG complex itself were recorded on a two-channel pen recorder (Sanborn). The cardiotachometer record presents a rate trace for each R-R interval of the ECG signal, and has a linear calibration.

Weight Loss

A beam balance platform scales was used to measure the weight of the clothed and instrumented subject at 20-minute intervals during the experiment. Nude weight was also measured before and after. The beam scale can be read to 0.01 lb or 4.5 grams. The zero setting was adjusted before the start of each experiment; subjects were trained to place their feet in marked footprints on the platform and to stand still during the weighing process. The experimentors developed a skill in adjusting the beam weight and observing the free swing of the beam pointer which permitted them to complete a reliable weighing in less than 60 seconds. The weight was called out over the inter-com system to the data coordinator who recorded it together with the time.

Water and other fluids fed to the subject were weighed on another semi-precision beam balance in a standard paper-cup container whose tare weight was known. Each serving of fluid was either 0.25, 0.3 or 0.5 lbs (111, 136, or 127 grams), and was recorded at the time of delivery to the subject by the data coordinator.

To control the effect of thermocouple, thermistor and cardiotachometer leads on the measured weight, these wires were collected into a bundle or "pig-tail" and taped to a fixed support at the same position for every weighing.

After each weighing the data coordinator computed the evaporative weight loss over the preceding interval. Any gross error in weighing or recording the data was thus immediately correctable.

Metabolic Rate

Douglas bag collections of expired air were made throughout one or more complete cycles of work and rest, using a Collins J-valve and a solenoid-operated by-pass valve controlled by a precision electronic timer. In a few experiments collections were also made during several successive work periods only.

The volume of the collected gas was measured by aspiration into a 120 liter gasometer, and its oxygen content and CO_2 content analyzed. The gas analyzers were calibrated each day and checked against a standard gas mixture.

Oxygen consumption and metabolic rate were computed from the volume and gas composition data by the method outlined in Consolazio et al (Ref. 21).

Performance Reserve Measurements

At approximately 20-minute intervals subjects spent one 60-second rest period performing a dual task which consisted of cancelling audio tones with one pair of push-buttons and pushing another button when a light signal was observed in the peripheral field of vision.

The two tones were presented over a pair of loudspeakers in the chamber, mounted to the left and right of the subject's working position, in a randomized sequence controlled by a punched-paper tape. The program of signals contained no blanks, and the rate of presentation was approximately 50% of the maximum rate at which the subject was able to achieve a perfect score when performing this task alone during the control period of each experiment in a comfortable environment at rest.

At the console of the apparatus the number of each type of signal (high or low) presented in a test session was recorded on digital counters, together with the number of correct and the number of incorrect responses. At the end of each session, the test operator wrote down these results and computed the number of missed signals by difference.

The subject rested his hands on a remote-control unit of the mechanical ultra-sonic generator type (Zenith) as he stood facing a corner of the chamber in which the peripheral lights were installed. The push-button unit has four buttons; the left and right outboard buttons cancelled the high tone and the low tone respectively, matching the positions of the speakers. The inboard pair of buttons were used to report detection of a peripheral light. Subjects were instructed to fixate their gaze on an aiming point directly in front of their eyes.

Six small lights were arranged at 20, 50 and 80 degrees to the left and right of the fixation point. When one of the lights was illuminated, a corresponding pen was actuated on an event recorder outside the chamber. When the subject pressed his response button signalling detection, a seventh channel of the event recorder was actuated. The ink record thus shows each signal and each response on a time continuum.

In most of the experiments the same event-record showed the audio tones and the responses to them which were occurring simultaneously with the visual detection task.

The apparatus for programming the presentation of light signals consisted of rotary stepping switches and a branching system of relays which had the effect of randomizing the intervals between signals and the choice of light to be illuminated. The duration of each signal, i.e., the period of illumination, was held constant at 800 milliseconds. The number of signals presented in a single session of 40 seconds varied from 1 to 7 and averaged 4.5.

Experimental Procedure

Subjects reported to the laboratory at the beginning of the morning. They applied their own electrodes and inserted their rectal probes, and entered the environment chamber which was controlled at 31 ±0.5°C (88 ± 1°F). After they had donned shoes, socks and shorts, the thermocouples were strapped in place using elastic ties. They were then weighed, and sat on stools until their body temperatures had stabilized and the experimenters were prepared to begin the experiment proper. The pre-exposure control period lasted from 30 minutes to 2 hours, with a median duration of one hour. During this period they were weighed every 20 minutes, and performed a number of 30-second testing sessions with the primary binary choice task (cancelling audio tones by the pressing of an appropriate button). The rate of presentation of signal tones was increased in successive sessions until the level was established at which errors were consistently made. The highest rate at which a perfect score was attained was recorded as the 100% capacity level for the subject on that day.

At the conclusion of the pre-exposure control period, the chamber control settings were changed to the appropriate values for the scheduled exposure condition; if the experiment called for work, the treadmill was started at the same time and one subject began to walk on the cue from a tape-recorded voice instruction. The tape ran continuously until the end of the exposure, providing instructions to each man as follows:

- Prepared to start marching
- START!
- Prepare to stop
- STOP!

To aid in maintaining alertness to the commands, the instructions to one subject were tape-recorded by a young woman and the alternating set of instructions, directed at the other subject, were given by a man's voice.

Between the end of one 30-second work period and the start of the other man's work period there was an interval of 15 seconds, which provided time for the man leaving the treadmill to readjust his "pig-tail" of trailing wires and make room for his partner to move onto the treadmill on cue without interference. The men learned to exchange positions with a minimum of exertion, and much of the time they carried paper-back books in their hand during both working and resting periods of each cycle. All developed the ability to read while walking on the treadmill, though some found it easier than others.

When a performance reserve testing session was scheduled, the subject simply moved directly from the treadmill to the corner of the chamber where the apparatus was set up and prepared for the verbal signal over the inter-com system from the Test Operator that he was about to start the presentation of signals. Ten seconds was found to be a sufficient interval between the end of work and the start of the testing period, and vice versa.

Similarly, when a weighing was scheduled, the subject moved directly from the treadmill to the platform scales, and was back at the treadmill when his cue to "START" came over the inter-com from the tape recorder output.

Observations of skin wetness were made by the subjects on each other and by observers who entered the chamber for the purpose, at periodic intervals during the exposure.

SECTION II
RESULTS

Central Core Temperature

In a scheme proposed by Lind (Ref. 22) combinations of work load and thermal stress are considered to be "prescriptive", that is, suitable for acceptance on a routine daily basis as a working condition, if the equilibrium rectal temperature resulting from the combination does not exceed the level typical of a cool or comfortable environment at the same work load. Blockley has suggested the terms "environment-independent zone" and "environment-driven zone" for the regions below and above the environmental temperature at which core temperature first deviates from its thermally neutral level (Ref. 23) for the particular metabolic rate concerned. Lind has shown that the probability of heat collapse or heat exhaustion increases sharply as this "Neutral Boundary Condition" (NBC) is passed (Ref. 24).

The collected individual data for 86 three-hour experiments, shown in Figure 5 indicate that all the working experiments were within the environment-independent zone for each subject. The one possible exception is the P4SR 3 condition at the lower of the two working metabolic rates (center panel of Figure 5); there is a slight suggestion that the 45.5°C environment may have been on the borderline of the environment-driven zone.

The resting experiments, on the contrary, are partly in the environment-independent zone and partly in the environment-driven zone, with the NBC or dividing line lying somewhere between P4SR 1 and 2 (i.e., between 39 and 46°C at a vapor pressure of 10 mm Hg). The pattern of sharply increased rectal temperatures at P4SR 3 as compared to P4SR 2 is marred by only one exception, subject A.H. The only unusual feature of this experiment was the subject's report of a minor gastro-intestinal disturbance that morning.

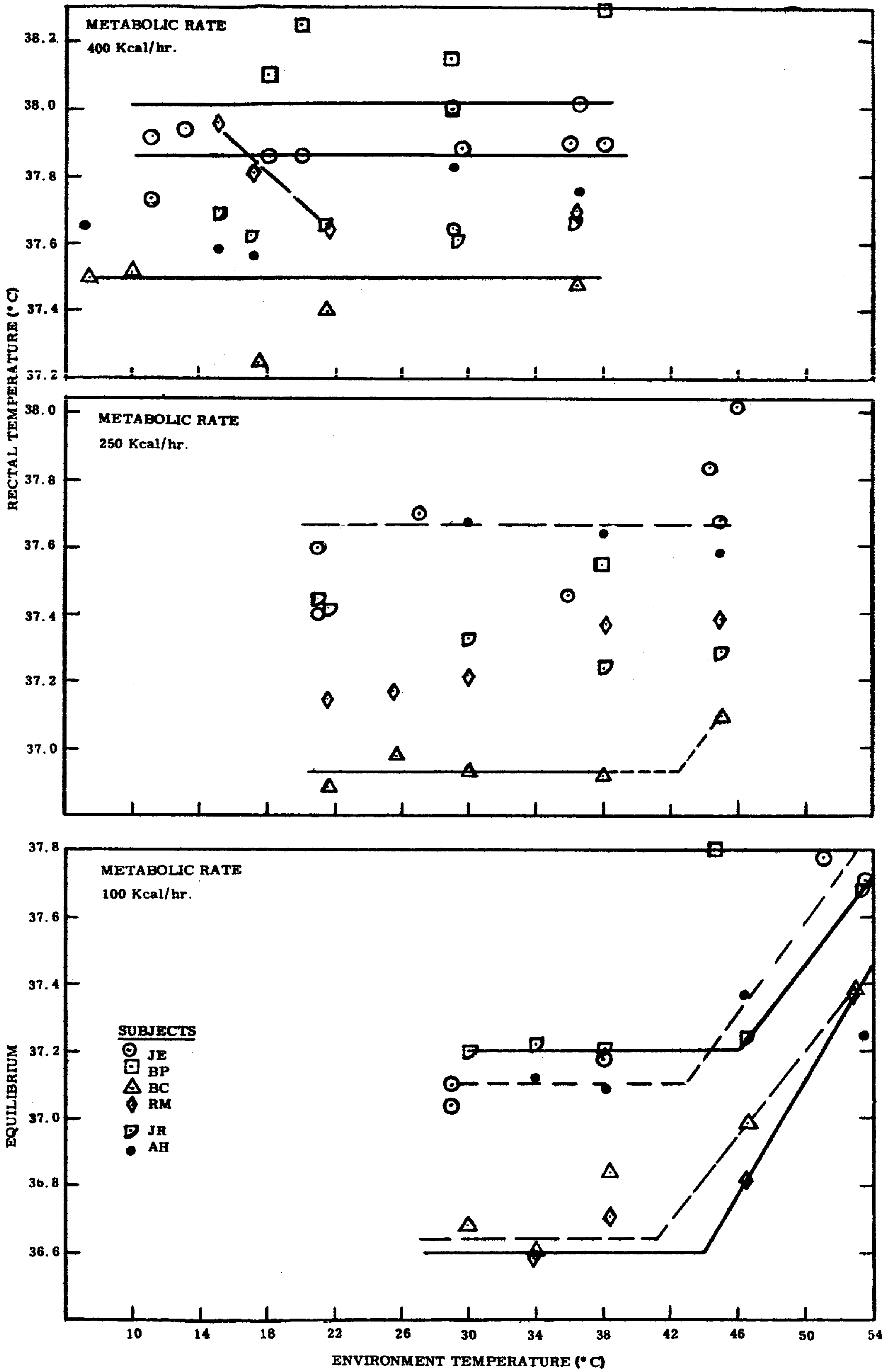


FIGURE 5: CORE TEMPERATURE AT THREE LEVELS OF ACTIVITY FOR 6 SUBJECTS VERSUS ENVIRONMENTAL TEMPERATURE

A second important aspect of the results displayed in Figure 5 is the wide range of inter-individual variation, contrasted with the relatively minor intra-individual differences. (Much of the scatter within the data for one subject may be ascribed to the variation in metabolic rate from one experiment to another within the same general activity level.) It will be noted that subject B.C. displayed the lowest equilibrium rectal temperature at all three activity levels whereas B.P. had the highest temperatures at rest and at the higher work load. The grand average rectal temperature for 35 experiments with 6 subjects at the nominal 400 Kcal/hr metabolism level was 37.79°C (100.3°F), and the range was 37.26 to 38.30°C (99.07 to 100.9°F).

The comparable lumped average for the 26 equilibrium rectal temperatures at a nominal metabolic rate of 250 Kcal/hr is 37.38°C (99.3°F), range 36.89 to 38.02°C (98.4 to 100.4°F).

To obtain a meaningful average for the resting condition to compare with the foregoing lumped averages, only the 14 experiments clearly within the environment-independent zone can be used; their mean is 36.93°C (98.5°F), range 36.5 to 37.22°C (97.7 to 99.0°F). The mean equilibrium rectal temperature for these 5 subjects for the P4SR 3 condition at rest was 37.47°C (99.4°F), range 37.25 to 37.70°C (99.0 to 99.9°F). The increment between the "neutral level" rectal and the value at P4SR 3 is thus 0.54°C or roughly 1°F, as compared to the difference between the neutral resting level and the mild work level of only 0.45°C (0.81°F).

In Figure 6 the rectal temperature data are arranged in a different manner to illustrate the basic dependence of this parameter on metabolic rate, and the similarity of the relationship between individuals despite considerable offset in the absolute levels of temperature found at a particular metabolism. The slopes of the individual curves between the mild and moderate work levels range from 1.5 to $3.6 \times 10^{-3} \frac{^{\circ}C}{Kcal/hr}$ for an average of 2.3×10^{-3}.

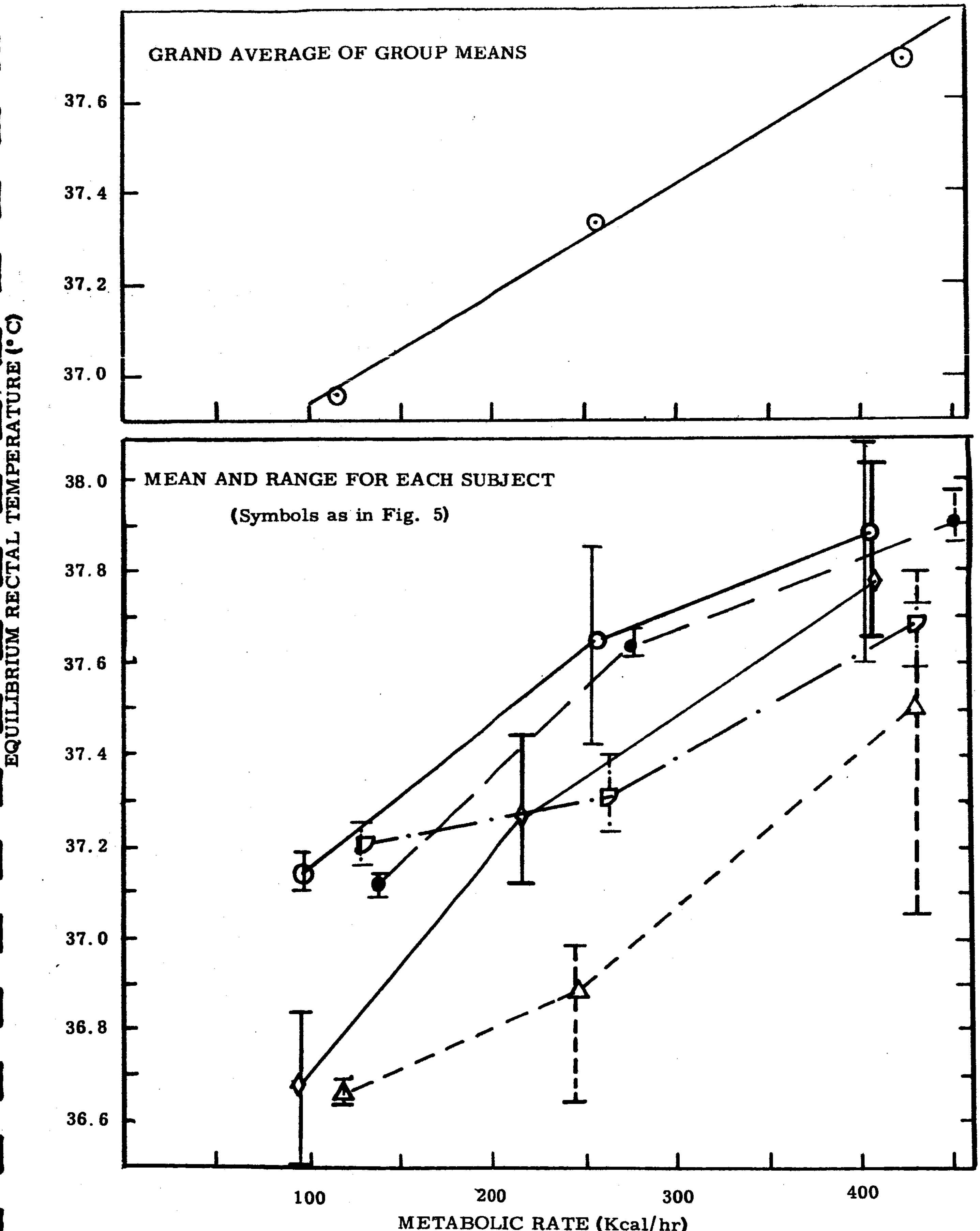


FIGURE 6: CORE TEMPERATURE VERSUS METABOLISM IN THE ENVIRONMENT-INDEPENDENT ZONE.

In the table below the means have been computed for each of 5 subjects at each of the 3 activity levels, using only the "neutral zone" or environment-independent rectal temperatures. When the grand averages for 5 subjects at each activity level are plotted, as in the upper part of Figure 5, they are seen to lie very nearly in a straight line, with a slope of 0.0024 $\frac{^oC}{Kcal/hr}$. A general equation can thus be considered for rough calculation, of the form

$$(t_r)_o = 37 + 2.4 \times 10^{-3} (M - 125)$$

where

$(t_r)_o$ = predicted equilibrium rectal temperature in the environment-independent zone of thermal loading.

Equilibrium Rectal Temperature Versus Metabolism:
Means for "Neutral Zone" Environments

Activity Level		J.E.	A.H.	B.C.	R.M.	J.R.	Mean
Rest	$\bar{M}$	97	137	121	93	126	115
	$\bar{t}_r$	37.14	37.12	36.66	36.62	37.21	36.95
Light Work	$\bar{M}$	256	276	258	228	263	256
	$\bar{t}_r$	37.65	37.64	36.87	37.16	37.31	37.33
Moderate Work	$\bar{M}$	406	440	430	407	429	422
	$\bar{t}_r$	37.88	37.62	37.50	37.77	37.68	37.69

Figure 7 presents a typical set of time histories for rectal temperature in experiments where the water deficit was not permitted to exceed 225 grams (1/2 lb) at any time during the three-hour exposure. The regularity of the one-hour delay before equilibrium is attained, and the relative stability of the rectal temperature thereafter is representative of the majority of

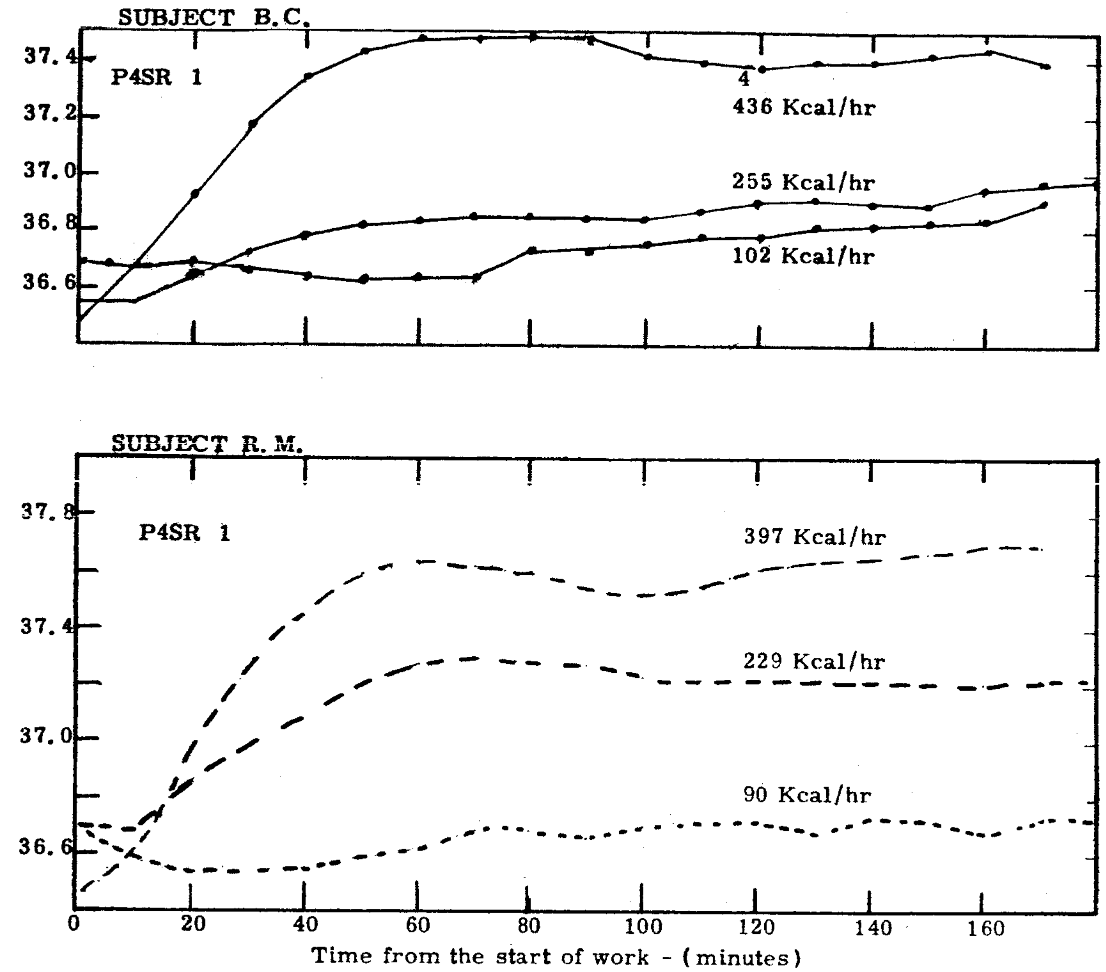


FIGURE 7: REPRESENTATIVE TIME HISTORIES FOR RECTAL TEMPERATURE

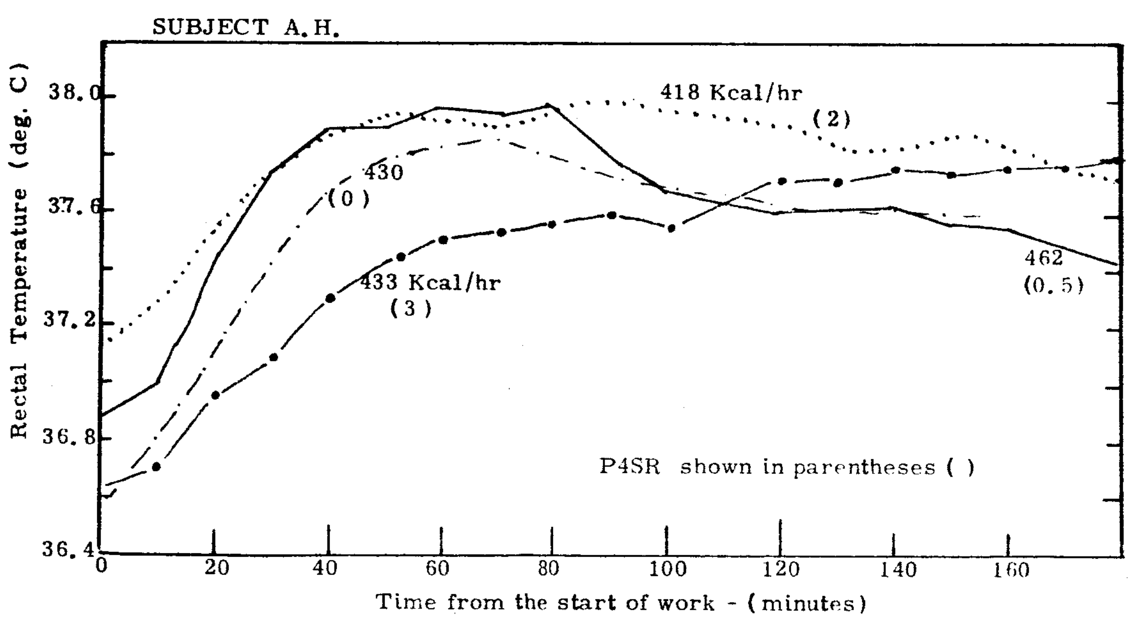


FIGURE 8 : Anomalous rectal temperature time histories in a thick - skinned individual at the moderate activity level of 440 ± 22 Kcal/hr

the experiments meeting the two criteria of: (a) insignificant water deficit, and (b) environment within the environment-independent zone.

One of the subjects displayed an anomalous pattern in several experiments, as shown in Figure 8. The decline of rectal temperature from its 80-minute peak in the two cool experiments may represent merely an exaggeration of a tendency which is faintly discernible in the high-activity experiment at P4SR 1 for subject B.C. shown in the upper panel of Figure 7. On the other hand, the distinctly lower rectal temperature for A.H. at 60 minutes in the warmest environment is suggestive of an interaction between skin temperature and long-term rectal history in the man with a thick layer of skin fat.

Skin Temperature

High Wind Experiments

In the first series of experiments with subjects J.E. and B.P., in which the feasibility of achieving minimal "wetted area fractions" was being explored, the wind velocity during work was high, ranging from 150 to 375 ft/min at the man's back and from 50 to 120 ft/min in front of him (76 to 190 and 25 to 61 cm/sec respectively). The air turbulence was produced by two 20-inch fans behind the man at the end of the treadmill. When he stood at the side of the treadmill during the 60-second rest period in each work/rest cycle, the air movement around his body was somewhat lower, ranging from 80 to 200 ft/min (40 to 100 cm/sec) over most body segments.

In the seated experiments of this initial series, the subject's body occupied a position where the output of the fans was most concentrated, so that the velocities over the various body segments ranged from 150 to 700 ft/min behind (average 390 ft/min) and from 50 to 250 ft/min in front (average 115).

The magnitude and variability of the air motion accentuated the variation in local skin temperature from one part of the body to another; the difference between the warmest and the coolest location was frequently as much as 6 Centigrade degrees. In Figure 9, two examples are shown of the distribution with time of individual skin temperatures, at a metabolic rate of 405 ± 2 Kcal/hr. The upper panel gives the data for an air and wall temperature of 20°C (68°F) in which the rate of evaporative weight loss was 90 to 100 grams per hour. The mean skin temperature averaged 31.2°C during the third hour when forehead temperature is included in the average, 30.8°C when the latter is omitted. As can be seen in the figure, the majority of the individual skin temperatures lie between 31 and 32°C (87.8 to 89.6°F); the three consistently low temperatures represent the arms and the upper back, and range from 28 to 29°C (82 to 84°F). The subject was observed to shiver occasionally.

The lower panel of Figure 9 displays data for the same subject in an earlier experiment at an environmental temperature of 11°C (52°F); the weight loss rate was only 75 grams/hr, considered to be the minimum achievable at this activity level. The subject shivered intermittently throughout the exposure, and complained that his calf muscles were "tightening up" at the 2-hour mark. Throughout the exposure he wore a wool cap, covering his ears, and gloves, in addition to the standard shorts and foot gear.

The lowest temperatures were again found on the arms, where they ranged from 20 to 22°C, and the scapula which averaged about 23°C in the last hour. Again, the forehead was consistently higher than all other skin locations, generally by more than 2°C. Excluding the forehead, the overall average mean skin temperature for the last 90 minutes was 25.1°C (77.3°F).

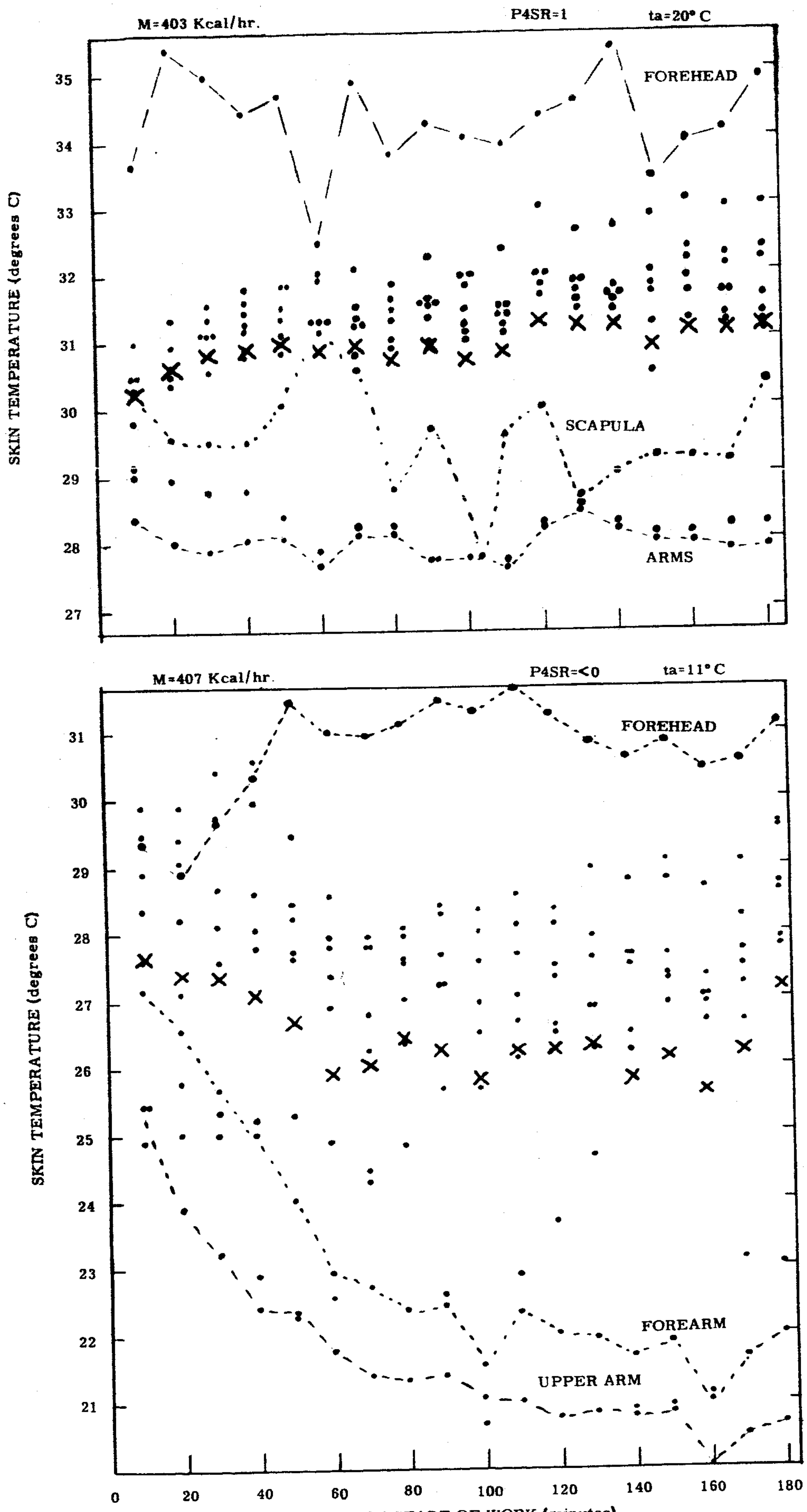


FIGURE 9: INDIVIDUAL SKIN TEMPERATURES DURING MODERATE ACTIVITY IN A COLD AND COMFORT NON-SWEATING ENVIRONMENT. SUBJECT JE

Figure 10 shows the range of skin temperatures which the second subject, B.P., displayed in the same experiment which produced the data on J.E. shown in the upper panel of Figure 9. For comparison, two other experiments in warmer environments are also shown for B.P. It is of some significance that in the 20°C environment this subject showed an evaporative weight loss of between 218 and 358 grams/hr, in spite of the low mean skin temperature (excluding the forehead) of 27.9°C as compared with the near-insensible loss rate of 95 grams/hr seen in subject J.E. in the same work-environment situation, with a higher skin temperature! The relatively high skin-fold thickness of subject B.P. (see Table 4) is probably critical in this comparison.

In the environment predicted to have a P4SR index of 2, subject B.P. had a sweat rate nearly identical to the expected value of 500 grams/hr, while J.E. produced 10% less at a skin temperature which was higher by about 2°C. In this warm environment (84°F) the wide swing in temperature of the skin overlying the working muscles is very evident in subject B.P. The cycle interval in this experiment was 1.5 minutes, while the skin temperatures were read off the recorder chart at 10 minute intervals. Thus, every third point tabulated or plotted for a particular location represents the same relative position in a cycle, and successive points are displaced by approximately 30 seconds in their relative position in the cycle. It is therefore possible for as many as 3 successive readings at 10-minute time intervals to fall in the resting portion of their respective work/rest cycles; the next one or two points will then represent the working portion. The fluctuations indicated in Figure 10 are thus the reflection of a 90-second cycle in which the skin temperature over the calf and thigh rises abruptly as soon as leg work stops in response to the shunting of blood flow from the muscle interior directly to the surface.

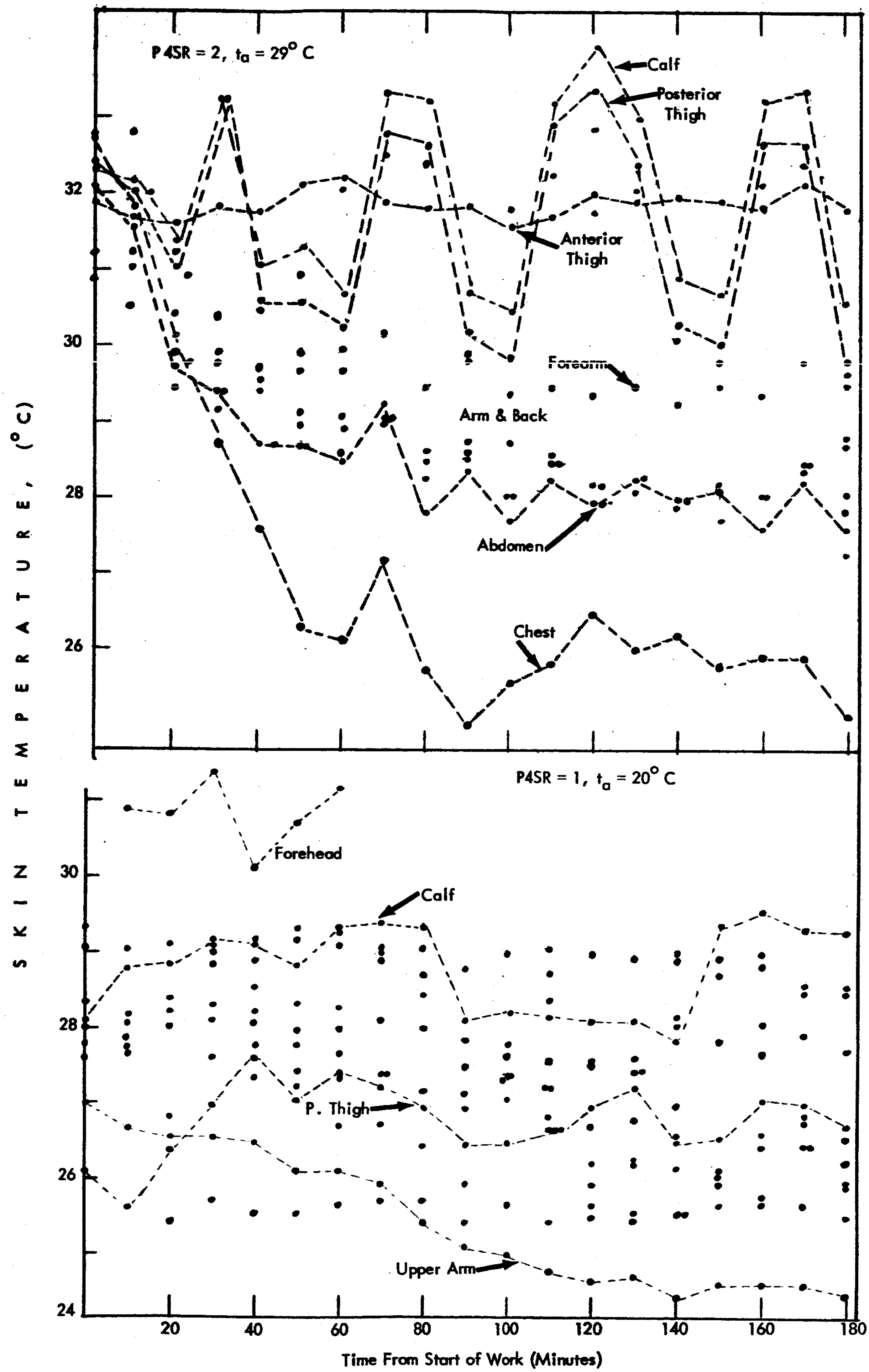


Figure 10:

Individual skin temperatures in two sweaty environments; Subject B. P. Metabolism 435 Kcal/hr.

In general, the temperature swings over the working muscles will be accentuated whenever the local sweat production rate in this area is high and the environment can act as a good heat sink.

Low Wind Experiments

The cyclic variation in skin temperature can be detected, though smaller in magnitude, in the data from the second series of experiments in which air movement was limited to that incidental to the recirculation of air through the chamber and its conditioning system. In Figure 11 each print-out of selected skin temperatures has been traced directly from the potentiometric recorder over a time span of 12 minutes (8 work/rest cycles). It will be seen that the spread from maximum to minimum is of the order of 1°C in the cold environment, although the average levels at individual locations are as much as 10°C apart. In the warmest of the experimental environments at this work level (nominal 400 Kcal/hr) the deviation between maximum and minimum is much greater at the forehead than in the cold, up to 5°C, but much less at the arms and zero over the working muscle on the calf.

The independent trend of the forehead temperature, and its consistent separation from the other 10 body locations has attracted our attention and led to the decision to eliminate it from the computation of area-weighted mean skin temperature for use in analyzing sweat response. The fact that fluctuations in forehead surface temperature with momentary activity persist in exaggerated form when they have disappeared over the working muscle suggests the possibility that the forehead temperature may, to some degree, reflect a mixed effective central blood temperature in a manner which other skin cannot. Figure 12 presents the overall time history of the forehead temperature for two subjects in each of their exposures at a nominal metabolic rate of 400 Kcal/hr. It will be noted that in one subject the two highest stress levels are distinctly separated from the other cool and moderately warm environments, while in subject J.R. only the highest stress condition, P4SR 3, shows a distinctly higher forehead skin temperature.

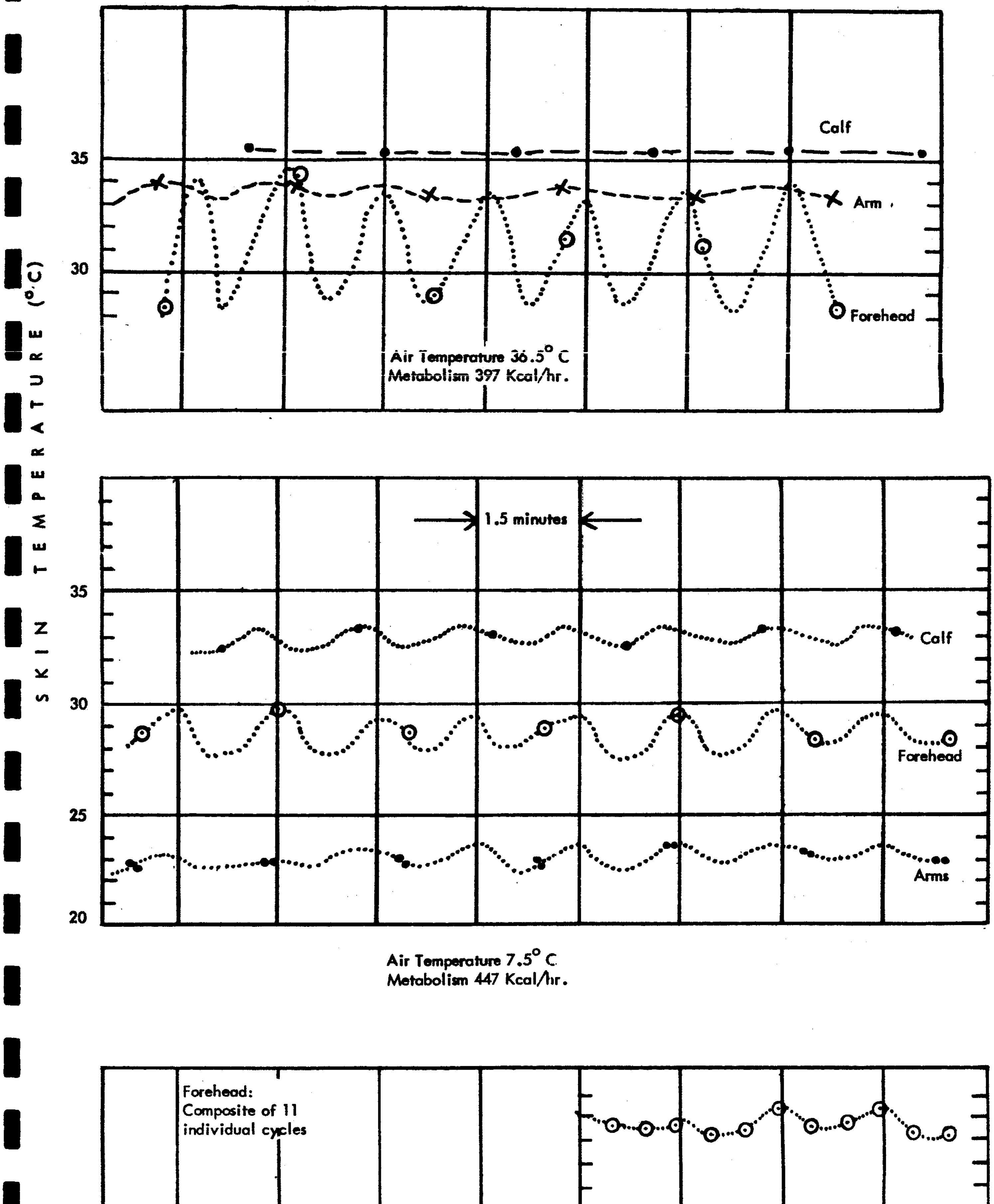


Figure 11: Cyclic variation of skin temperatures during work and rest; high activity level, coolest and warmest environments. Subject B.C.

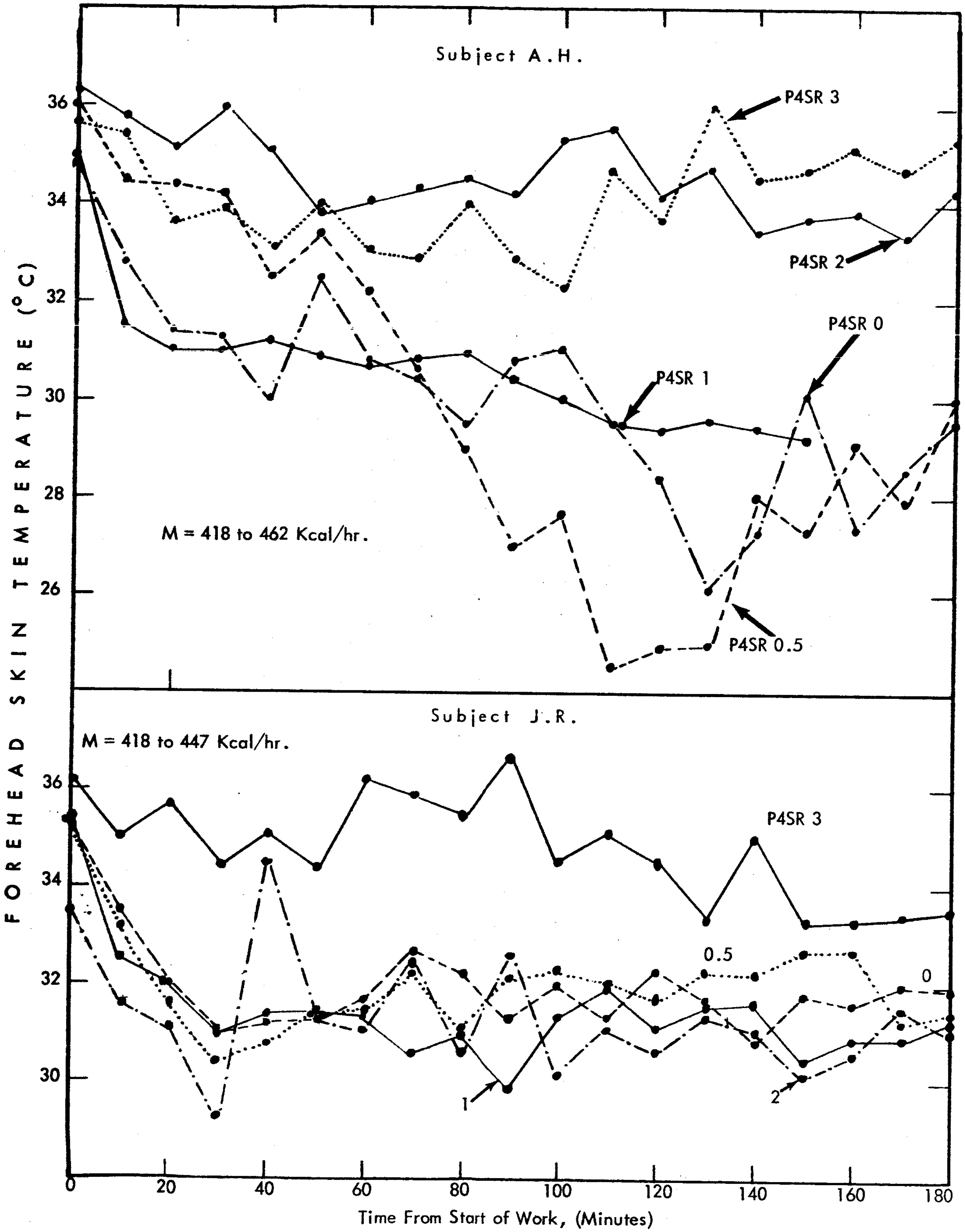


Figure 12: Forehead temperature history at the five levels of environmental stress, with an activity level of 400 Kcal/hr.

Each of the above patterns was displayed by one additional subject in the second series. In general, the cool and low-stress environments seemed to produce a forehead temperature of about 29 or 30 in subject R. M., about 32 to 32.5 in B.C., 28 to 38 in A.H., and 30 to 32 in J.R. (all temperatures in ^{o}C). The skin temperature at the forehead associated with high-stress environments at this metabolic level was of the order of 34 to 36 for all four subjects.

Figure 13 is a reconstruction of seven successive work/rest cycles of two subjects in the P4SR 3 experiment at 400 Kcal/hr. This graph is constructed by plotting each recorded temperature at its correct relative position in the cycle being sampled. The 20 individual points used to construct the hypothetical cyclic pattern cover a period of 40 minutes or 27 cycles between the 30th and 70th minutes of the experiment. It should be noted that during this period B.C. was running distinctly warmer at the forehead than R. M., except for an occasional high reading. However, R. M.'s 80 minute and 150 minute readings were over 36; from 100 to 140 his forehead temperature ran between 33 and 34, and was 35 at 180 minutes.

In a special experiment designed to discover the threshold skin temperature for sweating at 400 Kcal/hr in subject A.H., the chamber was cooled to 5.4^{o}C; at the end of 10 minutes the air temperature had dropped from 31 to 8.7^{o}C, and reached 6.3^{o} 20 minutes later. From the low point of 5.4^{o}C, reached at 70 minutes, the chamber temperature drifed upward to 6.3 at experiment's end at 150 minutes. Figure 14 presents the time history of all eleven skin temperatures. For four separate periods of 10 minutes, every individual skin temperature observation had been plotted in order to establish the relative repeatability of temperature measurements under these conditions.

Figure 15 presents data for a similar special experiment aimed at establishing the sweating threshold at 400 Kcal/hr for subject B.C. In this case, though the forehead temperature followed a course closely similar

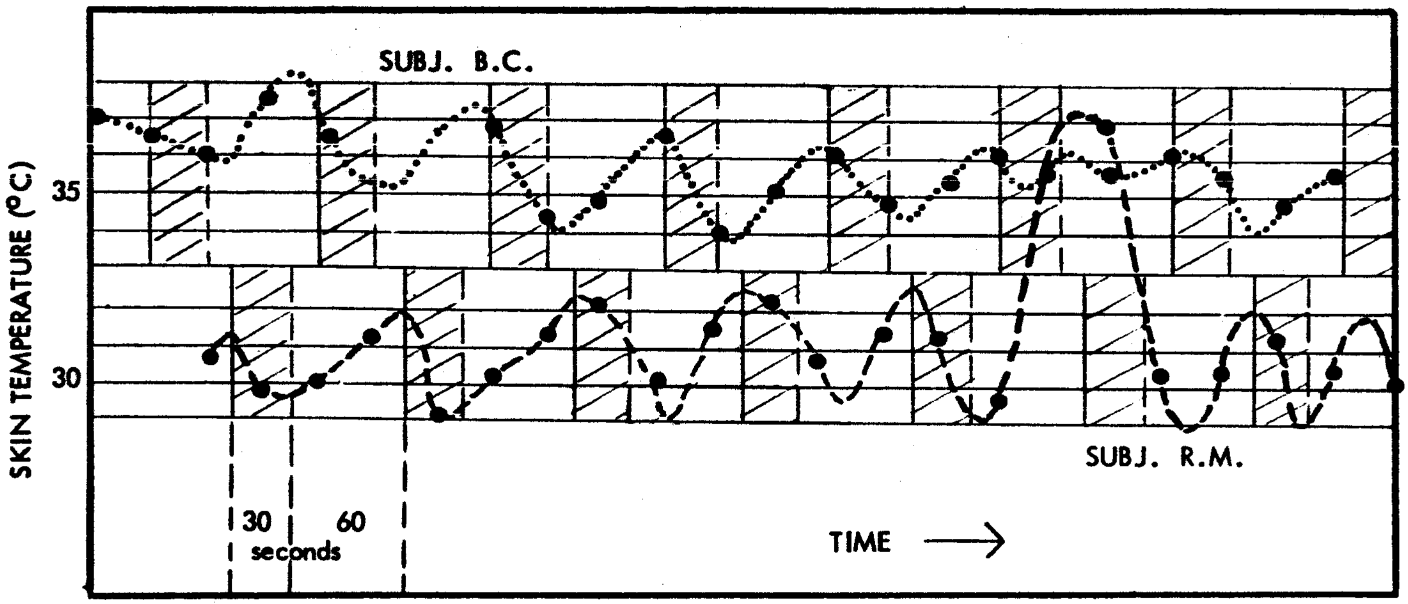


FIGURE 13: RECONSTRUCTED TIME HISTORY OF FOREHEAD SKIN TEMPERATURE in 2 subjects in the most severe environment at the high activity level (400 Kcal/hr)

NOTE: The seven cycles of work (shaded) and rest are a composite of 27 actual cycles for each man which occurred between 30 minutes and 70 minutes in the experiment. The actual interval between points was two minutes. They have been plotted on a relative rather than an absolute time scale, so that each appears at the correct position within a 90-second work/rest cycle.

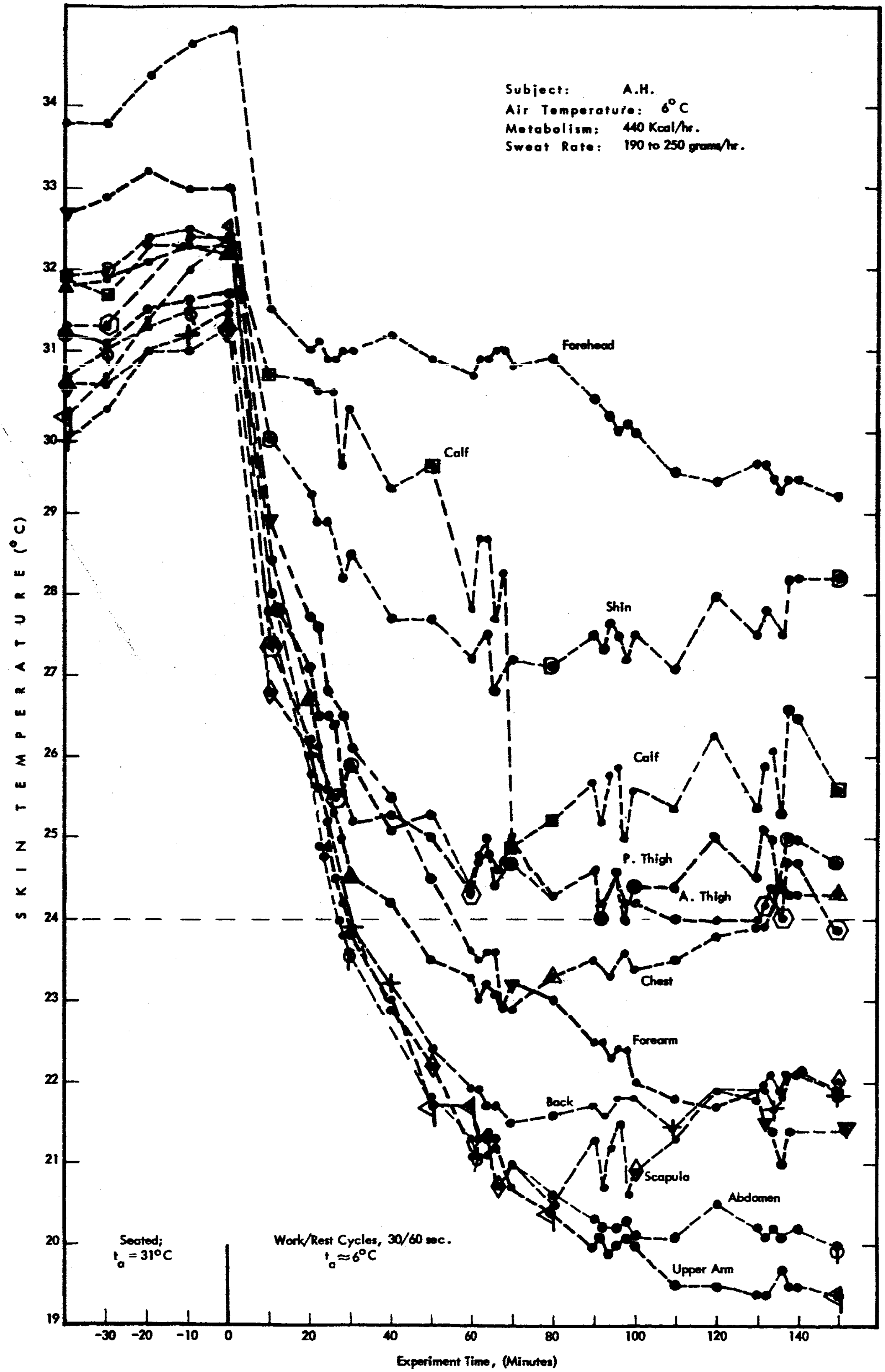


Figure 14: Individual skin temperatures in a thick-skinned man under low-sweat conditions

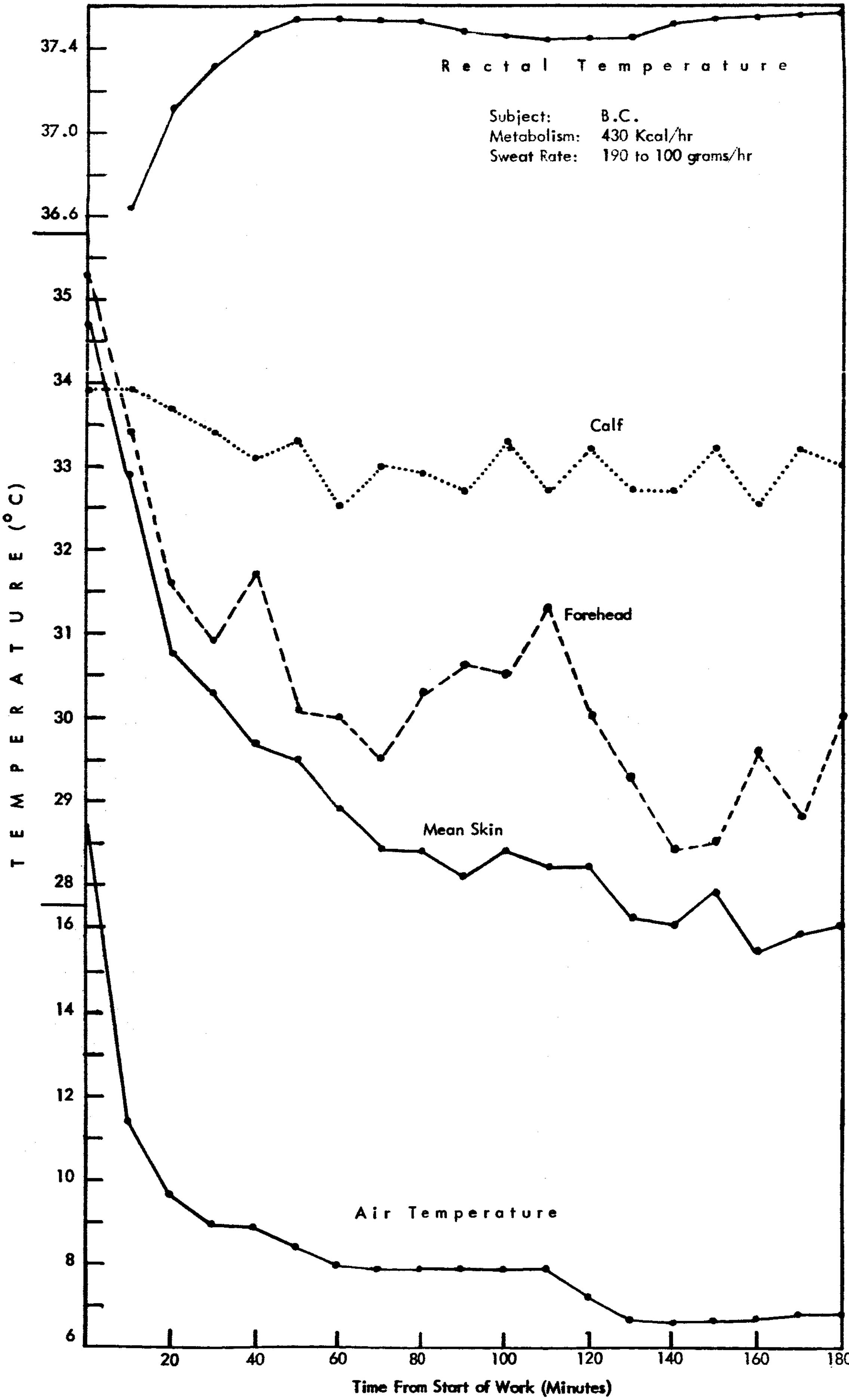


Figure 15: Mean and local temperatures during a low-sweat condition at high activity

to that of subject A.H., the calf temperature remained 2 to 4°C higher. Taking into account the heavier fat layer and consequent lower conductance in the skin of subject A.H., the notion of a close correlation between central blood temperature and forehead temperature is again supported by the comparison of these two experiments. It is noteworthy that the final equilibrium skin temperature achieved in the final half hour of these two experiments was associated with evaporation rates of 200 grams/hr in the case of A.H., and 140 grams/hr for B.C., both well above the pure diffusion plus respiratory loss level. At the end of the experiment on B.C., the skin temperature was measured on the backs of his hands; they read 17.9 and 20.8°C respectively (64.2 and 69.4°F).

A representative picture of the temporal stability and spatial variability of individual skin temperatures in the second series of experiments is presented in Figure 16. The following table summarizes the data for the second series.

Skin Temperature Summary
(Averages for 4 subjects)

Nominal Metabolic Rate Kcal/hr	Btu/hr	Nominal P4SR Index	Mean Air Temperature °C	°F	Mean Skin Temperature Av. °C	Max. °C	Min. °C	Spread (Max-Min) °C
100	400	0	30.0	86.0	34.5	35.0	34.2	0.8
		0.5	34.0	93.0	34.6	34.9	34.2	0.8
		1	38.5	91.0	35.1	35.4	34.6	0.8
		2	46.5	116.0	35.7	35.9	35.4	0.5
		3	53.5	128.5	36.2	36.7	35.6	1.1
250	1000	0	21.5	71.0	31.5	32.4	30.9	1.5
		0.5	25.5	78.0	32.8	33.3	31.5	1.8
		1	30.0	86.0	33.1	33.7	32.2	1.5
		2	38.0	100.5	34.2	34.6	33.9	1.7
		3	45.0	113.0	35.0	35.4	34.5	0.9
400	1600	0	15.0	59.0	28.8	29.8	26.7	3.1
		0.5	17.0	52.5	30.4	32.0	28.2	3.8
		1	21.5	70.5	30.7	31.2	30.2	0.9
		2	29.5	85.0	32.2	32.7	31.4	1.3
		3	36.5	97.5	33.6	34.7	32.7	2.0

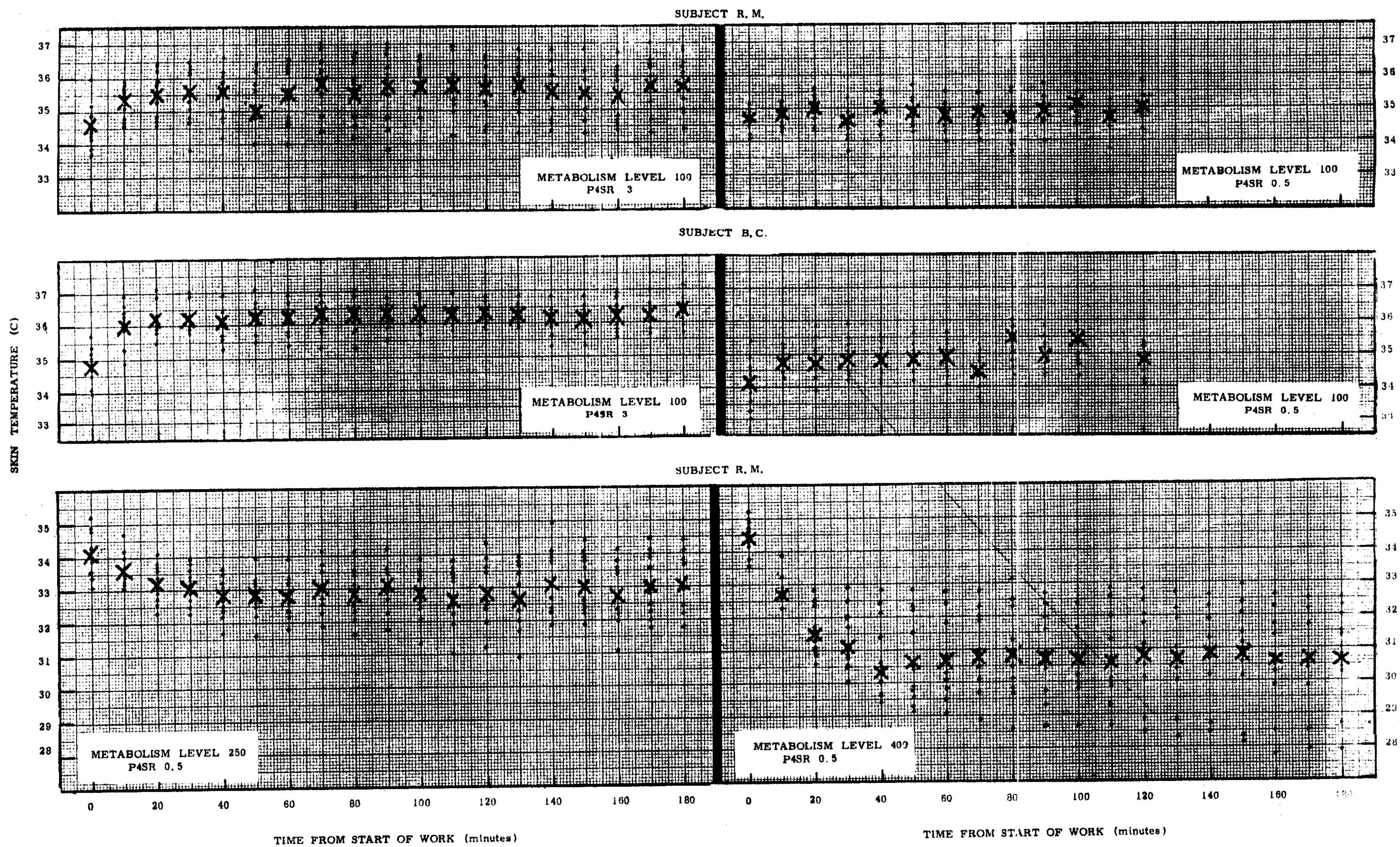


FIGURE 16: INDIVIDUAL SKIN TEMPERATURES IN REPRESENTATIVE EXPERIMENTS, COMFORTABLE & WARM ENVIRONMENTS

Two features of the tabulated skin temperature data deserve special notice, viz; the very small variance between subjects in the resting experiments, and the direct proportionality of the spread to the metabolic rate at the lower stress levels. As shown in Figure 16, there was relatively little variation between individual locations in the resting experiments (spread 2 to 3°C). Even at the highest activity level, the typical spread between the highest and lowest individual skin temperature was 3 to 5°C for all environments where some sweating was present.

As a final summary of the basic relationship between environmental stress level and skin temperature, Figure 17 presents the group averages for the low air movement series against P4SR, with activity level as a parameter. Particularly noteworthy is the relatively slight effect of environmental temperature at rest, compared with the strong dependency at the highest activity level (1.4°C increase per unit P4SR change). The figure illustrates clearly the basic fact that skin temperature must be at least 5°C cooler at 400 Kcal/hr than at rest to achieve a minimal sweat rate.

Circulatory Index

The gradient between the central core of the body and the surface provides a crude measure of the magnitude of the problem faced by the body's thermoregulatory system in moving metabolic heat to the environment. By far the major element in this heat-dissipation system is the cardiovascular system, which recirculates the coolant fluid, blood, from heat-producing organs and tissues to the skin and back. If the metabolic heat production rate is divided by the core to surface temperature difference, the resultant ratio has the dimensions of a thermal conductance -- heat flux per degree -- but use of this term can be misleading, particularly in a context of rigorous heat transfer analysis. The term "circulatory index" is preferable, reflecting as it does the fact that increases

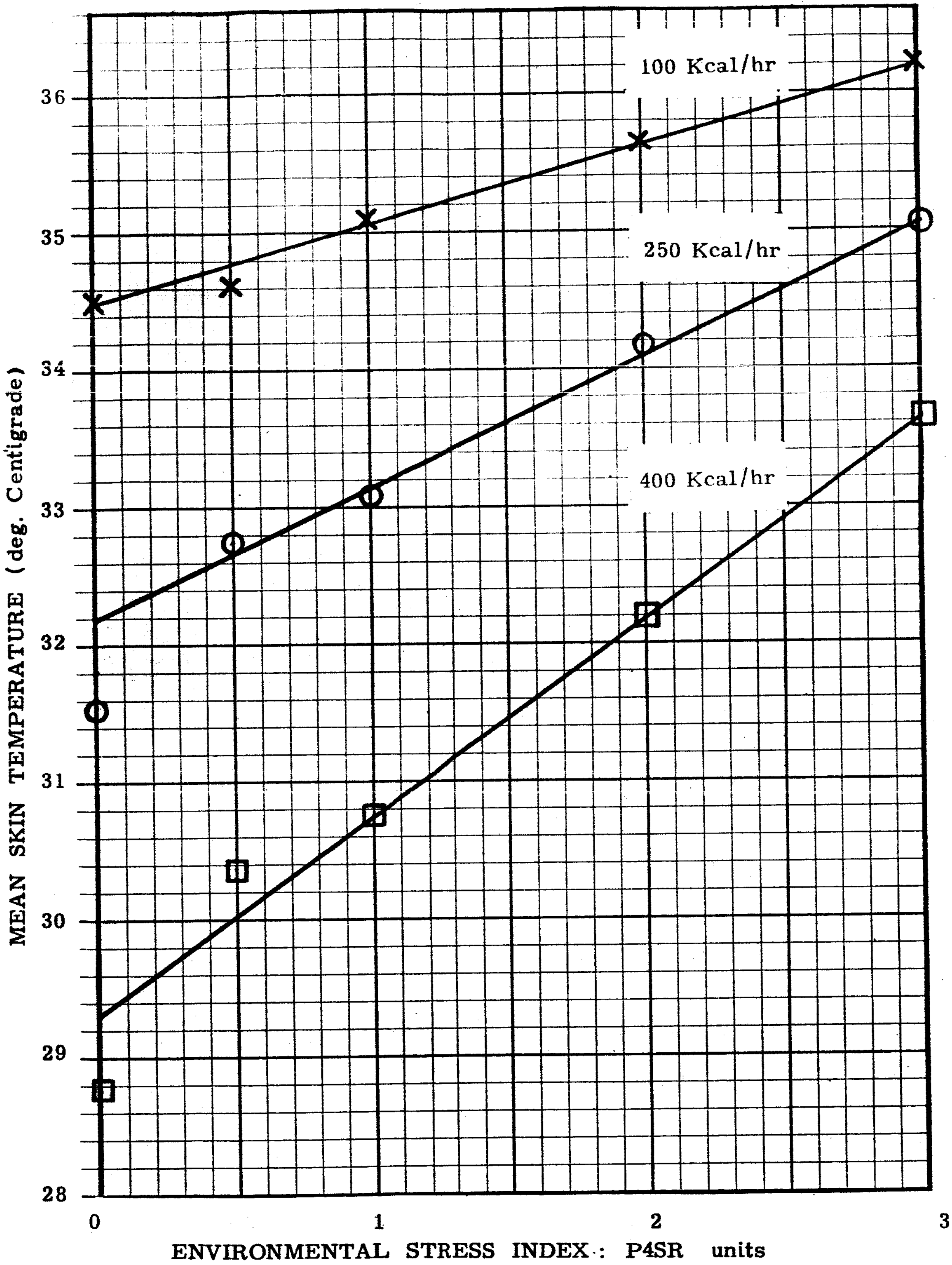


FIGURE 17 : EQUILIBRIUM MEAN SKIN TEMPERATURE
as a function of P4SR and metabolic rate;
(Group averages for 4 subjects)

in the ratio usually represent increases in the quantity of blood recirculated in unit time. Since a certain small proportion of the metabolic energy appears as external work, rather than heat, and since some heat is lost through the respiratory tract, a more precise ratio can be computed which relates directly to blood flow and heat loss through the skin. This is done by subtracting external work and ventilatory heat loss from the metabolic rate before dividing by core-to-skin differential temperature. This refinement has been deemed unnecessary for the present purpose.

Because one subject, A.H. had an atypical skin temperature response at low environmental temperatures due to his fat skin, he was excluded from the C.I. analysis in order to give the results more generality. The three remaining subjects of Series 2 are quite similar in fitness, skin-fold thickness and body type, and their averaged data are plotted in Figure 18. C.I. was calculated as the mean metabolic rate divided by the difference between the group averages for mean skin and rectal temperatures, both being equilibrium values. The uppermost symbol on each curve represents the P4SR 3 environments, the next lower set of 3 points are for P4SR 2 and so on. The similarity of the C.I. values at each of these P4SR levels lends weight to the validity of the P4SR system of predicting equivalence of physiological response. The lack of distinction between the C.I. at P4SR levels 0.5 and 1.0 suggests that the increase in environmental stress between them is compensated for by the body's regulatory mechanisms without a change in the cardiovascular load.

The slopes of the three curves of Figure 18 can be interpreted as a measure of the cardiovascular sensitivity to alterations in skin temperature. These eye-fitted lines indicate that circulatory index increases more rapidly as skin temperature rises under resting conditions (30 Kcal/hr^{o}C^{2}) than at a metabolic rate of about 430 Kcal/hr (13 Kcal/hr^{o}C^{2}).

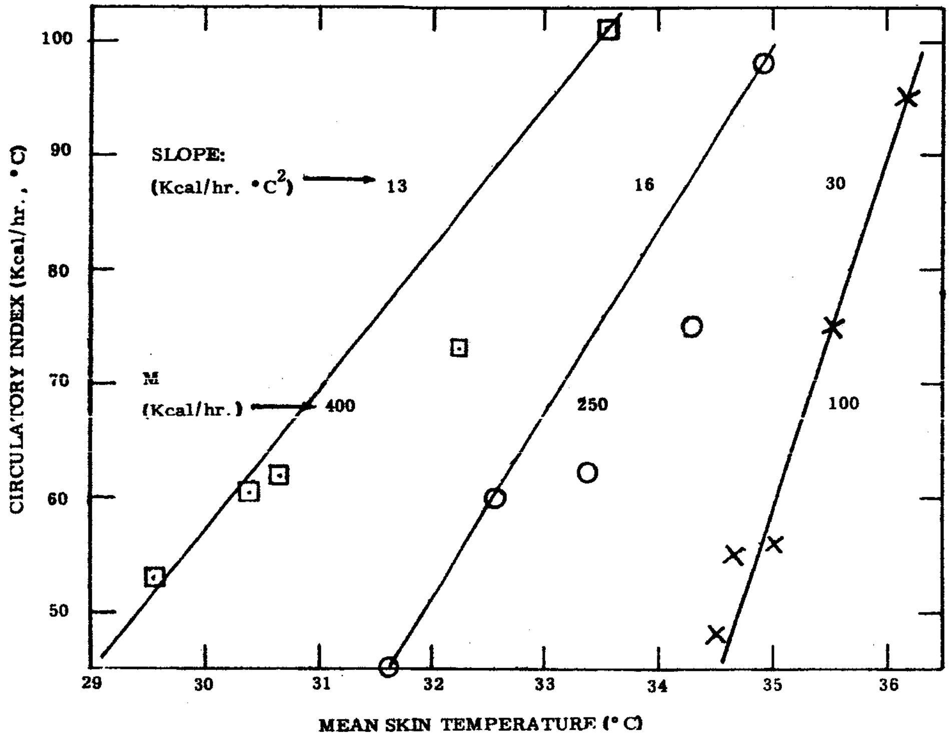


FIGURE 18: C.I. AS A FUNCTION OF SKIN TEMPERATURE AND METABOLISM FOR 3 REPRESENTATIVE SUBJECTS

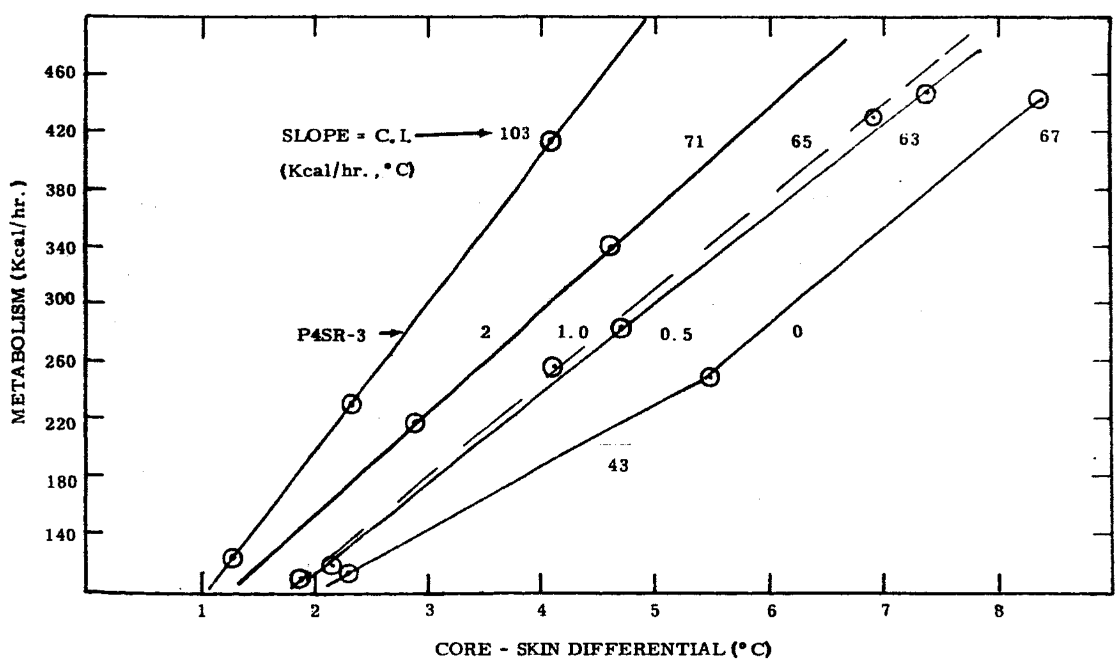


FIGURE 19: HEAT DISSIPATION AS A FUNCTION OF THE DIFFERENCE BETWEEN RECTAL AND SKIN TEMPERATURE, AT 5 LEVELS OF THERMAL STRESS

Figure 19 presents the basic data from which C.I. is computed. For each P4SR level of stress, the three metabolic rates and their corresponding average differential, rectal minus skin temperature, are plotted. The five resulting curves express the relationship between the differential temperature and metabolic load to be dissipated, as influenced by the level of environmental stress. The slopes of these lines could be called the "Dynamic Circulatory Index" for the various stress levels, since they express the rate of change of heat dissipation per unit change in rectal-skin differential temperature. It is of interest that these quite different procedures yield closely similar numbers for the circulatory index at each level of stress, as shown in the table below.

Circulatory Index Comparison

P4SR Level	Circulatory Index (Kcal/hr°C)	
	Average of 3 Metabolisms	$\Delta M/\Delta\ (t_r - t_s)$
0	49	43, 67
0.5	58	63
1	60	65
2	74	71
3	98	103

For orientation purposes, it may be helpful to recall that the literature identifies 148 Kcal/hr, °C as the C.I. representative of the most severe heat stress in which highly acclimatized men could maintain equilibrium for 6 hours while working; the corresponding maximal C.I. for resting men was 66.5 (Robinson, Ref. 25).

Heart Rate

The prime element in the circulatory response to increased thermal load is the pulse frequency of the heart. This parameter has been found very useful as an indicator of fatigue and for predicting long-term tolerability of work-environment combinations. (Ref. 26, 27).

Because of the cyclic nature of the activity, the data have been analyzed in several ways. First, the total number of heart beats in a complete cycle is sometimes counted, and an average "cardiac cost" for the cycle computed by dividing this count by the cycle duration. Secondly, the instantaneous tachometer record can be read at specific times within each sampled cycle, such as at the beginning and end of the work period, and the maximum and minimum values recorded by the tachometer can be read for any cycle. Figure 20 presents segments of an actual recording of the ECG trace and the cardiotachometer output for a comfort level environment (P4SR 0.5) at the higher activity level (M=419 ± 6 Kcal/hr) for the subjects J.E. and B.P.

The more typical response was for heart rate to increase moderately for 10 or 15 seconds after the end of each work period, so that the maximum rate in any particular cycle was usually observed during the rest period. Also typical was an anticipatory rise in rate just before starting work, probably triggered by the verbal instruction, "Prepare to start (marching)".

Careful examination of the data read from sample cycles throughout the three hour experiments indicated that in almost all cases the pattern of heart rate within a cycle remained essentially constant with exposure time.

This consistency is illustrated in Figure 21 which presents data for individual cycles in the most severe environment at the 250 Kcal/hr level for subjects J.R., B.C. and A.H. While there is a slight upward trend for A.H. in the peak heart rate, it is not strong enough to carry much significance.

Figure 22 illustrates the greater cardiac demand associated with the high activity level of 400 Kcal/hr, and at the same time emphasizes the effect of increasing environmental stress on the pattern of heart rate response. These data are for subject J.R., the "fitness-conscious"

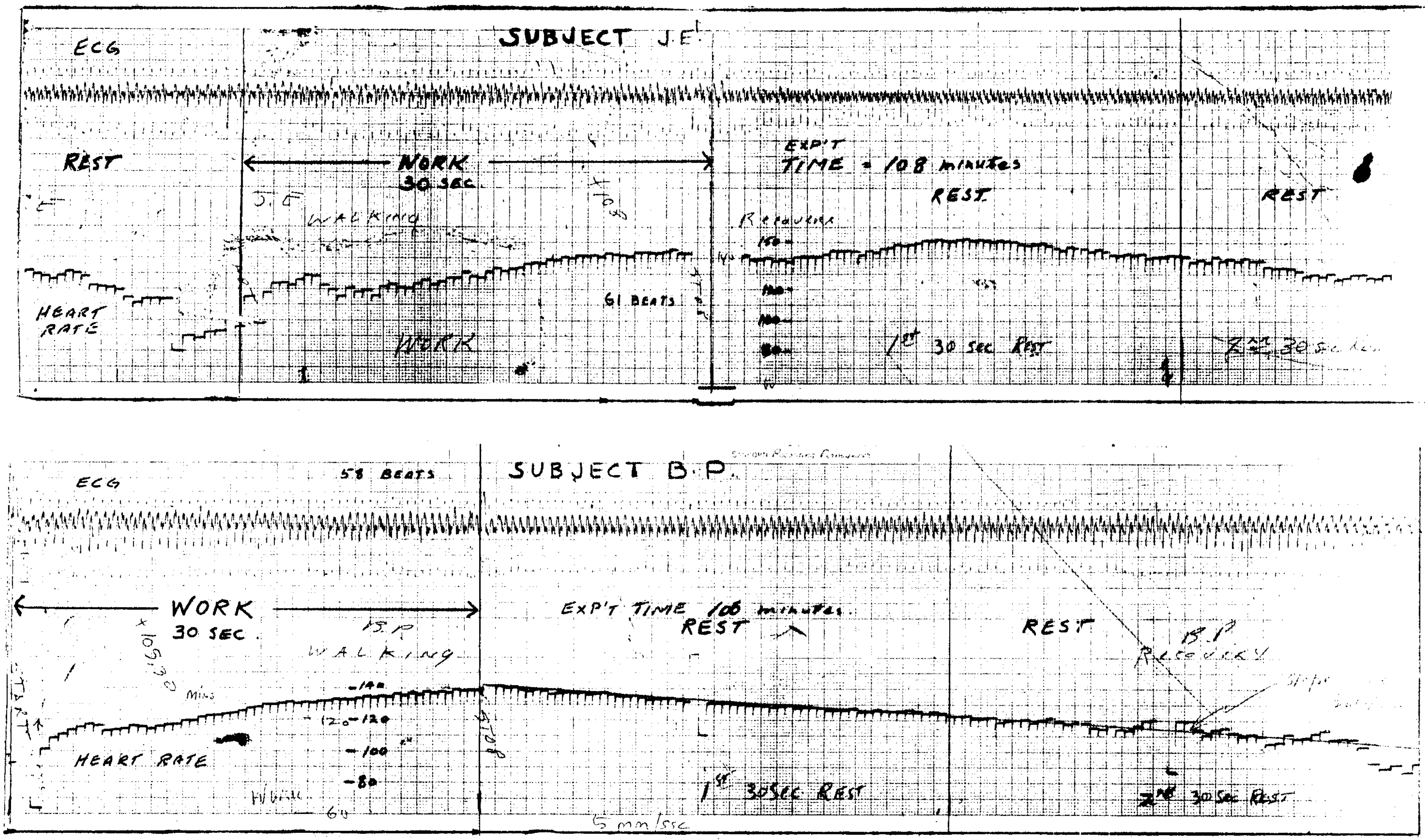


FIGURE 20: TYPICAL RECORDINGS OF ECG AND HEART RATE DURING INTERMITTENT WORK : 30 SECONDS CLIMBING A GRADE OF 15% AT 4 MPH, 60 SECONDS STANDING STILL.

AIR TEMPERATURE 18 C : AVERAGE METABOLIC RATE 413 Kcal/hour

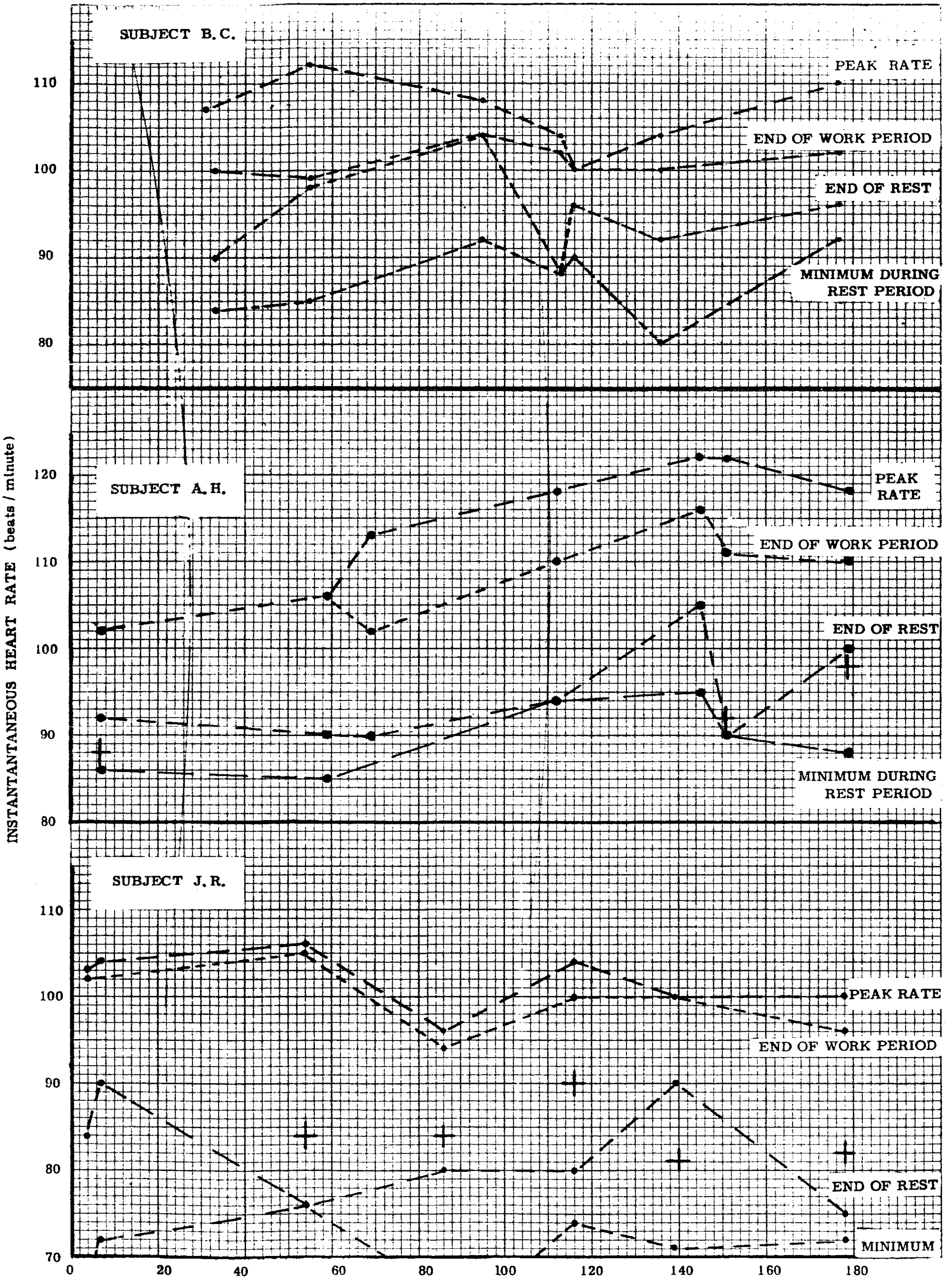


FIGURE 21: MAXIMUM, MINIMUM, START AND END OF WORK HEART RATES FOR 3 SUBJECTS AT 250 Kcal / hr IN THE MOST SEVERE ENVIRONMENT, P4SR 3.

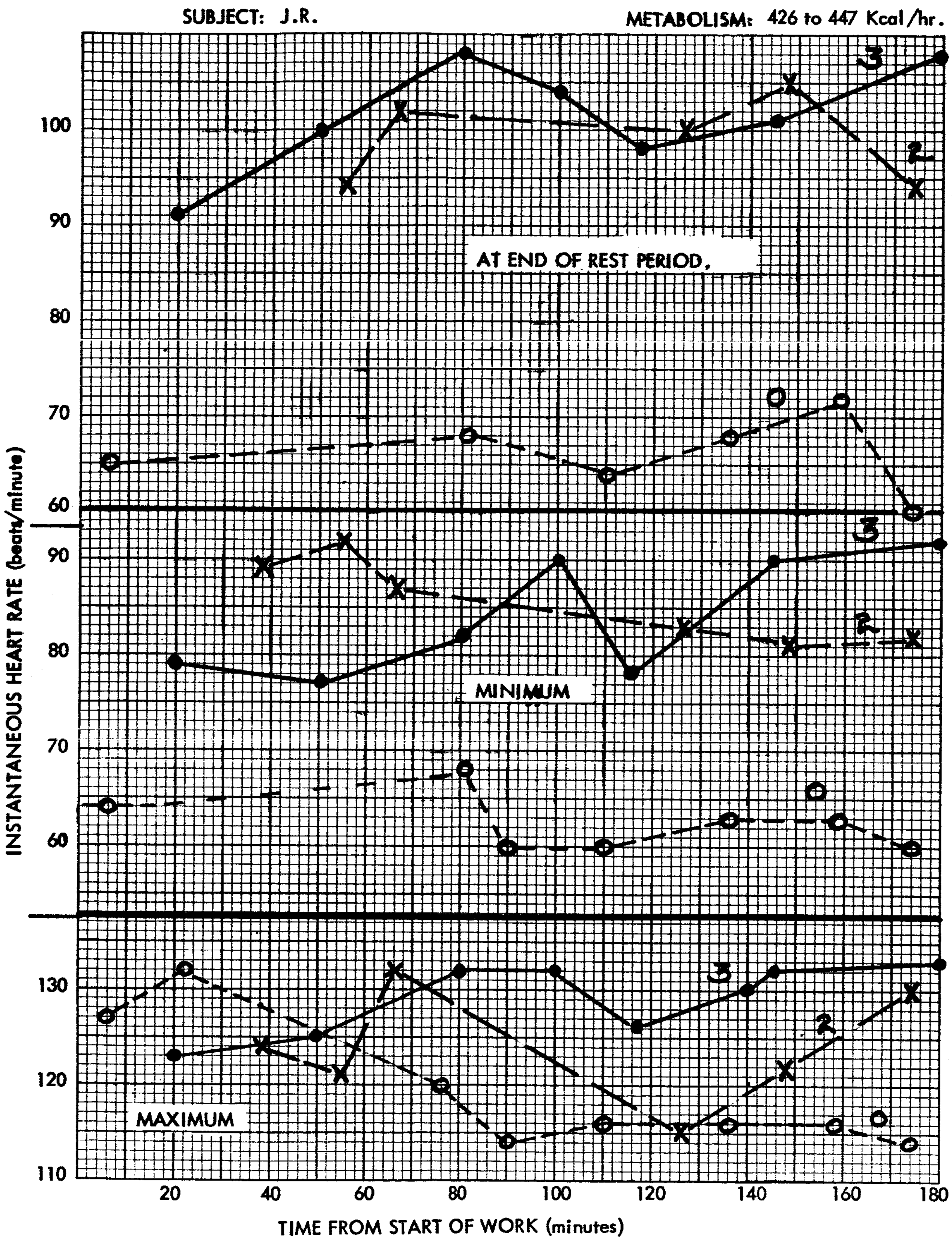


FIGURE 22: TIME HISTORY OF HEART RATE AT 3 POSITIONS IN THE WORK/REST CYCLE, FOR 3 ENVIRONMENTS; (P4SR 0, 2 and 3)

fireman. The upper panel shows the instantaneous heart rate at the end of the 60-second rest period; the middle panel gives the minimum heart rate (i.e., the longest pulse interval) in the sampled cycles and the bottom panel shows the maximum heart rate (i.e., shortest pulse interval) in the same selected cycles. In each panel the same three experiments are compared, representing the environment stress levels 0, 2 and 3 on the P4SR scale.

It is immediately apparent that it is the recovery period following each 30 seconds of work which is most strongly affected by the environment. The minimum and final heart rates in the rest period are roughly 50% higher in the "sweating" environments while the peak heart rate is only 15% higher, compared to the "no-sweat" environment whose P4SR index is zero.

Tables 6 and 7 summarize the data for maximum and minimum heart rate respectively. Each entry in these tables is an average for the work/rest cycles sampled in that particular experiment.

Table 8 is a summary of the average cardiac cost in each working experiment, computed as the average number of beats in a complete cycle divided by cycle length in minutes. There are fewer entries in this table than the preceding two, because fewer of the recordings were suitable for counting individual pulses over a complete cycle.

In half the subjects there is a clear-cut increase in cardiac cost between P4SR 2 and 3 at the highest activity level. At the median activity level the heart rate data are equivocal, while for the resting experiments there seems to be a slight tendency for increased cardiac cost at the highest stress level. Apparently the experiment design effectively obscures or eliminates the cardiac components of fatigue.

Table 6

Peak Heart Rate

(Average of cycles sampled in each experiment)

P4SR Index	Activity Level 100 Kcal/hr					250 Kcal/hr					400 Kcal/hr					
	BC	RM	JR	AH	JE	BC	RM	JR	AH	JE	BC	RM	JR	AH	JE	BP
< 0					86						136	127		131	143	
0	83	82			70		98	108		110		140	119	142	145	
0.5	84		86	95		103	92	101		126*	133	139	113	131	139	129
1	97	107	80	86		88	98	85	101		130	131	130		137	144
2	97	94	93	98		105	117	88	109	110	118	124	124	136	146	142
3	104	96	122	100	92	106	109	101	115	130	146	138	129	144	150	138

* 40/60 work/rest schedule

Table 7

Minimum Heart Rate

(Average of cycles sampled in each experiment)

P4SR Index	BC	RM	JR	AH	BC	RM	JR	AH	JE	BC	RM	JR	AH	JE	BP
< 0										111	75		90		
0		64				75						63	107		
0.5	68		65	73	74	62	65		94*	89	88	63	91	75	
1	80	60	70	61	62	62	63			88	84	69		89	113
2	68	63	62	61	73	68	65	70		77	68	86	102	112	118
3	80	65	84	73	89	80	68	86	96	128	92	82	117	123	106

* 40/60 work/rest schedule

Table 8

Cycle Average Heart Rate (beats/minute)

Stress Level	250 Kcal/hr						400 Kcal/hr					
P4SR	BC	RM	JR	AH	JE	BP	BC	RM	JR	AH	JE	BP
<0								140			132	
0	94	86	108		91							
0.5		76	89		116		116	108		104	120	112
1			80		119				104		119	131
2			82		118	108					132	133
3	101		84	93	130						135	131

Sweat Production

In general, the rate of evaporative weight loss reached a stable value in each experiment during the second half hour, and showed only minor variations thereafter. For each experiment the cumulative weight loss, adjusted for water intake, was plotted against time as a means of identifying the periods of greatest stability. The average weight loss rate and mean skin temperature during these most stable periods were taken as the characteristic datum for that experiment.

In Figure 23, the data for 59 three-hour experiments of the second series, low air movement, are plotted against mean skin temperature. The linearity of the relationship between these two parameters, at each level of activity, is striking, in spite of the inherent variability in actual metabolic rate which has been mentioned earlier. Where the variation from experiment to experiment is less, as in the seated condition, the scatter of the points is minimal.

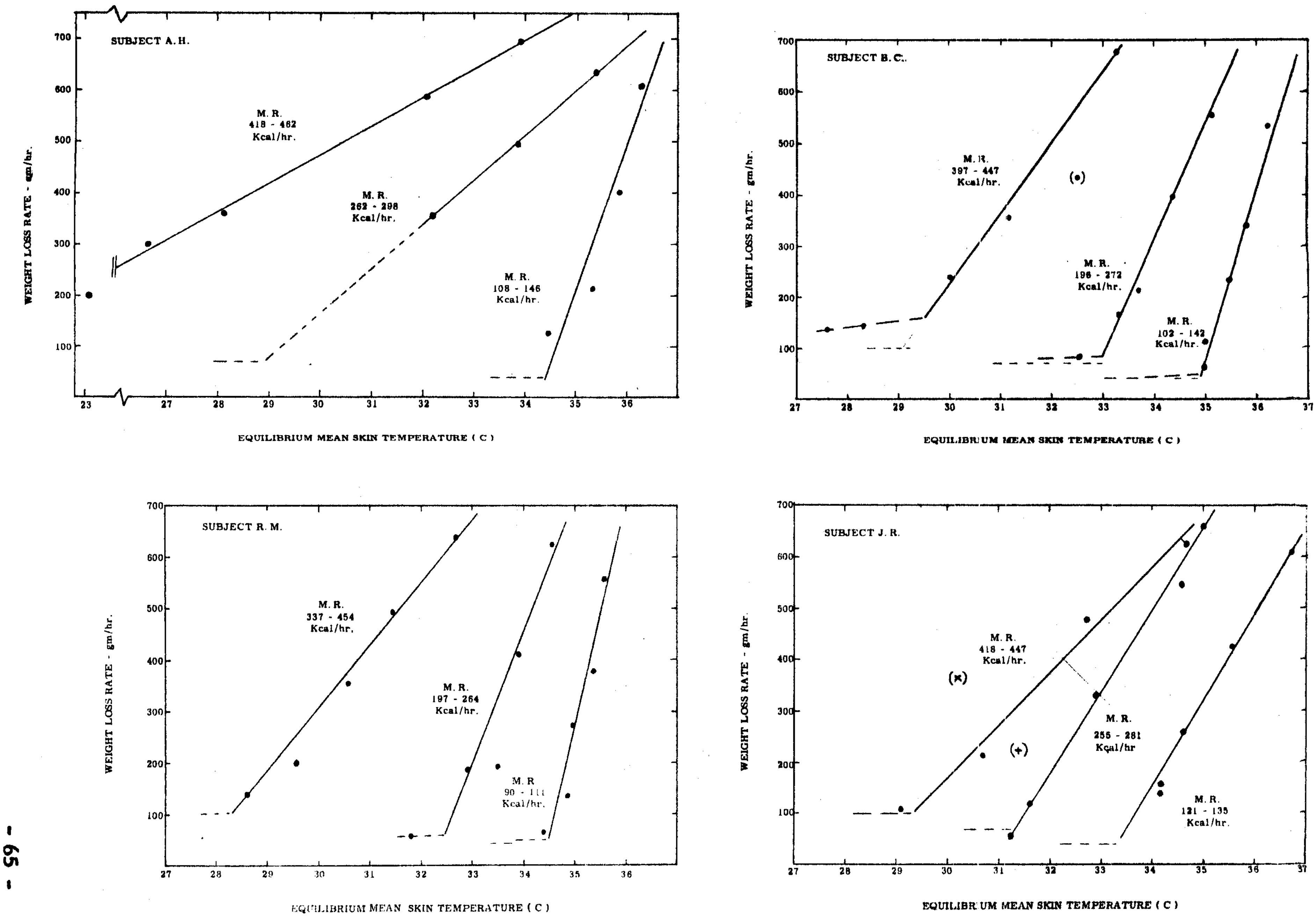


FIGURE 23: SWEAT RATE AS A FUNCTION OF SKIN TEMPERATURE FOR 4 SUBJECTS;
(BASED ON 15 COMBINATIONS OF ENVIRONMENT AND METABOLISM)

An unexpected finding was the reduction in slope with increasing metabolic heat production. The slope can be thought of as a sensitivity coefficient, expressing the differential response of the sweat mechanism to a unit change in temperature at the surface. Figure 24 shows the collected data for the two subjects used in the initial baseline series; the evidence indicates strongly that the slopes or sensitivity coefficients are equivalent at all three activity levels for subject J.E. Possible reasons for this discrepancy between J.E. and the other subjects will be discussed later.

The point of intersection of the sloping portion of each curve with the near-horizontal portion represents the estimated threshold of generalized sweating. The position of the horizontal segment is inferred for the majority of Series II subjects from a knowledge of the ventilatory evaporative loss plus insensible perspiration or skin diffusion loss. This calculated quantity is supported by the extensive exploration of the cool to cold region for each activity level with subject J.E., summarized in Figure 24.

It will be noted that in five experiments at the highest activity level where the mean skin temperature was below 31°C, J.E.'s gross evaporative loss ranged from 82 to 120 for an average of 97 grams per hour. Two experiments at the median activity level with skin temperatures below 32.5 had evaporative loss rates of 62 and 68 grams/hour, and two resting experiments with skin temperature below 34°C had rates of 35 grams/hr.

Adjusting for the fact that J.E. is the lightest and smallest of the subjects, we have rounded off these observations for generalized application to all subjects; the estimated nonsweating evaporative weight loss is taken to be 40, 70 and 100 grams/hour for metabolic rates 100, 250 and 400 Kcal/hr respectively.

Since this residual loss is due to physical processes which are essentially independent of physiological influence, there is no reason to expect

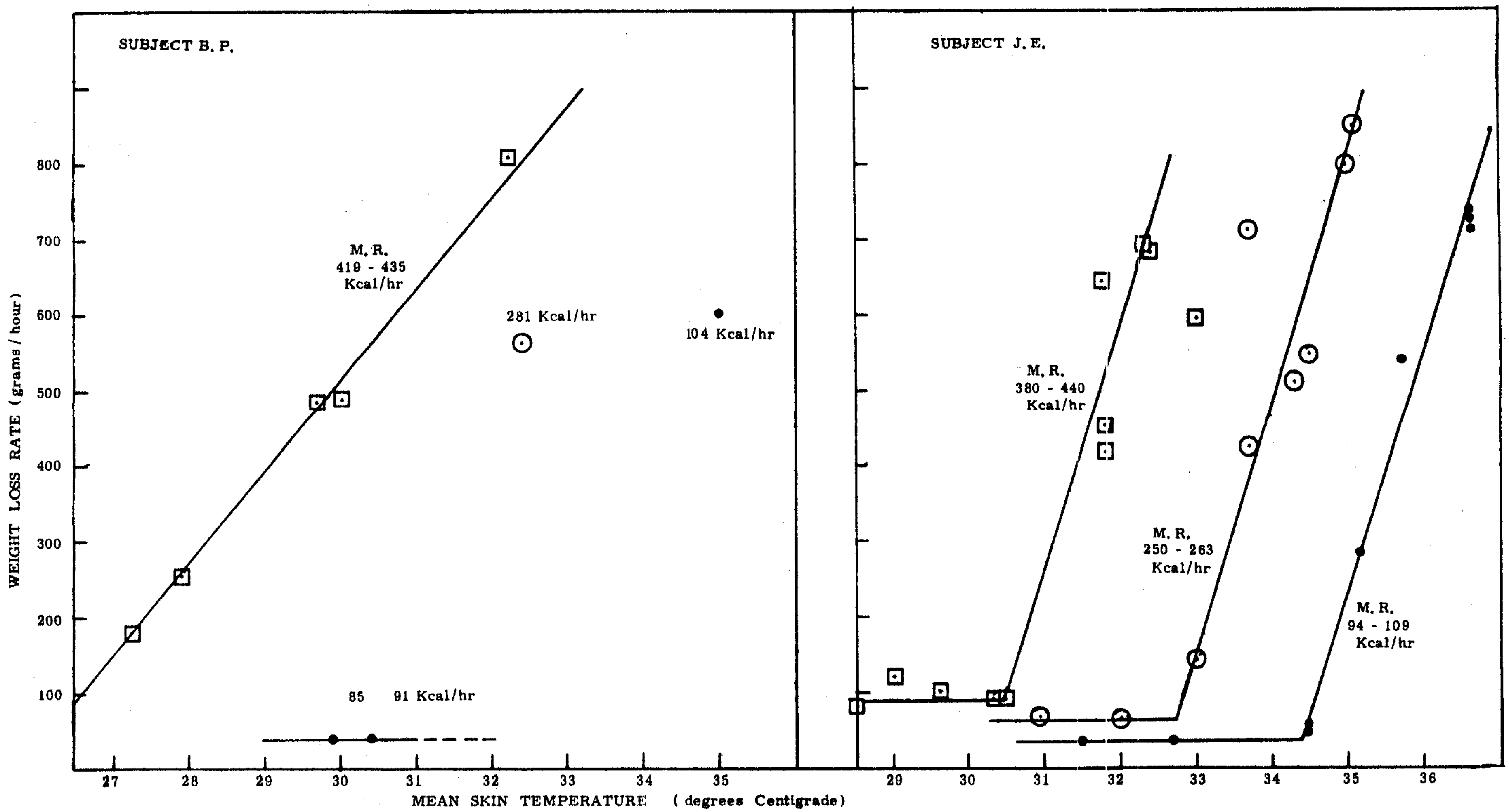


FIGURE 24 : SWEAT RATE AS A FUNCTION OF SKIN TEMPERATURE AND METABOLISM for two experienced subjects.

significant variation between subjects. On the other hand, there appears to be a tendency in the thick-skinned subjects, for a transitional zone between the end of generalized total-body sweating and pure diffusional loss. This is illustrated in Figure 25 for subject A.H. and may be detected in the data for subject B.C. in Figure 23.

A plausible explanation for the gradual approach of the evaporation rate to its minimal value in the fatter man is suggested by the individual skin temperature history of Figure 14, which corresponds to the lowest point on the curve of Figure 25. Note that five of the skin locations, or half the body surface was below 22°C, while the other half were above 24. If the blood vessels in the colder skin regions were constricted, their contribution to the overall mean temperature for returning peripheral venous blood could be minimal; if this were the effective stimulus to the sudomotor control system, its magnitude in this experiment might well be much higher than would be suggested by the average of all skin surface temperatures.

Returning to Figure 25, it can be seen that the extrapolation below 300 grams/hour of the straight line relationship for higher sweat rates intersects the 100 gram/hour axis (which we have assumed to be the insensible loss level for this activity) at a temperature of 24°C (75°F). It is significant that this is the dividing line between the two groups of skin temperatures in the coldest experiment mentioned above. There is a strong implication that if all skin locations could be reduced in temperature to below 24°C, sweating would cease. Thus the picture is consistent with concepts of local sweating control during work as well as with the idea of an integrated peripheral venous blood temperature.

The results for subject B.C. can be interpreted in the same way; the extrapolation of the main relationship to 100 gram/hr evaporative loss predicts 29°C as the threshold temperature, for a homogeneous skin surface.

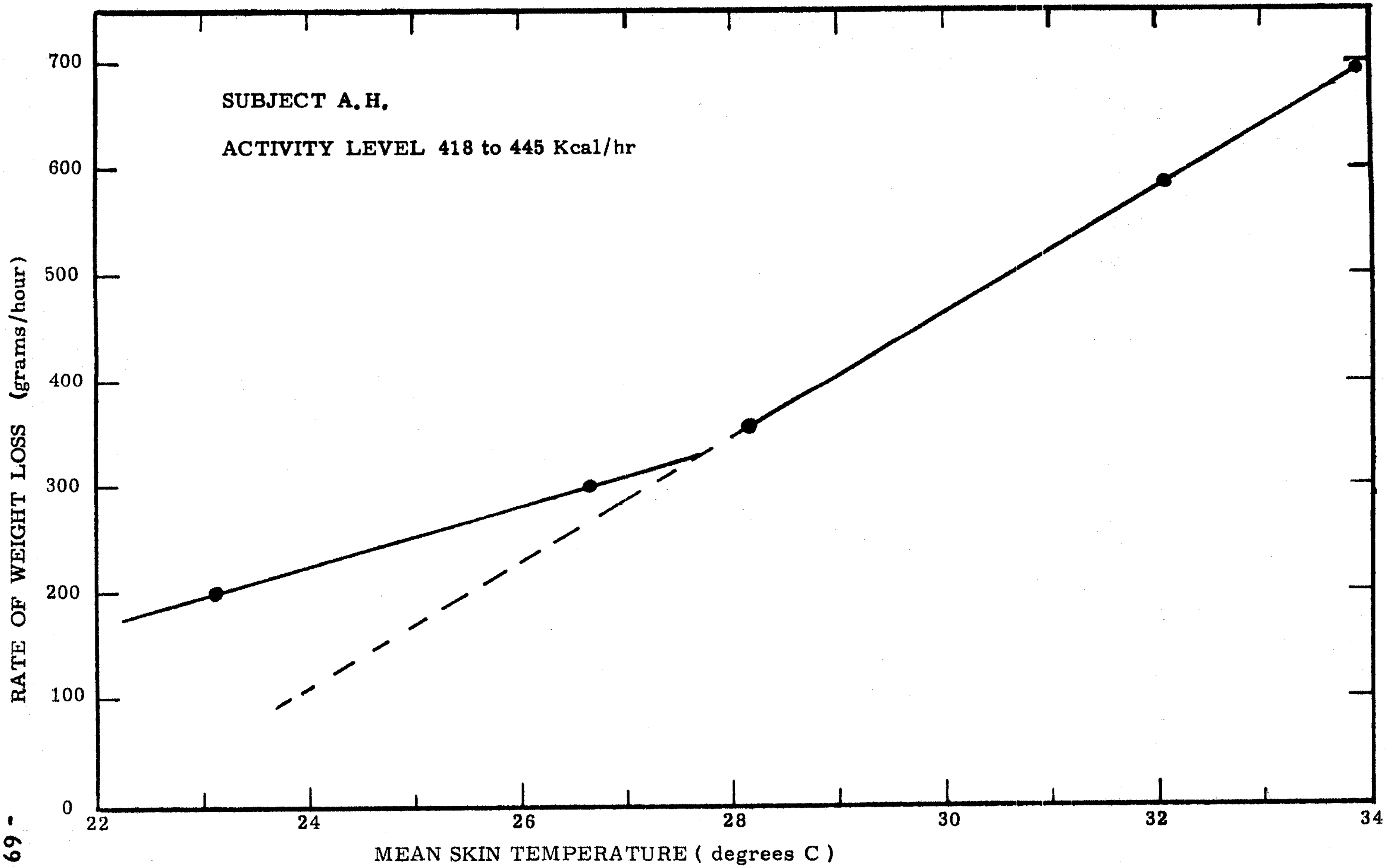


FIGURE 25: SWEAT RESPONSE AT THE HIGH ACTIVITY LEVEL IN A SUBJECT WITH THICK SKIN

In Figure 26, the intercepts of the sweat sensitivity curves with 40, 70 and 100 grams/hour weight loss lines respectively are plotted against the average of the metabolic rates included in each curve. The resultant graph depicts the range of individual variation in predicted threshold skin temperature at any given activity level, and indicates the order of magnitude of the conductance of the outer layer of epidermis. The solid line represents the nonsweating (i.e., homogeneous skin temperature) threshold for the subject with the heaviest layer of skin fat. An increase of 165 Kcal/hr in the heat flow through the skin (neglecting changes in ventilatory and diffusion losses) is associated with a drop in nonsweating skin temperature of 5.1°C. Neglecting the probably significant change in net effective skin blood temperature, this would suggest a skin conductance of 32.5 Kcal/hr, °C. for this thick-skinned man.

Applying the same reasoning to the subject J.E., we may estimate that his apparent skin conductance was 62.5 Kcal/hr, °C. Subject J.R. appears to have a slightly higher apparent skin conductance, 73.5 Kcal/hr,°C. Apart from the absolute validity of these estimates of conductance, the existence of a 2 to 1 range of variation within our sample population is well supported by the evidence.

It should be noted that the foregoing values for apparent skin conductance apply only to the cool, nonsweating skin condition; it is possible that the vasodilation which accompanies the onset of sweating may result in an increase in the number of active capillary loops, with the consequent reduction in the effective thickness of the bloodless layer of skin.

The near-identity between the slopes for A.H. and R.M. in Figure 26 in the upper range of metabolic rates is a surprising finding, which indicates a need for an intensive analysis of the logic underlying some of our common assumptions about the effect of skin fat. Subject R.M. had the lowest skin-fold thickness of any of the subjects, while A.H. had the highest. The

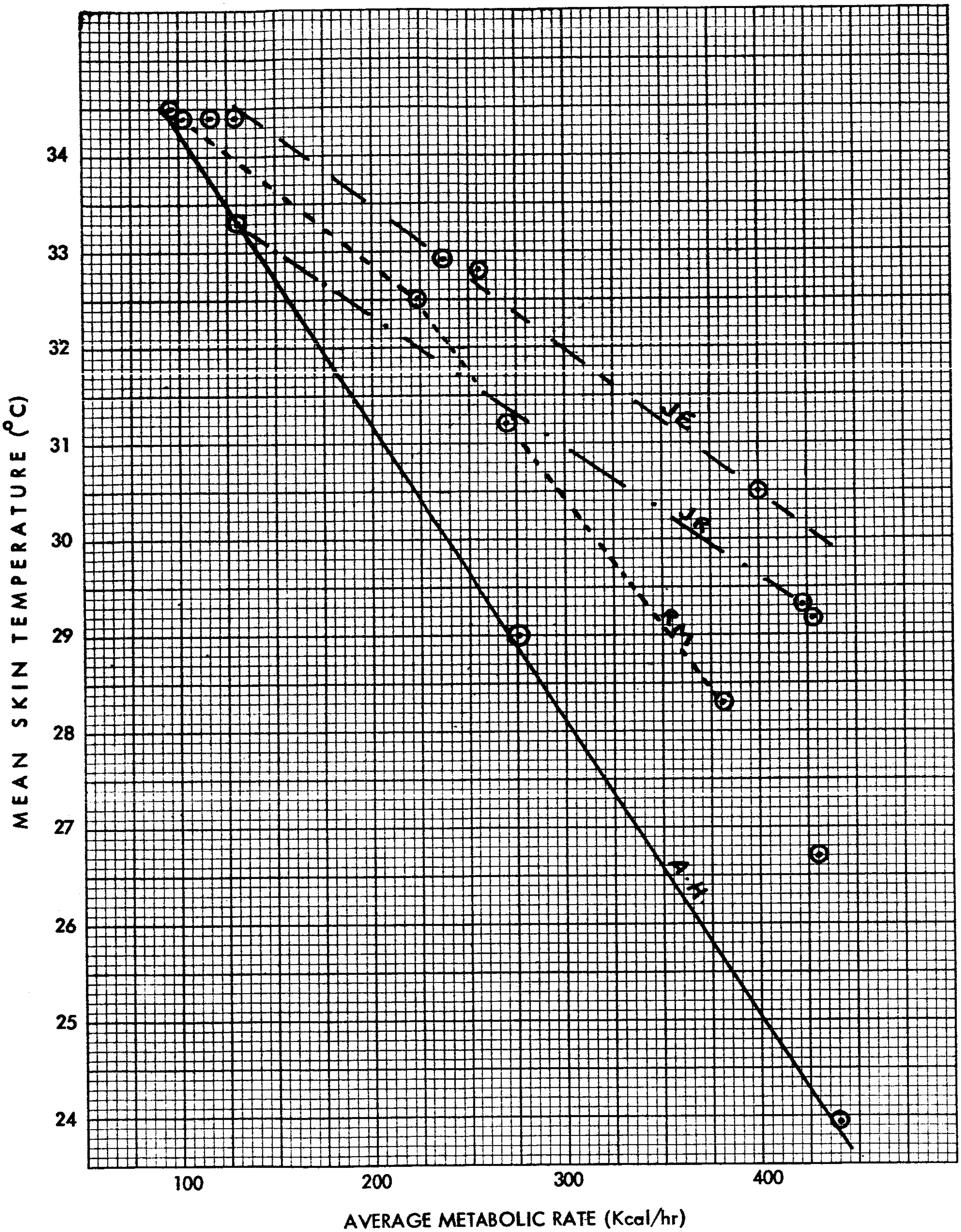


FIGURE 26: INTERPOLATED THRESHOLD FOR SWEATING: Mean skin temperature at which generalized sweating is predicted to begin in 6 individuals, as a function of metabolic rate.

difference of 2.6°C between their threshold skin temperatures at a metabolic rate of 400 Kcal/hr is in the expected direction, but it is noteworthy that the two men with intermediate skin-fold thicknesses show thresholds higher than R.M. by 1.8 and 1.9° respectively at this same metabolism. Subject J.E., whose skin-fold measurements were very close to those of R.M., has an indicated threshold at 400 Kcal/hr of 30.5°C, a full 2.7°C higher than the value predicted for the latter, and 5.3°C higher than that of Subject A.H.

When the subjects are compared with respect to the skin temperature associated with an evaporative loss of 500 grams/hr, the scatter is found to be much less than at the threshold of sweating. The greatest variance is found at the highest activity level, as is clear in Figures 23 and 24; at 400 Kcal/hr the skin temperature for a sweat rate of 500 grams/hr ranged from a low of 29.8 to a high of 33.4, with 4 out of 6 subjects falling between 30.5 and 32°C. At 250 and 100 Kcal/hr, the total spread of skin temperatures producing 500 grams/hr was only 0.9 and 0.7°C respectively.

It should also be noted that at the highest activity level, the lowest skin temperature producing a sweat rate of 500 grams/hr was 0.7°C <u>lower</u> than the maximum nonsweating skin temperature. At the median activity level, only 1°C separated the highest nonsweating skin temperature and the lowest 500 gram/hr temperature.

<u>Sweat Sensitivity Coefficient</u>

The slope of the relationship between sweat rate and skin temperature may be referred to as the sensitivity coefficient for sweating as a function of skin temperature. (Use of this term is not intended to imply a cause and effect relationship between these parameters.) For four subjects, the sensitivity coefficient varies inversely with the metabolic rate, whereas subject J.E. appears to display a constant sensitivity coefficient at all three activity levels.

In Figure 27 the individual coefficients (taken as the slope of the eye-fit curves in Figures 23 and 24) are plotted against activity level. The average coefficient of sweat response to skin temperature for four subjects at the high activity level is less than one-third of the coefficient for the experienced subject J.E. For comparison, the average sweat sensitivity coefficient for five college runners, studied by Piwonka, Robinson et al (Ref. 5) after a winter of training without heat exposure, is seen to be only 65% higher than the average of our four volunteer subjects (see discussion section).

Under resting conditions, the average coefficient for the group of four volunteers in Series II is within 10% of the value for the experienced subject J.E. From lowest to highest individual value, however, the range is 165 to 430 grams/hr, °C, or 160%. It is interesting to note that the coefficient for J.R. at rest, the lowest one for that condition, is equal to the average for Piwonka's runners at the highest activity level.

Skin Versus Rectal Temperature as a Correlate of Sweat Response

To illustrate the clear-cut superiority of skin temperature over core temperature as a point of reference for the analysis of sweat response, Figure 28 has been prepared from the averaged data of the three subjects in Series II who are most similar to each other and most representative of a healthy, physically fit population without special stress-resistance training.

In the upper panel is seen the familiar pattern of linear curves relating sweat output and skin temperature with metabolic rate held constant. In the lower section of the chart, no consistent pattern or relationship can be seen between sweat rate and rectal temperature. The mean sensitivity coefficients for these three men are 285, 148, and 131 grams of sweat per hour per Centigrade degree change in skin temperature (for activity levels 100, 250 and 400 Kcal/hr respectively).

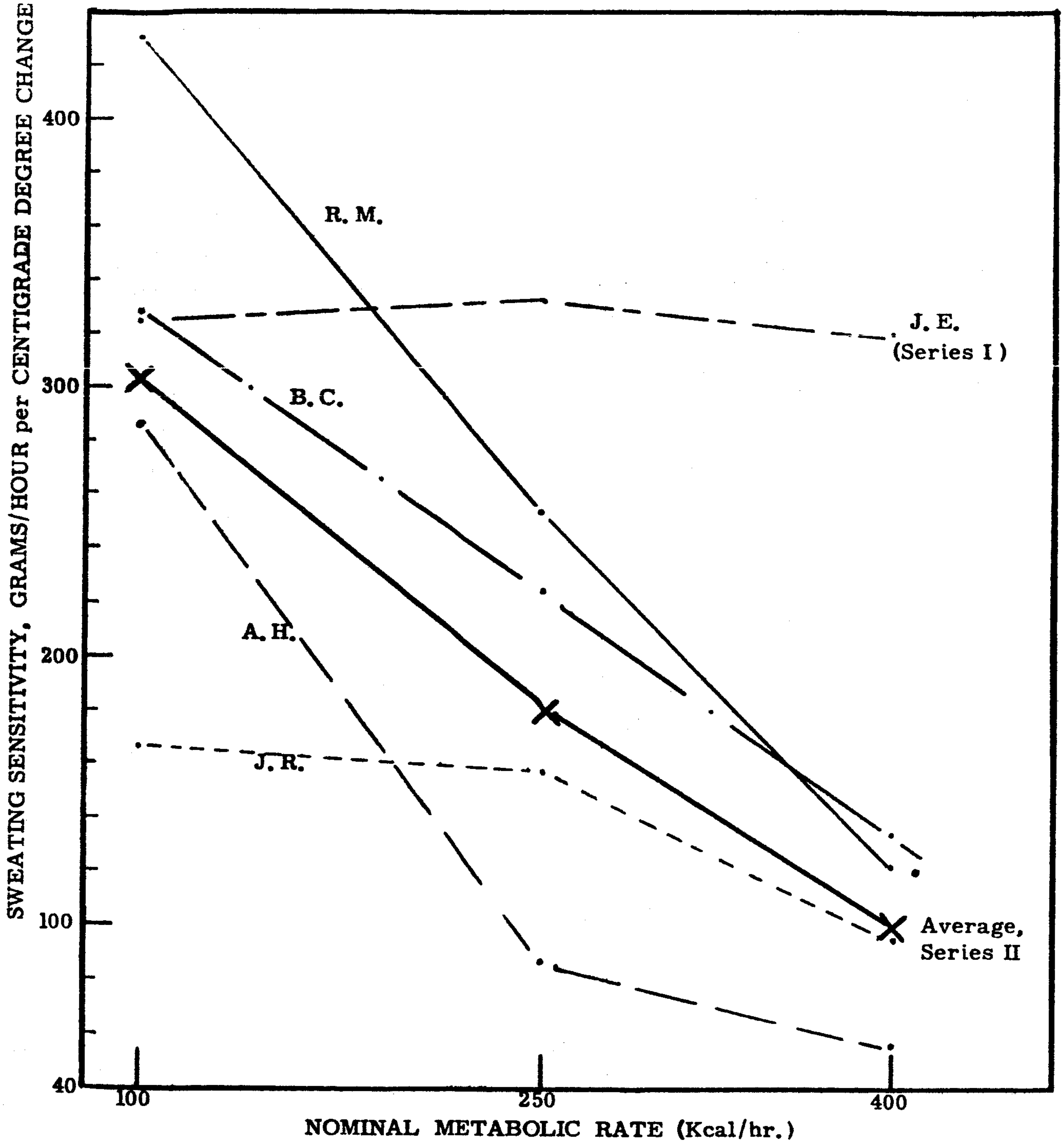


FIGURE 27: SENSITIVITY COEFFICIENT FOR SWEATING AS A FUNCTION OF SKIN TEMPERATURE VERSUS ACTIVITY LEVEL.

The sensitivity coefficient is the slope of the plot of sweat rate versus skin temperature, from Figures 23 & 24.

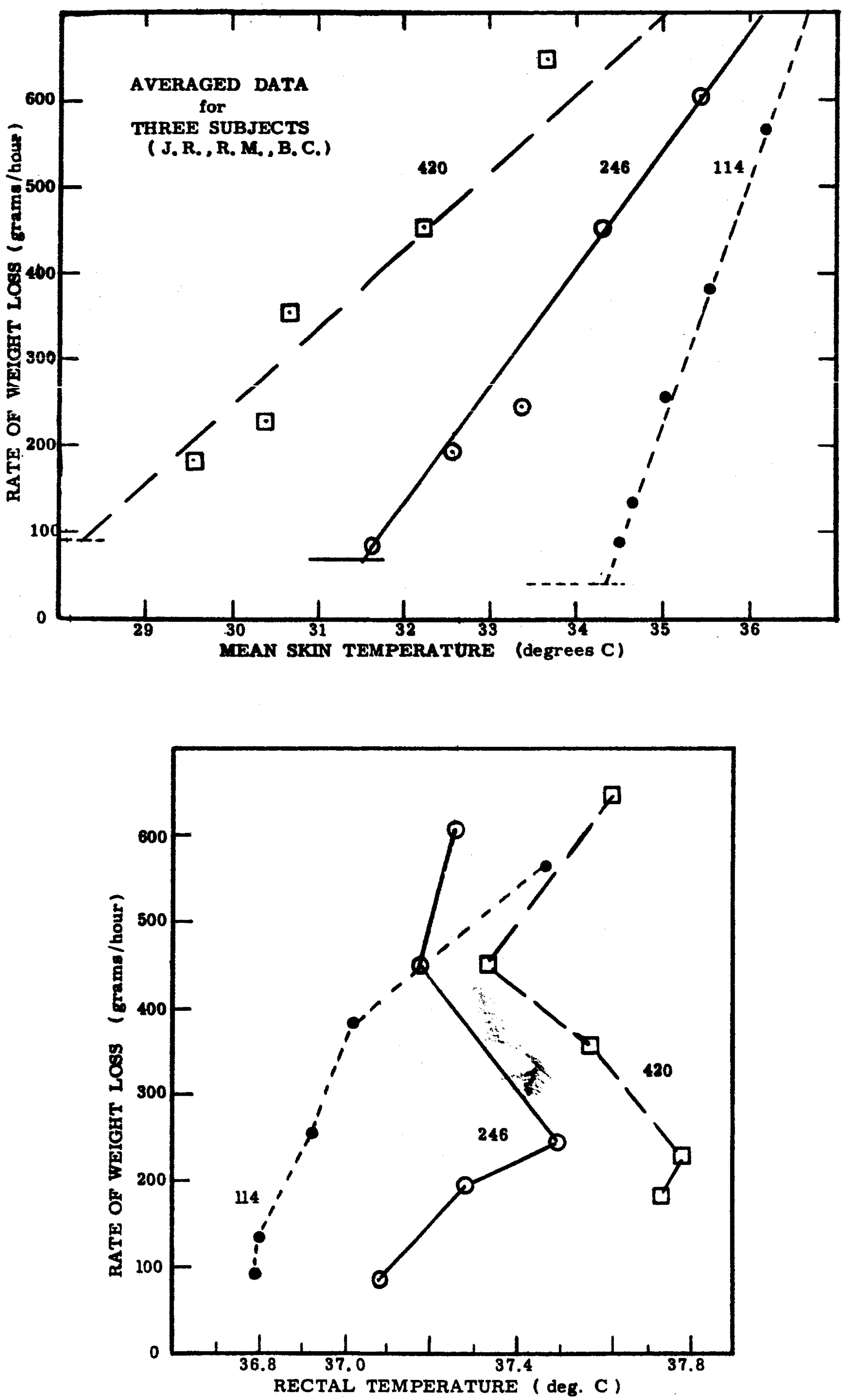


FIGURE 28: COMPARISON OF SKIN AND RECTAL TEMPERATURES AS MEANS OF CORRELATING SWEAT RATES IN 15 ENVIRONMENTAL SITUATIONS.

Figure 29 extends the comparison of skin and rectal as useful indicators of thermal strain to their correlation with environmental temperature. It can be seen that the means for this relatively homogeneous group are never confused between metabolic rates when skin temperature is examined as a function of environmental temperature, but cannot be reliably separated on the basis of rectal temperature. The relatively moderate scatter of points in the sweat rate plot is a tribute to the practical utility of the P4SR index system for predicting equivalence of environments. In this panel of Figure 29, the lower ends of the three straight lines represent the predicted air temperature which, at low humidity, should be associated with essentially no sweat; viz. 10, 20.5 and 29.5°C (50, 69 and 85°F) for the high, median and resting activity levels respectively.

By replotting the data shown in Figure 29, the operative conductance of the experimental environment can be deduced, that is, the combined radiative and convective coefficient for heat transfer between the skin and the environment. When average sweat rate is plotted against average differential temperature, skin minus environment, (see Figure 30) three highly linear curves are formed, (one for each activity level) whose common slope is 25 grams per hour per Centigrade degree difference between air and skin. This means that for every decrease of one degree in the potential for heat loss from the skin, or increase of one degree in potential for heat gain to the skin, the body's regulation system increased sweat production by 25 grams/hour, so that evaporative heat loss increased 14.5 Kcal/hr.

Since equilibrium was maintained in all cases, the increase of 14.5 Kcal/hr in evaporation per degree change in temperature difference must have been exactly balanced by a decrease of 14.5 Kcal/hr in the heat loss by convection plus radiation.

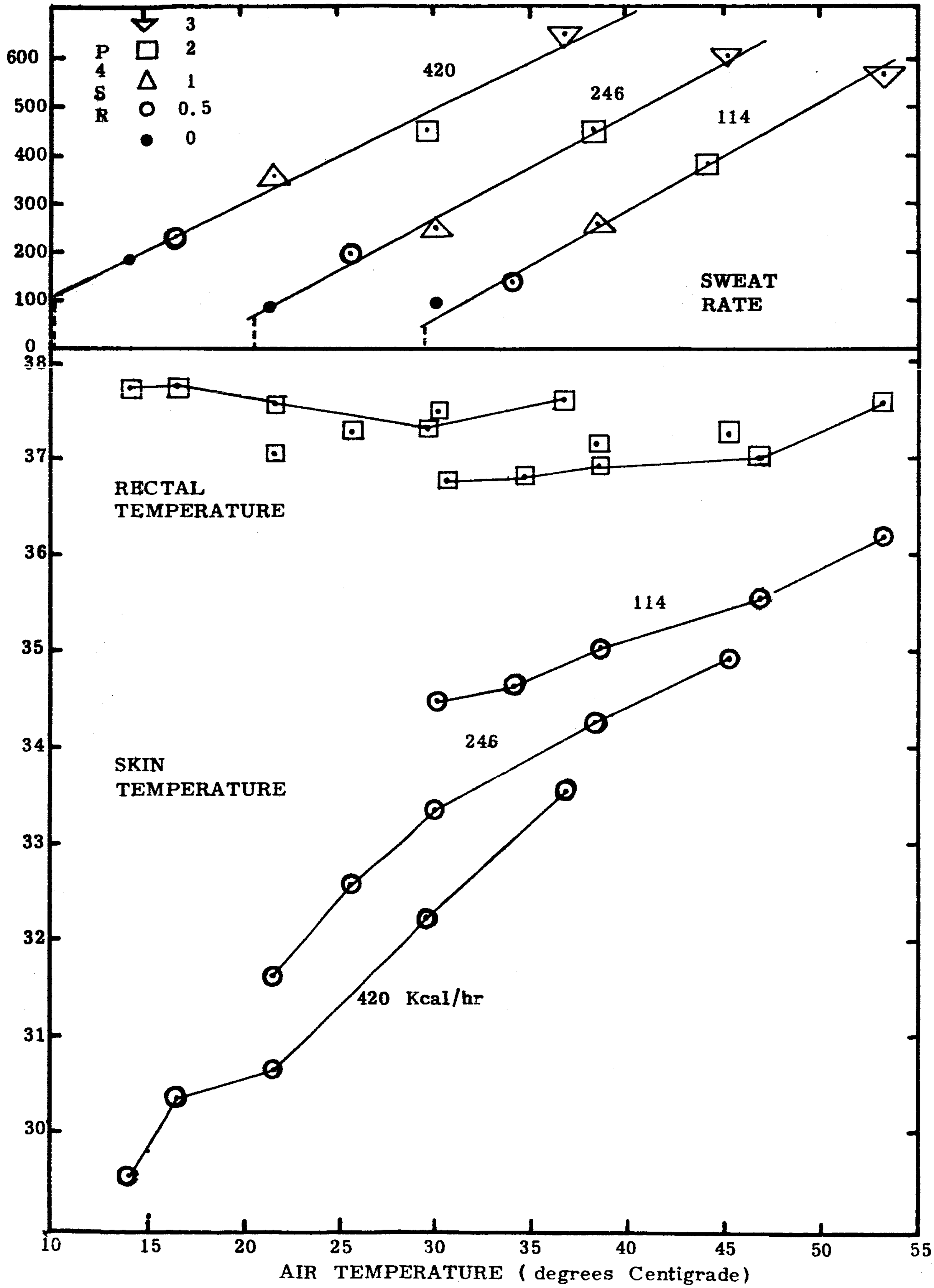


FIGURE 29: SWEAT OUTPUT, SKIN TEMPERATURE, & RECTAL TEMPERATURE AS A FUNCTION OF AIR TEMPERATURE AND METABOLISM (with a low and constant vapor pressure).

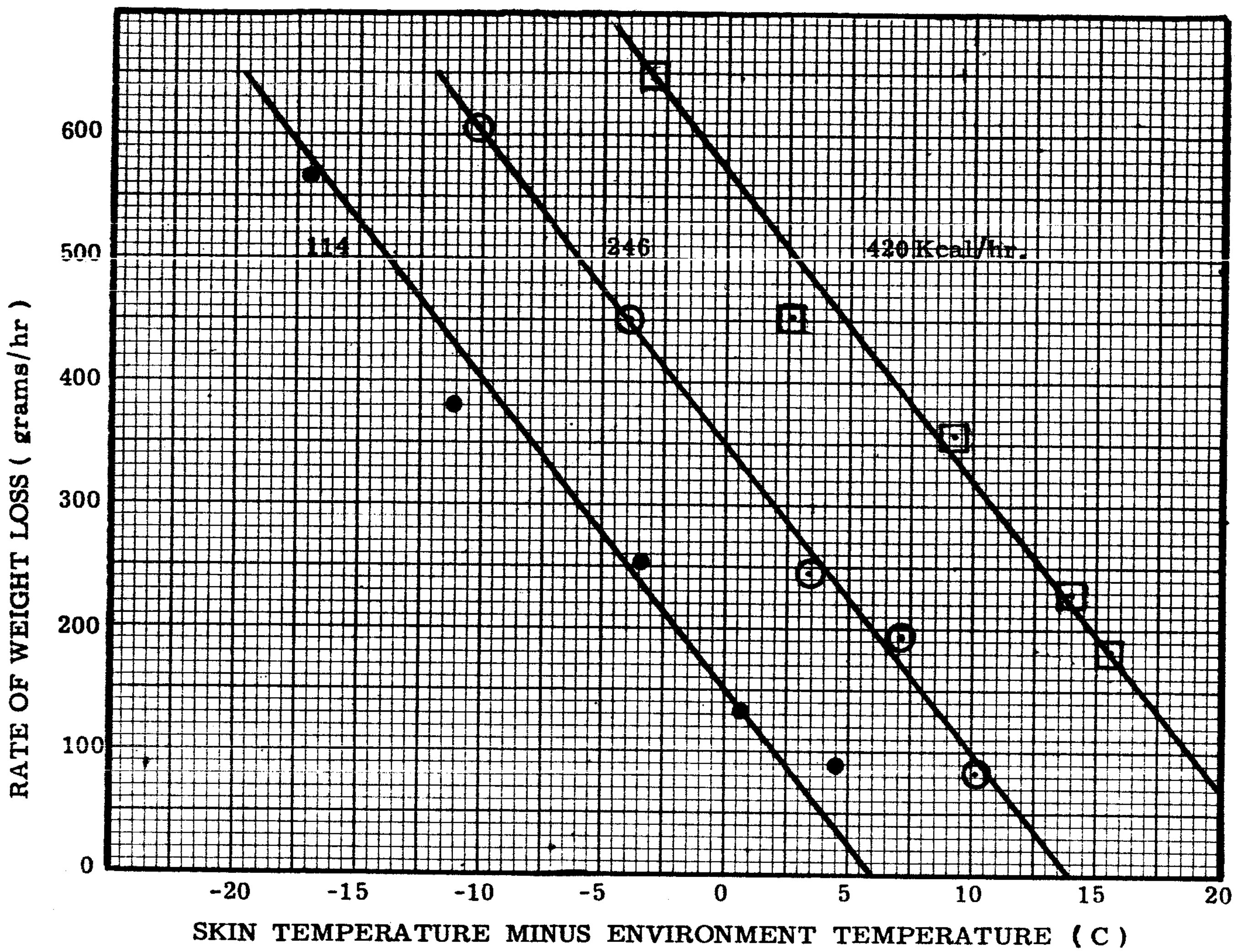


FIGURE 30: SWEAT RATE AS A FUNCTION OF SKIN TO ENVIRONMENT DIFFERENTIAL TEMPERATURE; mean data for 3 subjects.

In other words, the operative heat transfer coefficient (h_o in the notation of Blockley et al, Ref. 29) in all these experiments averaged 14.5 Kcal/hr, ^oC.

It can similarly be deduced from Figure 30 that the minimal skin to air temperature difference which will preclude the necessity of sweating at the three activity levels, at this rate of heat transfer from the skin, is 4.5, 11.5, and 19.5^oC respectively.

Water Balance

During Series I, a consistent and earnest effort was made to encourage the subjects to drink frequently in an attempt to replace the full sweat loss every 20 minutes or half hour. Short of coercion, it seemed to be impossible to meet that goal. We have had some experience in the past with gastric distress and nausea when subjects were pressured to drink on an arbitrary schedule while engaged in a marching task in the heat; it was felt that the risk of nausea outweighed the desirability of maintaining a perfect water balance in these experiments. Susceptibility to gastric and intestinal distress after ingestion of food is said to bear an inverse relationship to physical fitness, according to Karpovich (Ref. 28). We believe that a similar reduction in the adverse response to fluid intake accompanies the development of heat stress resistance ("heat acclimatization"). Table 9 summarizes the Series I data.

In seven experiments at a P4SR near 2, the sweat replacement ranged from a low of 24 to a high of 43%, with an average of 31%, resulting in an average dehydration, based on the initial nude weight, of 1.38% (range 1.11 to 1.53). The replacement proportion tended to be somewhat higher in the P4SR 3 experiments, ranging from 42 to 75% for an average of 55%. Three out of the five terminal dehydrations at P4SR 3 were higher than the highest value seen at P4SR 2; the average was 1.56% (range 0.79 to 2.14).

Table 9

Sweat Loss and Water Replacement

in Warm Runs of Series I

Exp't. No.	P4SR (nominal)	Net Loss in 3 Hours (lbs)	Water Intake	Total Evaporation (lbs)	Total Evaporation (liters)	4 Hour Evap. Rate (liters)	Sweat Replacement (%)	Final Dehydration (%)
A: Resting Experiments								
E12	1	1.75	0.25	2.0	0.91	1.22	12.5	1.20
E15	3	1.14	3.35	4.49	2.04	2.72	75.0	0.79
P2	2	2.29	1.75	4.04	1.84	2.46	43.0	1.38
B: Experiments at 250 Kcal/hr								
E5	1.8	1.70	1.25	2.95	1.34	1.79	42.0	1.23
*E8	2	2.21	1.25	3.46	1.57	2.10	36.0	1.50
E11	3	2.86	2.75	5.61	2.55	3.40	49.0	1.96
E11A	3	3.14	2.25	5.39	2.44	3.26	42.0	2.14
P5	2	2.50	1.25	3.75	1.70	2.27	33.0	1.53
C: Experiments at 400 Kcal/hr								
E13	1**	0.65	0	0.65	0.30	0.40	0	0.45
E14	2	1.90	0.60	2.50	1.14	1.52	24.0	1.33
E14A	2	1.63	0.75	2.38	1.08	1.44	31.0	1.11
E17	3	1.80	3.00	4.80	2.18	2.90	62.5	1.24
P4	2	2.53	0.80	3.33	1.51	2.02	24.0	1.51
P4A	2	2.19	0.75	2.94	1.34	1.79	25.5	1.30
P7	3	2.75	2.40	5.15	2.34	3.12	46.5	1.65

*High humidity - 28.5 mm Hg

**Estimate only - off-scale for nomogram

The voluntary dehydration which typified these early experiments seemed to be frequently correlated with the occurrence of small step-wise increases in rectal temperature. The first such increase usually occurred when the clothed weight dropped below its initial value by 1% of the nude weight. Figure 31 illustrates two examples of this phenomenon. In experiment E 11 equilibrium was established by 70 minutes, and remained stable for almost an hour; water replacement fell behind sweat loss by almost a pound between 40 and 60 minutes, which is the period when equilibrium normally is reached. Indeed, there is a slight suggestion of an approach to equilibrium at the 50-minute point, 4 hundredths of a degree below the eventual equilibrium level. Between 60 and 100 minutes 1.25 lbs of water were ingested, but in the subsequent 30 minutes the 1% deficit point was passed; apparently synchronous with this event the rectal temperature stepped to a new plateau 0.06°C higher than the previous level. At 150 minutes, while body weight continued to drop continuously because of inadequate water replacement, another step of equal magnitude occurred.

It must be kept in mind that the total weight of the body at any instant does not provide an accurate estimate of the relative water content of the body, since water still remaining in the stomach or gut is effectively still outside the body. The rate of water absorption from the gut is almost certainly subject to wide fluctuations depending on splanchnic blood flow, degree of dehydration etc. Thus the significance of a deficit in total body weight of 1%, relative to the starting condition depends on how much of the water previously ingested has passed into the blood stream.

The situation reflected in the lower pair of curves in Figure 31, for experiment E 17, differs from the previous case in that 0.6 lbs of water was ingested shortly after the 1% deficit level was passed; if one assumes that absorption was sufficiently rapid to prevent further imbalance from developing in the blood and tissues, the return of rectal temperature to its original plateau level can be interpreted as a reflection of the return to an optimal blood volume.

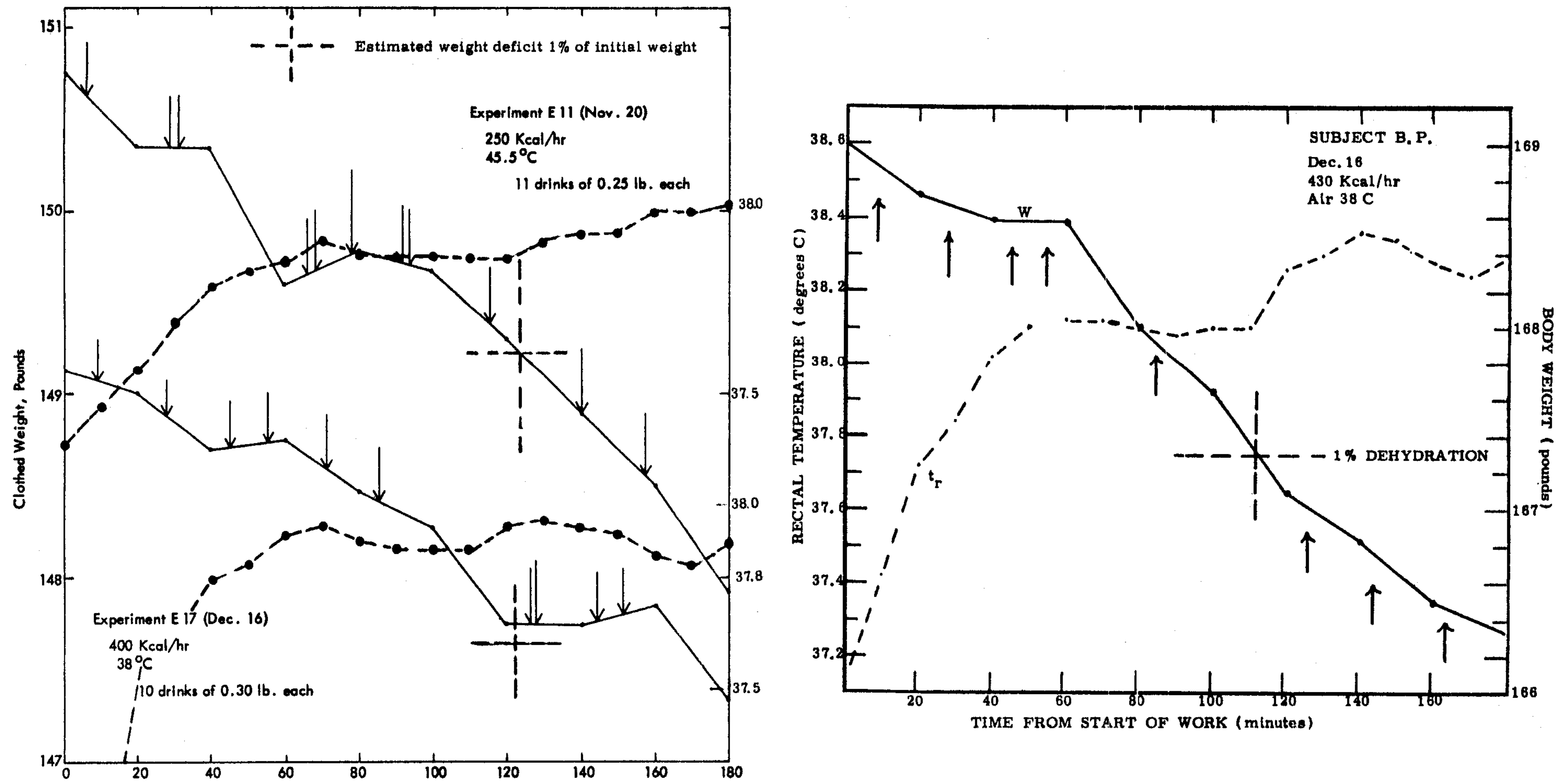


FIGURE 31: EFFECT OF WATER DEFICIT ON RECTAL TEMPERATURE

The fact that the step in rectal temperature occurred before the 1% gross deficit was reached in the experiment where 25 minutes without water ingestion precedes this point, and simultaneously with the attainment of a 1% deficit when water had been taken 5 minutes before, suggests that the critical level of actual body water content may be closer to the 0.75% deficit point than the 1%. Several experiments provided evidence in support of this view.

Experiment P 7 gives a most dramatic demonstration of the phenomenon. Thermal equilibrium was attained with almost classical precision at 50 minutes, and was maintained for a full hour while body weight dropped steadily, (one drink during this period had little influence on the developing deficit). Almost precisely at the moment body weight passed the 1% deficit mark, rectal temperature stepped 0.16°C to a new high. The three subsequent drinks did nothing to stop or reverse the growing deficit and rectal temperature continued to oscillate round its new high.

Early in Series II, a new policy was adopted with respect to the replacement of sweat loss. The data coordinator made sure that water was presented to the subject after the first weighing, and after every subsequent weighing, in an amount sufficient to counterbalance or exceed the estimated or anticipated sweat loss. The critical feature of this strategy is the early initiation of water ingestion and the positive limitation of early deficit to the sweat production in one 20-minute period. To further insure against a hidden water deficit related to absorption delay, subjects were encouraged to take a long drink of water before starting the preconditioning period -- in a sense "prehydration."

The result of the foregoing strategy was that the men of Series II made virtually no complaints about discomfort or distress associated with water intake, and willingly downed the weighed rations in the time segment prescribed (the men were allowed to take up to 15 minutes or so to drink the portion, but seldom used the whole time). The following table summarizes the 16 "heavy sweat" conditions (P4SR 3) with respect to the maximum deficit encountered during the 3-hour experiment.

Maximum Water Deficit (grams)

Metabolism	JR	AH	BC	RM
400 Kcal/hr	27	59	23	41
250 Kcal/hr	50	0	64	122
100 Kcal/hr	154	68	390*	510*

* observed at 155 minutes

It is apparent that nothing even approaching a deficit of 1% of body weight was allowed to develop except in the case of the resting experiment with R.M. and B.C. Examination of the rectal temperature record for this experiment reveals a slight upturn of a few hundredths of a degree in the last 20 minutes, not distinct enough to be more than suggestive. This experiment occured early in the series, and was the first high-sweat condition encountered under the new water replacement strategy.

Skin Wetness, Visual Observations

The relative success in achieving the original goal of a minimally wet skin is best judged in the P4SR 3 environments, where sweat rate ranged from 550 to 850 grams/hr.

The following tabulation summarizes the rank order data for Series II taken in the experiments at the high environmental stress condition (four subjects).

Summary of Skin Wetness Ratings*

	400 Kcal/hr, P4SR 3			250 Kcal/hr, P4SR 3		
	Max. Rating	Min. Rating	Average	Max. Rating	Min. Rating	Average
Forehead	7	3	4.2	8	4	5.5
Chest	5	3	3.9	5	3	3.5
Abdomen	6	2	4.2	6	2	4.1
Upper back	5	2	3.8	6	3	4.1
Lower back	6	2	4.1	6	3	4.2
Arm	6	2	3.6	4	3	3.1
Palm	3	1	1.3	3	1	1.0
Thigh	3	2	2.4	4	2	3.1
Calf	3	2	2.3	3	2	2.7
			Av. 3.3			Av. 3.5

* (1) Dry skin (2) Slightly damp (3) Moist (4) Lightly beaded (5) Heavily beaded (6) Running in spots (7) Generally running (8) Occasional dripping (9) Continuous dripping

The most frequently assigned rating was #3, "moist"; out of a total of 235 individual wetness ratings on which the preceding table is based, 91 or almost 40% of them were in this category. Of this group of 235 judgments, the ratings 5 through 9 (i.e. "heavily beaded" to "continuous dripping") were used a total of only 27 times, or 11%.

In Series I, with two subjects, the highest rating assigned any location at any time was 6, and the overall average rating at P4SR 3 was just under 4.

It may be particularly significant that the thigh and calf locations were frequently judged to be only "slightly damp" and only seldom more than "moist", in situations where parts of the trunk were beaded with sweat.

Performance Reserve Tests

The intent had been to exclude errors from the primary task, (binary choice of responses to audio tones) and force errors of omission to occur in the secondary task (detection and response to randomly presented peripheral lights.) In practice, a few errors almost always occurred in the primary task, and there were relatively few failures to respond to lights. A tabulation was prepared showing for each of the 57 experiments of Series II the following:

(a) The maximum rate of performance on the primary task when it was performed alone during the comfortable preconditioning period (defined as the highest rate of signal presentation producing more than one error in a 30-second session).

(b) The rate of presentation of audio signals used in the first test during the experiment proper (usually approximately 50% of (a)).

(c) The rate of presentation in the first session in which more than one error was made (if any) in the 40-second period.

(d) The highest rate of presentation of signals at which errors were less than 3 for the 40-second session.

(e) The total number of peripheral lights presented in all testing sessions.

(f) The total number of ignored lights.

(g) Failures to respond to lights as a percentage of the number presented.

From this table of data no significant trends were detectable with respect to the influence of P4SR or metabolic rate on the scores for primary and secondary tasks. The signal presentation rate at which more than one error per session was made in the audio choice task ranged from 33% to 89% of the single task capacity, with the higher performance occurring generally in the later experiments, which were the most stressful. The highest presentation rates for which errors did not exceed 2 per 40-second session, and the experimental conditions in which they occurred, were as follows for the four subjects:

J.R.	78	signals/minute	(400 Kcal/hr; P4SR 2)
A.H.	78	signals/minute	(400 Kcal/hr; P4SR 2)
B.C.	72	signals/minute	(400 Kcal/hr; P4SR 3)
R.M.	73.5	signals/minute	(400 Kcal/hr; P4SR 3)

These rates represent from 69 to 85% of capacity without a second task. In the test sessions where the above scores were obtained on the primary task, the number of failures to respond to peripheral lights was, respectively, 0, 1, 0 and 3. In both cases, the failure to respond was due to timing conflict in the button-pressing activity, rather than failure to detect the light signals.

Out of 57 experiments, each involving close to 9 testing sessions, 35 had fewer than 3 missed responses to lights. In only 14 experiments was there a total number of missed responses greater than 4, and there were 15 experiments in which all the light signals were responded to. In the light of these results, no analysis was made of the effect of light position on the probability of failure to respond. From the comments of the subjects it appears likely that very few, if any, light signals were not detected. Failure to respond represented a choice by the subject, in accordance with his instructions to give priority to the primary audio task, to allocate his attention and direct his fingers to the buttons which extinguished the audio tone. Successful response to all audio and light signals, without error, represents the application of an effective strategy of time sharing between two channels of attention and action.

It happened that the subject who was the latest to join the program, and therefore received least practice on the performance reserve test tasks, was also the one least suited temperamentally to the demands of performing two conflicting jobs at the same time. This man, A.H., missed one-third of the light signals in his first experiment, one-fifth of them in the subsequent two experiments, and again had one-third failures to respond in his fourth experiment twelve days after the first experience. All these were relatively mild thermal conditions; in his final experiment of the series, which was the most severe condition (400 Kcal/hr, P4SR 3), A.H. missed no lights at all, while performing on the primary task at up to 61% of his capacity within the criterion of two errors per 40-second session.

The other three subjects did not show such striking evidence of improvement in their strategy for handling the demands of the simultaneous tasks. In 71% of their experiments, missed responses to peripheral lights did not exceed two per experiment, and 31% had no misses. In the final experiment with subjects B.C. and R.M. (an extra cold run performed for the purpose of establishing the sweating threshold for B.C. at 400 Kcal/hr), the rate of presentation of audio signals in the primary task was raised to over 80% of the day's unstressed capacity before the error criterion was exceeded. In the session where this happened, there were eight and nine mistakes respectively on the primary task but only one missed response to a peripheral light. The motor component of the skills involved in this task was handicapped in this particular experiment by numbness and stiffness of the fingers due to the very low environmental temperature involved (6 to $8^{o}C$).

The immediately preceding experiment for these same subjects, two days previously, was the highest activity, highest stress index combination. They both attained 75% of their comfort level, single task capacity without exceeding the error criterion on the primary task; B.C. missed only one peripheral light response, early in the experiment when the pace imposed by the primary task was only 50% of his capacity while R.M. missed a total of 15, or 34% of the light signals presented. In spite of the apparently large difference between the two subjects in their response, they are found to show a closely similar pattern when the time histories in the cold and hot runs are compared.

Figure 32 presents the comparison. For each man the sum of the errors and omissions in both primary and secondary tasks are plotted against the signal presentation rate on the primary task. Since the latter rate was progressively increased in each successive test session, the lines joining the points show the time course of the performance, each point being roughly 20 minutes after the preceding one. The finding which is thought to have potential significance is that the sudden increase in errors and omissions occurs earlier and at a lower fraction of the maximum single-task capacity when the environment is a sweat-demanding one than when it is cool. The difference between the zero-sweat and the P4SR 3 environments seems to be between 10 and 20% of maximum capacity for these two individuals. This can be speculatively interpreted as an indication that the effect of environment stress of the magnitude of P4SR index 3 can reduce the performance reserve drastically; the reasoning is as follows:

(1) When sweating was essentially zero, the secondary task reduced performance (to the adopted criterion of near-perfection) to about 72% of the single task unstressed capacity (which was between 98 and 104 responses per minute in these final two experiments on the two men).

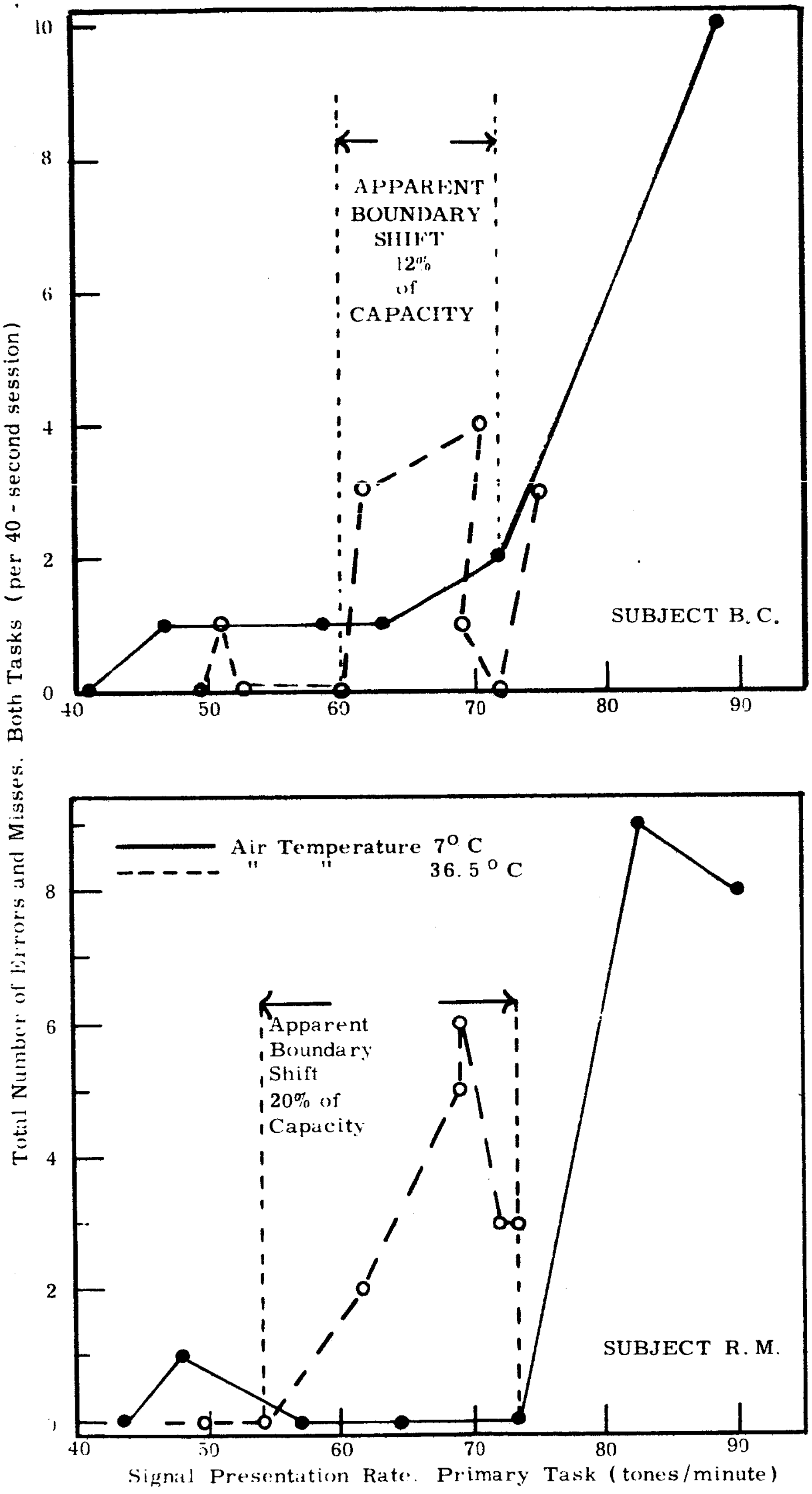


Figure 32 : LOSS OF PERFORMANCE RESERVE DUE TO THERMAL STRESS : Successive trials over a three hour period with a binary choice primary task and response to randomly presented peripheral lights as the secondary task. One day intervened between the experiments.

(2) The secondary task plus severe thermal stress reduced performance to about 60% of capacity.

(3) The "unavailable capacity", that is, the portion not utilized in the primary task at the maximum rate meeting the criterion, was 28% in the cool condition, and 40% in the sweaty environment; the discomforts and physiological strains associated with a P4SR index of 3 thus eliminate 12% of the total capacity for making binary choices, or 43% of the amount which is used up by a simple vigilance task.

(4) In other words, the capacity for near-perfect performance of a simple binary choice task is reduced by the thermal stress of P4SR 3 to a value which is only 73% to 83% of the capacity in a cool, sweat-free environment.

In the other experiments, at intermediate levels of stress index and other activity levels, the difficulty of the tasks was not sufficiently high to cause a significant number of errors and omissions. At the present time, more detailed analysis of the data does not appear warranted.

Arithmetic Tests

In the final nine experiments on subjects A.H. and J.R., a preliminary exploration was made of simple subtraction as a secondary task which might be more sensitive to the effects of thermal strain than the P. L. test appeared to be. Subjects were presented with 11" x 17" pads of tabular paper on which were rows of two-digit subtraction problems which had been selected from a table of random numbers by a procedure which favored the more difficult type of operation such as 72 minus 39 where a unit must be "borrowed" or "carried." Subjects were asked to fill in the answer in pencil below each problem, which was hand-lettered in large numerals using a fine-point felt tip pen with bold black ink.

In a comfortable environment, with no distractions, the two subjects were able to accomplish these subtractions at the rate of 20 to 26 correct answers per minute, with only an occasional mistake. When required to perform the audio primary task simultaneously (holding the ultra-sonic remote control response unit in their left hand), for the 40-second duration of the regular experimental test sessions their output of correct solutions dropped sharply. A.H., at an average signal presentation rate on the primary audio task of 33% of his maximum capacity could complete only 4 problems in one 40-second session, and 7 in another, or an average of 30% of his capacity for subtraction alone. J.R. was more resistant to the interference effect of the primary task, and achieved 45 to 60% of his maximum number of subtractions when the primary task rate of presentation was set at 50%.

In the experiments where thermal stress was added to the dual tasks of audio tone cancelling and subtraction, no clear-cut distinction could be seen between experiments at P4SR 0, 2 and 3, and activity levels rest, 250 and 400 Kcal/hr. The difference between the two subjects was consistent; in one experiment A.H. was able to complete only one problem in each of three sessions, two in another, and four in each of the remaining two sessions. J.R. in the same experiment (resting, P4SR 2) completed between 7 and 12 problems per 40-second session. However, for both men their best performances were in working experiments at P4SR 3, and their poorest during rest at P4SR 2.

SECTION III

DISCUSSION

Physiological Data

That a linear relationship exists between sweat output and skin temperature, when metabolism remains constant, is not a new discovery. The preciseness of the relationship, that is, the small amount of scatter or residual variance, has been obscured in much of the experimental data of the past, probably by training and acclimatization factors. The systematic character of the present investigation makes possible a detailed analysis of the possible implications of this relationship, which may provide insight as to the underlying physiological mechanisms.

Perhaps the most pregnant question is why the four subjects of Series II showed a strong dependency on metabolism of the skin temperature sensitivity or slope function, whereas subject J.E. in the first series presented a common slope at all three metabolic activity levels. A satisfactory explanation of this discrepancy may shed light on several of the perplexing aspects of contradictory findings in thermoregulatory studies.

Kerslake in 1954 (Ref. 30) measured the sweat response of a small number of his full time laboratory assistants and himself in a procedure which did not wait for thermal equilibrium, but provided only long enough at a particular combination of metabolism and environment to permit a reliable measurement of weight loss (20 minutes). He found that a multiple regression equation, relating skin temperature, sweat rate and estimated heat flow through the skin, permitted all the data for one subject, at three metabolic rates, to be correlated in a single relationship. The parameter against which all the sweat rate data were plotted was a "deep skin" temperature. The increment to be added to mean surface skin temperature to yield deep skin temperature was computed for each point as the product of skin heat flow and the ratio of regression coefficients for skin temperature and heat flow. This ratio has the dimensions of a thermal resistance, viz. temperature differential per unit change in heat flow.

The four subjects of Kerslake, who were in various stages of relative acclimatization to heat stress, displayed "estimated skin resistances" of from 0.0134 to 0.0175 degrees Centigrade per unit heat flux (Kcal/m^2hr), equivalent to conductances of 108 to 142 Kcal/hr, ^{o}C. It should be noted that these estimates of conductance for the outer layer of skin are in agreement with Robinson's estimate of maximal values for the circulatory index, or overall "conductance" from core to surface. The mean conductance for Kerslake's subjects D.B., B.H., D.T., and D.K. was 125 Kcal/hr, °C. Using this value to compute "deep skin temperatures" for each of the 15 conditions of our experiment, the three-subject average data for Series II was plotted in the Kerslake manner. Three distinct curves resulted, roughly one degree apart, indicating that the assumed value for the skin conductance is quite incorrect for this group.

Next, the data for subject J.E. was examined from the point of view of the Kerslake concept. The change in threshold skin temperature per unit change in heat flow through the skin, which has the same dimensions as a thermal resistance, is 0.021°C, hr/Kcal between the two working activity levels and 0.0134°C, hr/Kcal between the median activity and rest. In order to derive a single threshold value of a hypothetical "deep skin" temperature which would satisfy each of the three individual relationships between heat loss and surface temperature shown in Figure 24, it is necessary to postulate two different values for thermal resistance of the outer skin layers, one for the high activity data, and another for the median activity and resting conditions. By trial and error, the resistance values 0.0165 and 0.0130°C, hr/Kcal were found to provide an acceptable consolidation of the data for subject J.E. Figure 33 shows the results, where deep skin temperature is calculated as mean surface temperature plus the product of skin heat flow and the above values of assumed skin resistance.

The equation of the heavy line, calculated by the method of least squares, is:

$$\dot{W} = 292\ (t_d - 35.3) \text{ grams/hr}$$

or

$$\dot{E} = 168\ (t_d - 35.3) \text{ Kcal/hr}$$

where

$$t_d = t_s + R_s H_s$$

and $R_s = 0.0165$ for $t_s < 32.5°C$
$\quad 0.0130$ for $t_s > 32.5$

H_s = Metabolism less work less ventilatory heat loss.

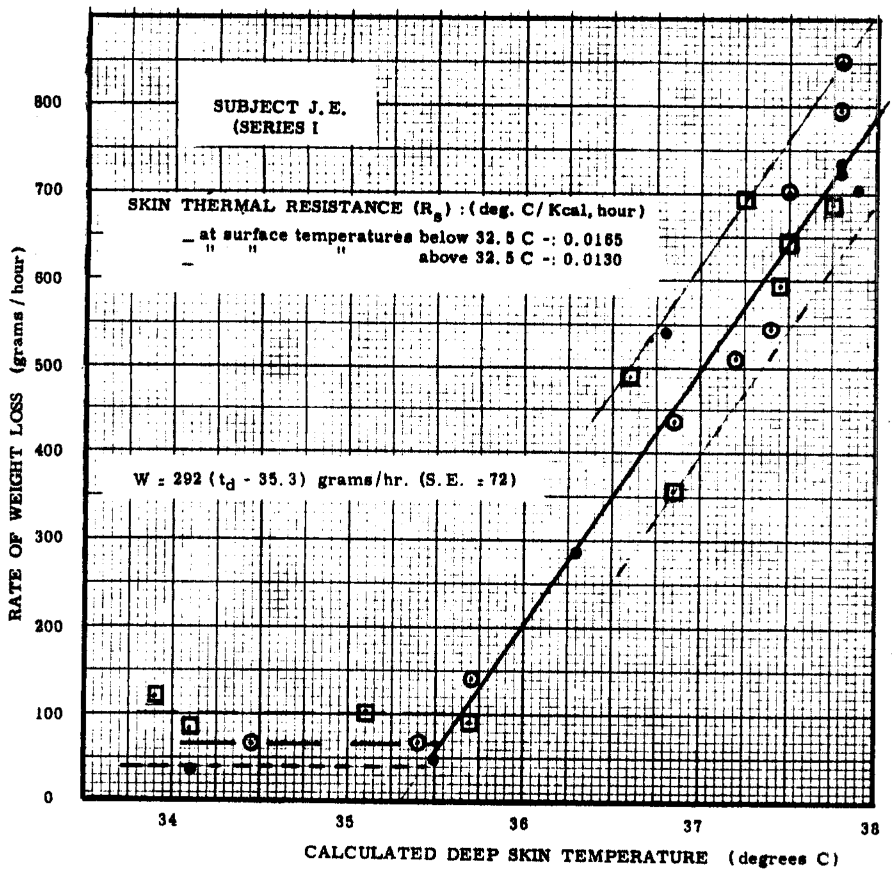


FIGURE 33 SWEAT RATE AS A FUNCTION OF DEEP SKIN TEMPERATURE, CALCULATED FROM SKIN HEAT FLOW AND ASSUMED VALUES OF THERMAL RESISTANCE OF THE BLOODLESS SKIN LAYER.

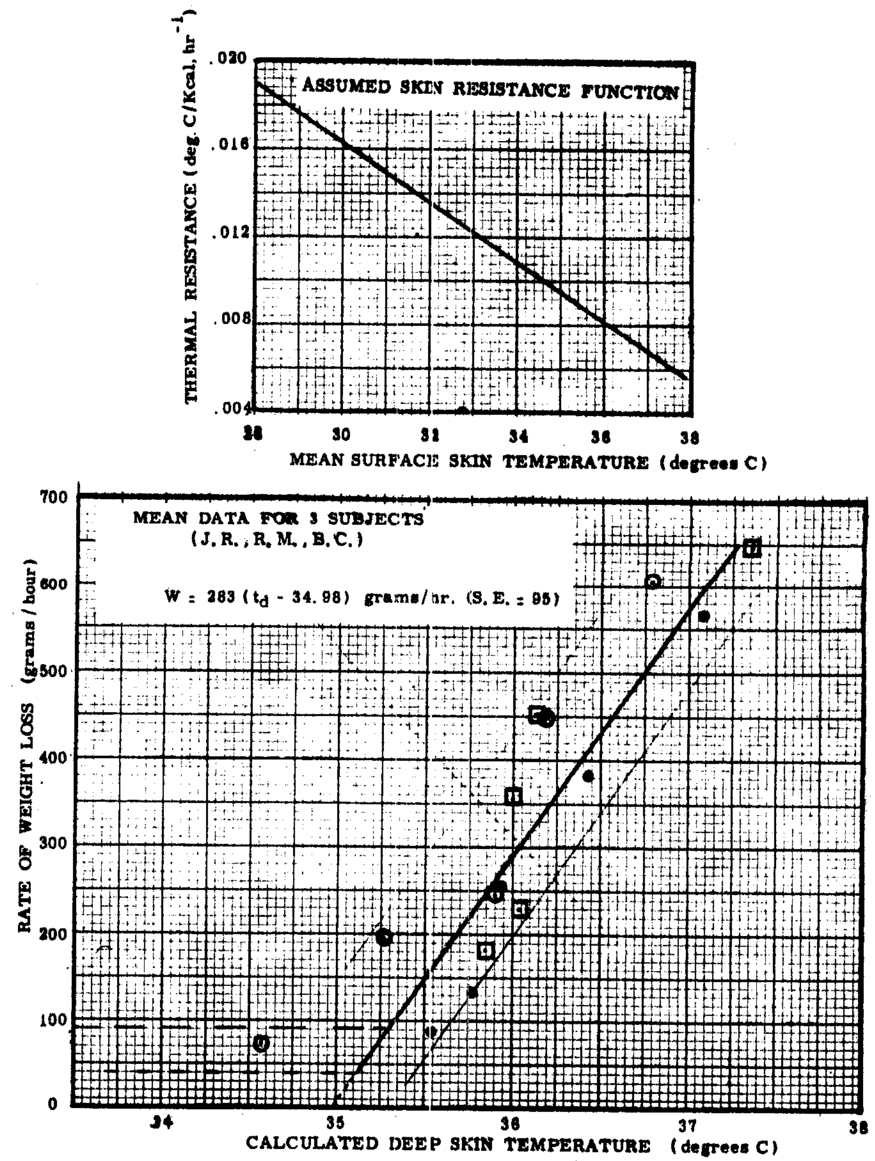


FIGURE 34 SWEAT RATE AS A FUNCTION OF DEEP SKIN TEMPERATURE, CALCULATED FROM SKIN HEAT FLOW AND A VARIABLE THERMAL RESISTANCE OF THE SKIN, ASSUMED TO BE A FUNCTION OF SURFACE TEMPERATURE (as shown in the upper panel).

Expressing evaporation and skin heat flow per unit of body surface area, as Kerslake did, the equation becomes

$$\dot{E}' = 89\ (t_s + R'_s H'_s - 35.3)\ \text{Kcal/m}^2\text{hr}$$

where

R'_s is either 0.0314 or 0.0247°C, m^2, hr/Kcal for skin temperatures below and above 32.5°C respectively.

In Figure 33 the maximum scatter of points for individual experiments about the line of relationship, bounded by the two light lines, is three-. quarters of a Centigrade degree. The standard error of estimate for W is 72 grams/hr. Considering that the experiments were done over a period of 6 months, included more than one level of air movement and several humidities, this degree of regularity is quite impressive. Nevertheless, the relationship remains a speculative one in the absence of a rigorous determination of skin resistance, and without a mechanism to explain the change in resistance between the two working activity levels.

The same rationale for estimating skin resistance which unifies the data for J.E. will probably not work when applied to the subjects of Series II, because the separation between skin temperatures producing equal sweat rates at different metabolic rates becomes less as sweat rate increases (Figure 23). This pattern of results is consistent with the concept of an inverse relationship between skin thermal resistance and skin surface temperature.

Taking the averaged data for the three lean subjects of Series II (as shown in Figure 28) a reiterative process of trial and error was undertaken to find a workable assumed relationship between skin temperature and skin resistance. Restraints on the analysis included the requirement that R_s can not exceed, and probably should not equal, the total core-to-skin resistance, R_t; that is, the deep skin temperature should not equal or exceed rectal temperature.

After several attempts, each of which improved the correlation of the sweat rate data for all three activity levels, the relationship shown in Figure 34A was found, which produced the rather good consolidation shown in Figure 34B. The adopted relationship for R_s assumes that 75% of the total resistance between core and surface resides at the skin, at the threshold of sweating in high activity and at the most severe resting condition, and varies linearly with skin temperature between these two extremes at the rate of 0.00136 resistance units per degree change in skin temperature.

The equation of the arbitrary sweat response relationship generated by the foregoing assumption about skin resistance as a function of surface temperature is as follows:

$$\dot{W} = 283\ (t_d - 34.98)\ \text{grams/hr}$$

or

$$\dot{E} = 163\ (t_d - 34.98)\ \text{Kcal/hr}$$

or

$$\dot{E}' = 86\ (t_d - 34.98)\ \text{Kcal/m}^2\text{hr.}$$

The writer was somewhat startled to find so close an identity between the equations for the experienced subject J.E. and the three neophyte subjects of Series II. If this is not a matter of pure coincidence, which seems unlikely, there is a strong implication that the primary difference between J.E. and the other subjects was in the vasomotor response to work and warmth. Again, no claim is made that the assumed relationship between skin temperature and thermal resistance is the correct description of vasomotor response; the position is simply that such an assumption produces a plausible and reasonable correlation of the data for all three activity levels (standard error 95 grams/hr).

The most probable explanation for the apparent difference in vasomotor response between subject J.E. and the Series II group is that it results from differences in the order and frequency of exposure to work/environment combinations. In the case of J.E., the fifth experiment was at a P4SR level of 2, and the eighth was at P4SR 3; the eleventh, thirteenth, fifteenth, and seventeenth exposures were all at P4SR 3, so that a total of 7 exposures at lesser levels of severity followed these maximal-sweat conditions. Furthermore, there were a total of 13 experiments on this subject at or near the P4SR 3 level, compared with 3 only for each of the Series II subjects.

The latter group were exposed to the working environments in ascending order of severity, so that the circulatory demand imposed by the environment was higher in every working experiment than it had ever been before at the same activity level. (This procedure was not adhered to in the case of the resting experiments, in that the P4SR 3 condition was presented relatively early in the schedule.)

We are thus left with an uncertainty as to whether the difference between J.E. and the others was due to acclimatization effects attributable to the repetition of high-sweat runs, to training effects, that is, an improvement in the circulatory adjustments of inexperienced men to the work load with each successive trial, or to basic anatomical or genetic differences. Of the three possibilities, the last appears to us the least likely, and the first only slightly more plausible. On the basis of all the evidence presently available, it seems most probable that, in a person accustomed to physical exercise and "in training", one or two exposures to a severe sweat-demanding condition is sufficient to ensure that the vasomotor response to future work loads of the same magnitude in less severe environments, will be independent of the external environment. The converse situation, in persons not fully trained for the specific exercise under study, would be that each successive exposure to a given work load elicits a vasodilation response which is proportional to the resultant surface temperature rather than being optimal for the level of metabolic load.

Experimental validation of the foregoing hypothesis would, of course, require that a pattern of sweat response (as a function of skin temperature) of the type seen in Series II (Figure 23) be changed to the pattern of subject J.E. (in Figure 24) as a result of several high-stress exposures. During classical heat acclimatization procedures, the daily output of sweat increases while the skin temperature either decreases (dry environments) or remains the same (humid environments - Ref. 31). Ronald Fox has recently shown that the same phenomenon occurs when core temperature is driven to the same level on successive days (personal communication); he attributes the improvement in sweat response to "training" of the sweat glands, and sees no beneficial circulatory effect of his "heat treatments" (Ref. 32). It may be that the essential difference between Fox's acclimatization process and the conventional procedures which involve physical work as well as heat is that passive heating does not improve the vasomotor response of the skin blood vessels when the skin surface is relatively cool, whereas work in the heat <u>does</u> produce this as a lasting effect.

As has been elegantly demonstrated by Rowell (Ref. 33), increasing the heat stress at constant work load diverts blood flow from the splanchnic and hepatic region to the surface; a 50% improvement (i.e. reduction) in the skin resistance, as a result of increased vascularization, would have the same effect as doubling of the blood flow to the skin. It is thus clear that the vascular effects of training under conditions of thermal stress are at least as important as the sweat gland effects which Fox has emphasized in his analyses of the phenomena of acclimatization. The practical effect of an improvement in skin resistance to heat transfer is to raise the threshold stress level at which circulatory strain becomes critical, in terms of any set of criteria which are appropriate to the particular practical situation. It follows that the individual whose skin resistance is highest of a group would be expected to show a break in circulatory strain at a lower stress level than the others, all other things being equal. However, other factors are usually not equal within a group of subjects, and subtle elements of training and fitness may easily compensate for the handicap of a high skin resistance. An obvious compensation available in the fat man is an increase in total blood volume; less commonly appreciated is the fact that for such an individual even mild exercise of an every-day character such as climbing stairs represents a training and conditioning experience, which confers an advantage vis a vis an equally sedentary small man.

A preliminary examination of the data for the thick-skinned subject A.H. has been made to determine whether a similar set of assumptions regarding thermal resistance of the outer layer would consolidate these results into one relationship. The indications are that it would be possible to find a relationship between skin resistance and surface temperature which would produce a very similar sensitivity coefficient (or slope) for sweat rate as a function of calculated deep skin temperature, and also a similar intercept or threshold constant, in the neighborhood of 35°C.

Taken all together, the results of preliminary analysis for Series I and Series II suggest strongly that a common basic relationship between "deep skin" temperature and sweat production would fit all the data which appears so varied in terms of skin surface temperature. By taking one more small speculative step in reasoning, this observation can be fitted into the larger picture of population differences due to training and heat exposure experience. This step is to imagine that the calculated deep skin temperature really represents the integrated, area-weighted mean temperature of blood in the most superficial venous plexi and capillary loops in the skin.

If the sudomotor control system is triggered at a fixed value of this skin blood temperature, and has a fixed gain function tied to increases in it, the differences between individuals which we have observed could be explained as differences in the fluid dynamics controlling transfer of heat to the surface. To illustrate the point, we may consider the extreme case of the man with heavy deposits of subcutaneous fat; due to this extra insulation, blood on its way from the core to the superficial network is cooled less by returning venous blood and by the peripheral tissues through which it passes than in a lean man. It consequently enters the superficial plexi at a higher temperature, in a given environment. This tends to elicit a higher sweat production, which produces a lower surface temperature. Thus the fat man may have a higher sweat rate and a lower surface temperature than his lean counterpart under identical metabolic and environment conditions, although each of them might sweat at the same rate when their skin blood temperatures were equal. As the stress level rises, all the peripheral tissues become warmer, the amount of heat which can be lost from the arterial blood be before it reaches the final superficial plexi is reduced to an insignificant level; under these conditions, the differences between individuals, even between the fat man and the lean man, tend to disappear.

The foregoing picture is entirely consistent with the observations in this study as illustrated graphically in Figure 35. It leads logically to the prediction that it may be possible to discriminate in the future between training procedures which influence primarily the vascular elements in resistance to heat stress, and those which influence primarily the sensitivity and threshold set-point of the sweat control system. More fundamentally, the evidence strongly favors the hypothesis of a single stimulus source for thermoregulation, namely the integrated mean temperature of blood in the superficial skin vessels, as opposed to current concepts of a dual role of core and surface temperature stimuli.

Performance Reserve

While the absence of a clear-cut relationship between stress index or sweat rate and the test results in the dual task testing sessions is disappointing, the data from the final two experiments on two of the subjects indicates that the reason lies in the details of the performance test protocol rather than in any basic flaw in the underlying theories of performance reserve and the interaction of environmental stress with the expenditure of effort.

Under the experimental conditions of a 40-second test every 20 minutes or so, it is probable that the discomfort aspects of thermal stress constitute a stimulus which raises the "level of arousal", to use the terminology of Broadbent (Ref. 34), tending to increase the amount of effort expended. Increase in the effort required to perform the experimental tasks can only be detected at the point of breakdown -- i.e., when the difficulty of the tasks is sufficient to exceed the individual's "channel capacity" so that errors are inevitable. It is clearly not easy to design an experiment so that for each subject the combined-task difficulty is beyond the capacity at maximum effort yet short of the level where total breakdown occurs. Neither the peripheral light task, as used in this study, nor the two-digit subtractions, when combined with a simple binary choice task at the pace used in most of our experiments gave sufficient sensitivity to reveal the effect of thermal stress on higher mental processes.

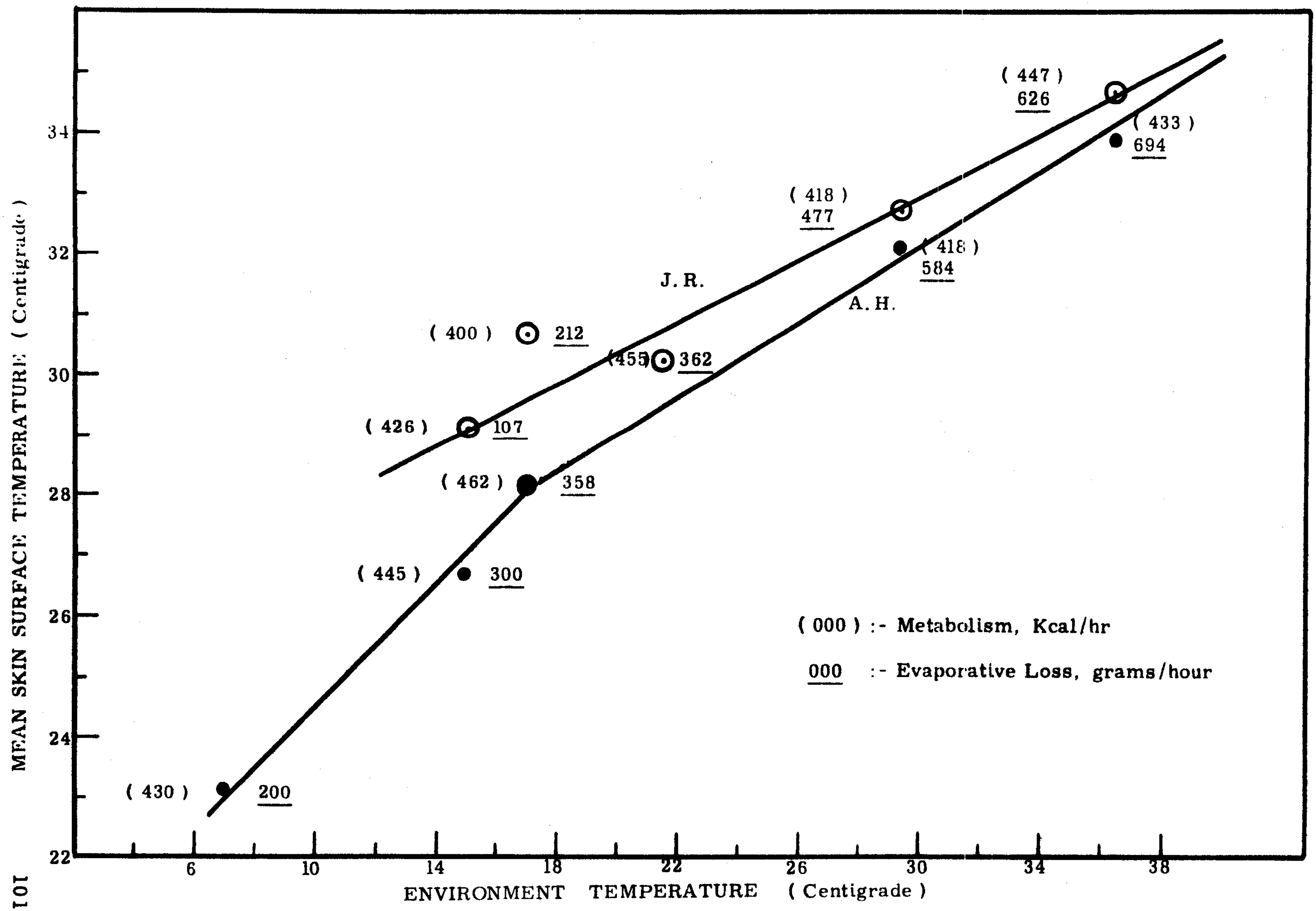


FIGURE 35 : COMPARISON of a LEAN ATHLETIC TYPE and an OVERWEIGHT SEDENTARY TYPE: Skin Temperature and Sweat Output versus Environment Temperature at the Moderate Activity Level.

To quote E.C. Poulton of Cambridge (Ref. 35), "If no reliable effect can be established, this may be ... simply because the tasks selected to represent the psychological function are insufficiently sensitive." As is suggested by Figure 32, the rate of binary choice decisions at which the simple response to a randomized light signal causes errors or omissions in either or both tasks seems to be different between a very cool environment and a very warm one, but a much more reliable and large difference would be needed to allow decisions about where the acceptable physiological strain level lies from a performance standpoint.

In general, it appears that the development of a test battery and schedule for testing which is optimal for the purpose of detecting subtle changes in the reserve capacity for performance due to environmental stress, will call for additional experimentation of an exploratory nature. The requirements for homogeneity in protocol which the generation of a systematic matrix of data from many environment-activity combinations imposes, are incompatible with the search for the best tool with which to measure an elusive thing like "effort" or "distraction".

SECTION IV

CONCLUSIONS

Summary of Significant Findings

1. This study has confirmed that an inverse linear relationship exists between sweat production and mean skin temperature when metabolism is held constant. The slope of this relationship, which has been referred to in this report as the "sweat sensitivity coefficient" for skin temperature, is inversely proportional to metabolic rate when neophyte subjects, fit and healthy, are exposed in serial order to progressively more severe environments. A randomized order of exposure, with some severe stresses early in the program, was associated with a common sensitivity coefficient for all three metabolic rates. Since this pattern was observed in only one subject, the possibility that it was due to his greater degree of experience with, and consequently higher state of training for treadmill grade-walking, cannot be excluded.

The more common pattern of a shallow slope at high activity levels and a steep slope at rest (i. e. greater increment in sweat rate per unit change in surface temperature as skin heat flow diminishes) is consistent with the hypothesis that the thermal resistance of the skin, between the most superficial blood vessels and the surface, becomes progressively lower as skin surface temperature is raised. The parallel pattern of relationships between skin temperature and sweat rate can be explained if it is assumed that skin resistance has a single value below a critical skin temperature and a different, lower value above it.

Under these two related sets of hypotheses, the sweat rate under a variety of combinations of activity and environment stress can be expressed as a single function of a deep temperature, calculated as the sum of skin temperature and the product of skin heat flow times skin resistance. It can be demonstrated that this calculated deep temperature might logically represent the integrated mean temperature of blood in the superficial capillary plexi of the skin; as such it appears to be a sufficient and satisfactory stimulus source for the sudomotor control system and possibly for thermoregulation control generally.

2. The threshold skin temperature for the initiation of sweating is heavily dependent on the skin-fold thickness of the individual (i. e. the amount of sub-cutaneous fat) and also varies with the state of training for heavy muscular activity. The evidence suggests that a thick skin reduces the heat loss by counter-flow exchange in the major vessels and by tissue

conduction from subcutaneous levels, so that a greater requirement for sweating exists as compared with a thin-skinned lean individual, even when skin resistances are equal. The threshold values of the calculated deep skin temperature for the initiation of sweating (independent of metabolism) are found to be essentially the same for fat and lean, sedentary and athletic adults. The skin temperatures corresponding to this threshold level below the surface, in contrast, show an extreme variation between individuals. For example, a mean skin temperature of less than 22°C (72° F) was necessary to stop sweating in one thick-skinned individual at high activity, yet in another man the surface at threshold was 30.5°C (87° F). Under resting conditions the skin temperatures at the sweating threshold were identical for these two men, and for two others.

The data suggest that differences between men in thermal resistance of the skin play a secondary role in the variability of the sweat-surface temperature relationship; the increased resistance which is associated with the sweat threshold at high activity in a thick-skinned individual appears to be consistent with the relationship between resistance and surface temperature which fits the data for normal and thin-skinned subjects. Minimum experience of heat stress plus work appears to significantly reduce the skin resistance associated with a cool skin during work so that sweating begins at a distinctly higher skin and environmental temperature than in the inexperienced and less trained individuals. This is consistent with the concept of a sweating control system which is triggered by a deficiency in the heat loss by radiation, convection and conduction; such a deficiency is instantaneously reflected in the temperature of the superficial skin bood vessels, independent of whether the deficiency arises from internal or external changes.

3. If sweat production is directly proportional to skin blood temperature, as our analysis indicates, the most appropriate location for a sensor designed to supply input data for the guidance of a micro-climate control system would be along the skin capillaries. Since this is impractical, the next best location would be one which most nearly matches the temperature fluctuations of the mean skin blood temperature.

Our data suggest that the forehead surface temperature, particularly over a blood vessel, may have definite advantages as a candidate for the role of a control parameter. The interrelationship between forehead temperature, mean skin blood temperature and metabolic rate will depend on the detailed nature of the micro-environment and means of heat transport from the body. Under the experimental conditions of the present study, the forehead temperature appeared to be usable as a means of differentiating between mild and severe stress conditions but insensitive to lesser increments in P4SR index.

4. Voluntary dehydration was encountered as an intractable experimental variable initially in this study, but was successfully eliminated by a simple procedure in which pre-experiment fluid intake was encouraged, and a deficit was not permitted to reach more than 50 to 100 grams nor to last more than 20 minutes, from the start of each 3-hour exposure.

Before the zero-deficit procedure was instituted, it was observed that within a minute of the instant when gross water deficit reached a value of 1% of initial body weight, rectal temperature rose in a step fashion by one or two tenths of a Centigrade degree. This temporary heat storage process is accompanied by subjective distress symptoms, which are related to the reluctance or even refusal of subjects to imbibe sufficient water to halt or reverse the dehydration.

When water intake is initiated early enough, and is matched in rate as well as total quantity to the sweat output (i. e. frequent small drinks in every 20-minute period) neither the objectionable subjective symptoms nor the disturbances of thermoregulation are observed. In an early phase of the new hydration protocol one subject reported that when the interval between drinks (in a severe stress, resting, environment) was "longer than usual" the first sip or two produced a sensation of incipient nausea and "tightness" in the epigastric area; after the third or fourth sip the sensation subsided and he would finish the drink without further incident.

These observations are consistent with long-term experience in our laboratory and elsewhere with respect to the susceptibility of unacclimatized persons to distress from imbibing fluids when stressed, in contrast to the willing acceptance of similar fluid intake regimes by acclimatized individuals. They suggest an imperative need for apparatus within current space activity suits to supply drinking "water" on a continuous ad libitum basis and a training rationale to guide prophylactic use of such equipment.

In the absence of objective criteria to determine the need for water, as in the field, a probably safe rule would be to drink to satiation or more at the start of a period of sweating, repeat the process as frequently as possible; upon experiencing initial sensations of nausea slow down the rate of intake until the symptoms subside, then carefully continue to imbibe until the total quantity of intake exceeds the total in the preceding interval of time. This strategy should prevent the development of a water deficit which might compromise the circulatory system.

5. The P4SR index system of equating the stress imposed by various combinations of activity, clothing and diverse environmental variables is extremely effective in predicting environments which will produce equal sweat rates at different activity levels. It would seem to be worthwhile to develop an analogous system for predicting combinations of conductive and convective cooling with metabolism which would be equal in sweat generation potential, for use in the area of pressure-suit micro-climatology.

While the P4SR system is eminently successful in predicting environmental stress, it does not yield an index of equal physiological strain, as has been suggested by some in the past. This is revealed by the fact that at rest, an environment with a high P4SR index lies in the environment-driven or stressful zone with respect to rectal temperature, whereas the same P4SR value characterizes working environments which lie in the environment-independent, (or prescriptive, or neutral) zone.

The present results thus reaffirm and emphasize the need for a reliable index of strain which will be as sensitive and universal a measure of physiological response as the P4SR system is for external and internal load.

A second implication of our findings with respect to rectal temperature is that sweating at a given rate is more costly, physiologically, when at rest than when operating at a high metabolic rate.

6. If it were necessary to choose a line of discrimination in the present results between "more difficult" and "less difficult" conditions, the most promising of the available parameters would be Circulatory Index and the surface to core temperature differential. On the basis of very tentative criteria, it appears that a significant increase in physiological strain probably occurs between P4SR 1 and 2; a much larger step occurs between 2 and 3, and of course, the lowest physiological strain in these terms is associated with a P4SR of zero.

The present results justify a recommendation of 250 grams/hour as the upper limit of acceptability for sweating during activity, on the basis of a desire to maximize the reserve capacity for adjustment of the circulation to emergency demands of many kinds.

7. Performance Reserve, or the amount of reserve capacity for mental performance utilizing the higher levels of the brain, was not successfully quantified in these experiments. The hypothesis that increasing environmental stress and physiological strain would be correlated with a reduction in the performance reserve when a simple decision-making task was performed at a constant level of difficulty has been neither proved nor disproved.

Effective testing of the hypothesis will require more careful attention to the details of construction in the experimental tasks, and devotion of primary attention to this facet of the problem in the design of a new matrix experiment. The definition of the physiological aspects of the problem which the present study has achieved should simplify the task of meeting these objectives.

Conclusions and Recommendations

1. Sweat rate and skin temperature are linearly related, but the slope of the relationship depends on the rate of heat flow through the skin and the thermal resistance of the outer layer of bloodless skin.

2. By estimating the skin thermal resistance as a function of skin surface temperature, a deep temperature can be computed for every combination of environment and metabolism which is linearly correlated with sweat rate independently of activity level. The slope of the relationship is approximately 290 grams/hour, ^{o}C for this group.

3. The threshold of sweating is highly variable in terms of surface skin temperature, being dependent not only on metabolic rate but also on skin thermal resistance and skin-fold thickness. The highest skin surface threshold temperatures are found in well trained lean men with thin skins, the lowest in overweight men who are sedentary in their habits. At 400 Kcal/hr metabolism the threshold skin temperature can be less than 22 and as high as 30.5 degrees Centigrade.

4. The threshold for sweating in terms of deep skin temperature appears to be relatively constant among men widely divergent in habitual activity patterns and in body build, but all classifiable as "unacclimatized to heat." Its numeric value, which is independent of metabolic rate, appears to be for the subject group studied in the vicinity of 35.5^{o}C. The highest value computed for deep skin temperature under severe stress was 37.9^{o}C, very close to rectal temperature. This parameter is tentatively conceived to represent the integrated mean temperature of the blood in the most superficial skin capillaries.

5. If water intake is started early enough and maintained faithfully by frequent drinks at brief intervals, body weight can be maintained unchanged in the face of sweat rates as high as 750 grams/hr. If a deficit is permitted to accumulate, the ingestion of water becomes unpleasant and produces symptoms of incipient nausea. When the gross deficit equals 1% of the initial body weight, a compensatory upward shift in the level of rectal temperature, indicative of a strain on the thermoregulation system, is observed.

6. Environment-activity combinations equal in P4SR index are not necessarily equal in physiological strain, as shown by the elevation of rectal temperature above the environment-independent level in rest as contrasted to activity at P4SR 3. This emphasizes the need for an index of physiological strain which can be used to evaluate the relative difficulty of combinations which involve some requirement for sweating.

7. Further refinement of the techniques for quantifying performance reserve are required and recommended. In their current form the tests are too brief, too simple, and too attention-demanding to achieve their purpose. The deleterious effect on performance capability of a sweat rate of 700 grams/hr has, however, been demonstrated.

8. Recommendations include the development of constant-availability drinking systems in space suits, the development of an index system to equate micro-environments in space suits, comparable to the P4SR system, and the exploration of the effects of training for work in heat on the sweat response relationships defined in this study.

REFERENCES

1. BILLINGHAM, J., and T. L. HUGHES. Protection of aircrew against the high cabin temperatures which may occur in prolonged supersonic flight after failure of the cabin cooling system. FPRC 1109. Air Ministry, London, 1960.

2. BILLINGHAM, J., R. H. FARROW, and D. G. ROBERTSON. An air ventilated suit for convective cooling (type 3B). FPRC/Memo 159. Air Ministry, London, 1961.

3. BILLINGHAM, J., and D. G. ROBERTSON. A design for an air ventilated suit type 5. IAM-TM 118. Institute of Aviation Medicine, RAF, Farnborough, 1961.

4. BURTON, D. R., and L. COLLIER. The development of water conditioned suits. Tech. Note M. E. 400. Royal Aircraft Establishment, Farnborough, 1964.

5. PIWONKA, R. W., S. ROBINSON, V. L. GAY and R. S. MANALIS. Preacclimatization of men tc heat by training. J. Appl. Physiol. 20: 379-383, 1965.

6. ÅSTRAND, I., P. ÅSTRAND, E. H. CHRISTENSEN, and R. HEDMAN. Intermittent Muscular Work. Acta. Physiol. Scand. 48: 448-453. 1960.

7. CHRISTENSEN, E. H., R. HEDMAN, and B. SALTIN. Intermittent and continuous running (a further contribution to the physiology of intermittent work). Acta Physiol. Scand. 50: 269-286. 1960.

8. WOODCOCK, A.H., J. R. BRECKENRIDGE, and J. J. POWERS, JR. Man's thermal balance in warm environments. TR EP-30. Q. M. R. and D. Center, U. S. Army, Natick, 1956. (same material in Ergonomics, 8: 224-235, 1965)

9. HATCH, THEODORE. Assessment of Heat Stress. Chapter 29 in: Herzfeld and Hardy, Temperature - Its measurement and control in science and industry. Vol. 3: Reinhold, 1963.

10. GAGGE, A. P. A new physiological variable associated with sensible and insensible perspiration. Am. J. Physiol. 120: 277-287, 1937.

11. SCHOUTEN, J. F., J. W. H. KALSBEEK, and F. F. LEOPOLD. On the evaluation of perceptual and mental load. Ergonomics. 5: 251-260. 1962.

12. BROWN, I. D., and E. C. POULTON. Measuring the spare mental capacity of car drivers by a subsidiary task. Ergonomics. 4: 35-40, January 1961.

13. BLOCKLEY, W. V., and J. LYMAN. Psychomotor performance of pilots as indicated by a task simulating aircraft instrument flight. AF TR 6521. Wright-Patterson AFB, Ohio, 1951.

14. BROWN, I. D. The measurement of perceptual load and reserve capacity. The Transactions of the Ass'n of Ind'l Med Officers. 2: 44-49, 1964.

15. BURSILL, A.E. The restriction of peripheral vision during exposure to hot and humid conditions. J. Exp. Psychol. 10: 113-129, 1958.

16. McARDLE, B., W. DUNHAM., H. E. HOLLING, W.S.S. LADELL, J. W. SCOTT, M. L. THOMSON, and J. S. WEINER. Prediction of the physiological effects of warm and hot environments. RNP 47/391. Royal Naval Personnel Research Committee. London. 1947.

17. MACPHERSON, R. K. Physiological Responses to Hot Environments. Spec. Rept. Series 298. Medical Research Council, London, 1960.

18. BOBBERT, A. C. Energy expenditure in level and grade walking. J. Appl. Physiol. 15: 10-15, 1960

19. FROESE, G., and A. C. BURTON. Heat losses from the human head. J. Appl. Physiol. 10: 235-241, 1957.

20. GOLDBERG, M. N., W. V. BLOCKLEY, and T. NEELY. Instrument package for inflight physiological studies. WADD TR 60-83. Wright Patterson AFB, Ohio, 1960.

21. CONSOLAZIO, C. F., R. E. JOHNSON, and E. MAREK. Metabolic Methods. Mosby, St. Louis, 1951.

22. LIND, A. R. Determination of environmental limits for everyday industrial work. Industrial Medicine and Surgery. 29: 515-518, November 1960.

23. BLOCKLEY, W. V. Temperature, Section 7. in Bioastronautics Data Book, P. Webb (ed.), NASA SP-3006. NASA, Washington, 1964.

24. LEITHEAD, C. S. and A. R. LIND. Heat Stress and Heat Disorders. F. A. Davis, Philadelphia, 1964.

25. ROBINSON, SID. Physiological adjustments to heat. Chapter 5 (p. 193) in: Newburgh, Physiology of Heat Regulation and the Science of Clothing. W. B. Saunders, 1949.

26. MICHAEL, E. D., JR., K. E. HUTTON, and S. M. HORVATH. Cardiorespiratory responses during prolonged exercise. J. Appl. Physiol. 16: 997-1000, 1961.

27. BROUHA, LUCIEN. Physiology in Industry. Pergamon Press, New York, 1960.

28. KARPOVICH, P. Physiology of Muscular Activity. Saunders, Philadelphia, 1953. (p. 232).

29. BLOCKLEY, W. V., J. W. McCUTCHAN, and C. L. TAYLOR. Prediction of human tolerance for heat in aircraft: A design guide. WADC TR 53-346. Wright Air Development Center, Ohio, 1954.

30. KERSLAKE, D. McK. Factors concerned in the regulation of sweat production in man. FPRC 879. Institute of Aviation Medicine, RAF, Farnborough, May 1954. (also as J. Physiol. 27:280, 1955).

31. HANIFAN, D. T., W. V. BLOCKLEY, M. B. MITCHELL, and P. H. STRUDWICK. Physiological and psychological effects of over-loading fallout shelters. Office of Civil Defense. Dunlap and Associates, Inc., Santa Monica, California, April 1963.

32. FOX, R. H., R. GOLDSMITH, D. J. KIDD, and H. E. LEWIS. Acclimatization to heat in man by controlled elevation of body temperature. J. Physiol. 166: 530-547, 1963.

33. ROWELL, L.B., J.R. BLACKMON, R.G. MARTIN, J.A. MAZZARELLA, and R.A. BRUCE. Hepatic clearance of indocyanine green in man under thermal and exercise stresses. J. Appl. Physiol. 20: 384-395, 1965.

34. BROADBENT, D.E. Differences and interactions between stresses. Quart. J. Exper. Psychol. 15: 205-211, 1963.

35. POULTON, E.C. On increasing the sensitivity of measures of performance. Ergonomics 8: 69-75, 1965.

36. BENZINGER, T.H., C. KITZINGER, and A.W. PRATT. The human thermostat, Chapter 56 in Temperature - Its measurement and control in science and industry. Vol. 3: Reinhold, 1963.