

THE INFLUENCE OF
CLOTHING AND POSTURE ON
RADIANT HEAT TRANSFER IN MEN

BY

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DECLARATION BY CANDIDATE

This dissertation is my own work and has
not been submitted for a degree of this
or any other University.

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NOTATION

E	electrical capacitance	cm ²
C	electrical capacitance	cm ²
	rate of convective heat exchange per unit area of total body surface	kcal m ⁻² h ⁻¹ = 1.16 W m ⁻²
E	rate of evaporative heat exchange per unit area of total body surface	kcal m ⁻² h ⁻¹ , W m ⁻²
F	radiation surface area	m ²
H	heat transfer rate	W
M	rate of metabolic heat production per unit area of total body surface	kcal m ⁻² h ⁻¹ , W m ⁻²
I	insulation of clothing	clo, see Eq 1
R	rate of radiant heat exchange per unit area of total body surface	kcal m ⁻² h ⁻¹ , W m ⁻²
S	rate of storage of heat (in body) per unit area of total body surface	kcal m ⁻² h ⁻¹ , W m ⁻²
T	temperature (absolute)	K
V	voltage	V
A _i	integration area (sphere)	m ²
F _{tot}	total or true geometrical surface area of the body	m ²

(x)

F_{se}	radiation surface area in spread-eagle posture	m^2
q_{ir}	radiant flux density	$W m^{-2}$
f_{eff}	$= F/F_{tot}$	1
f_{cl}	$=$ (radiation surface area, clothed, for a certain posture)/(radiation surface area, nude, for the same posture)	1
r	radius	m
ϕ	radiometer output	μV
ϵ	emissivity	1
α_{ir}	absorptivity of surface	1
σ	standard deviation	1
	Stefan-Boltzmann constant $=$ $5.67 \times 10^{-8} W/m^2 K^4$	

SUBSCRIPTS

b	body
bb	black body
e	environment
ext	external
eff	effective
i	general, inner

mr mean radiant temperature

o outer

p projected

r, R radiometer

se spread-eagle

t target

tot total

umr mean radiant temperature with respect to
unirradiated person

1 SYNOPSIS

The aim of this work was to investigate aspects of the effects of thermal radiation (within the infrared spectrum) on a worker. It is part of a general study of industrial heat stress.

For this purpose the radiation surface areas of subjects in different working postures (8) and clothing (4) were determined. An investigation of the emissivity of different types of clothing was also made. As a result, it was found that the radiation area of typical working postures varied between 89.0% and 65.0% of the total skin area of nude subjects. For the two extreme postures, the radiation surface area of clothed subjects was determined to be (maximal) 113.9% (mine suit) and (minimal) 77.5% (overalls) of the nude total skin area.

Emissivity was found to have values between 1.02 ± 0.111 (common canvas garment) and 0.74 ± 0.108 (special high reflecting fireman's suit).

2 INTRODUCTION

The aim of this work was to make a contribution to the knowledge of industrial heat stress, caused by thermal radiation, on a worker. This is intended to be one part of a general study of his entire heat balance (convective heat transfer, respiration, evaporation, etc).

In order to show its importance, a short survey of the problem is first given.

2.1 Heat stress in industry

Thermal stress is an important primary or complicating factor in many industrial situations. As a primary factor, it can seriously affect the health of the worker, and as a complicating factor, it can diminish the tolerance of the worker to other industrial hazards. The problem discussed in this thesis can therefore be considered partly as an ergonomic problem. We will later see that an equally important aspect of the problem has a purely engineering character.

The determination of the thermal stress arising from an industrial environment and the translation of this stress in terms of physiological and psychological strain is a complex problem, yet for practical industrial situations, acceptable limits for thermal exposure are established and methods for evaluating and predicting the thermal impact of an industrial environment must be available. Such limiting levels must take into account all of the factors that might affect heat exchange between the worker and his environment as well as all the factors that might influence the responses and tolerance of the worker to the total heat stress.

In order to illustrate heat stress situations in industry, a few examples will be given:

(a) A man is operating a glass moulding machine for forming molten glass into bottles. The bottles, still red-hot, leave the machine on a conveyor belt, passing the operator at a distance of approximately 2 m.

(b) Near a submerged-arc furnace a labourer is shovelling material into the furnace. After shovelling, the man pushes the material against the arc with long metal pokers, standing at a distance of about 3 to 4.5 m from the furnace [1].⁺

(c) In a semi-automatic rolling mill, a man with a pair of tongs has to catch the front end of a long red-hot bar coming out of the first rolling mill and put it into the next one.

(d) Finally, not only are industrial workers often faced with exposure to an extreme radiant environment, but soldiers also sometimes find themselves exposed to direct solar radiation. It is reported that helicopter pilots flying AH-1G "Huey" Cobra gunships in Vietnam frequently return from missions showing definite symptoms of moderate heat strain, typically with complaints of dizziness, stomach cramps and prolonged fatigue [2]. It was found that the cockpit canopy absorbs large amounts of solar radiation and emits it as thermal radiation of considerable intensity.

Returning to industrial conditions, a typical (constructed) daily environment profile for one position in an aluminium plant is shown in Fig 1. It is evident that the thermal load in industry can be severe.

2.2 Physiological aspects of the problem

The normal human body is capable of making remarkable adaptations in buffering the effects of extreme environmental temperatures and of maintaining, in all naturally hot climates,

⁺ Numbers in square brackets refer to the references listed at the end.

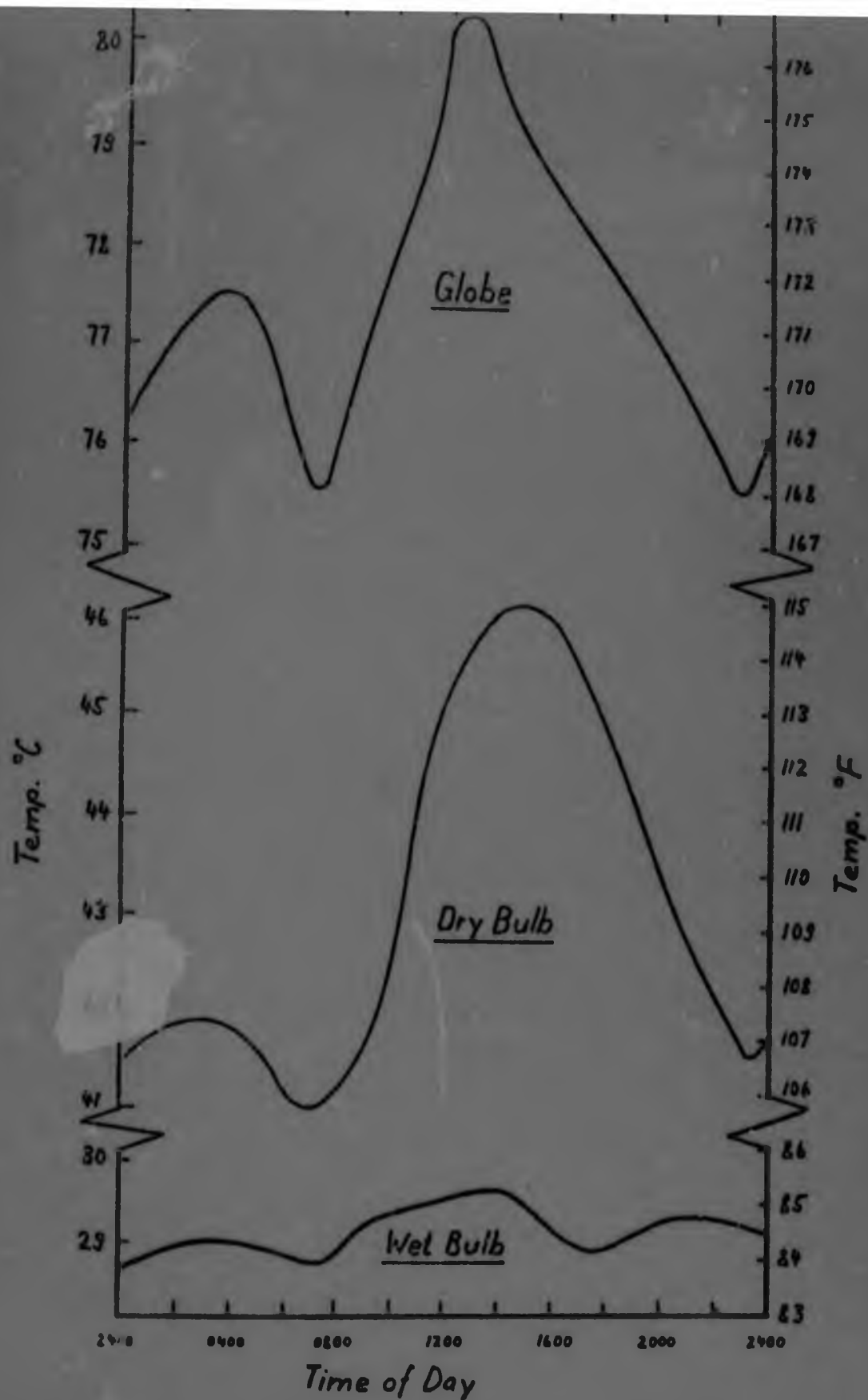


FIGURE 1

Twenty-four hour wet bulb, dry bulb and black globe temperature cycles at a point between the pots in an aluminium plant. Each curve is an average of values recorded during 21 consecutive days [23]

its internal temperature within rather narrow limits. Nature has endowed us with an excellent thermostat which, on the one hand, controls mechanisms that can maintain heat dissipation from the body against surprisingly large environmental heat resistances, and, on the other hand, controls mechanisms which can husband the body's heat store when the cooling power of the environment becomes large.

In order to maintain a constant internal body temperature the organism must balance its rate of heat dissipation against its heat gain from metabolism plus any heat gained from the environment by radiation, convection and conduction. Deviations from this balance involve alterations of the body's stored heat and thus its temperature. This balance can be expressed by the equation

$$M \pm S - E \pm R \pm C = 0$$

where the sign of M (rate of metabolic heat production) is always positive; E, rate of evaporation, is always negative because heat is always removed from the body; S, rate of heat storage, with a positive sign, indicates a lowering of the body temperature; R, rate of radiant heat exchange, is positive when the surrounding surfaces are of higher temperature than the body surface and thus add heat to the body by radiation, and is negative when these surfaces are of lower temperature than the body surface; C, rate of convective heat transfer, is positive when the air temperature exceeds that of the body surface, and is negative when it is lower than that of the skin.

The three external heat exchange terms in this equation are only physically - but not physiologically - different. As far as the body is concerned, it does not matter how the heat exchange with the environment takes place; the effect of radiation, for instance, is not, by its nature, significantly different from that of the effect of the other heat exchange terms. From the point of view of physiology, it is only the sum of the three terms contributing to the external heat

exchange, according to the physical laws in operation, that must be taken into consideration.

As far as our problem of heat stress is concerned, it has been repeatedly demonstrated that sweat loss correlates with the total heat load, including both metabolic and environmental heating. Two other physiological responses which reflect the level of thermal stress are work and recovery pulse rates, and internal body temperatures. The pulse rate response can be used to assess the cardiovascular cost of meeting the combined load of the heat and the work. The internal body temperature will indicate how successful the body has been in meeting the thermoregulatory challenge.

2.3 Parameters describing heat stress situations

Several methods and indices have been proposed for assessing and predicting the thermal stress of a hot environment. However, most recent critical reviews emphasize the point that the indices are valid only for situations comparable with those upon which the indices were based. They are not therefore applicable to industrial situations in general. To further complicate the problem, the acquisition of the basic physiological and environmental data required to calculate an index of thermal stress is extremely difficult under conditions of routine plant operation. Many of the methods and instruments are designed primarily for use in the laboratory and are not adaptable to workshop conditions where the climatic factors vary over short intervals both in space and in time. Ideally, the determination of the heat stress in an industrial environment (from the point of view of determining potential physiological and psychological strain) requires data on factors related to the environment (eg, air temperature, vapour pressure, air movement, long wave and solar radiation), to the worker (eg, clothing, acclimatization, physical and mental capacities, age, sex, nutritional and health status, body hydration, and ethnic origin), and the job (eg, patterns of heat exposure, intensity of physical work, and required job performance). Data on many

of these factors are, of course, difficult to obtain, because many cannot be controlled, reliably measured or fully described, yet in estimating thermal stress and the associated physiological and psychological strain, we are concerned with the total man in his total working and living environment.

At least a substantial part of the total environment can be described with variables. Of these a group of four represents an attempt at describing the thermal environment. The first one, the mean radiant temperature (T_{-r}), describes man's radiant environment most conveniently, and is defined as that uniform temperature of black surroundings which will give the same radiant heat loss from a person as in the actual case under study. The mean radiant temperature, together with the air temperature, the relative air velocity and the air humidity make up the four main environmental variables. Also influencing man's thermal comfort are his metabolic rate, which may be assumed to be a function of the activity he undertakes, and the thermal resistance of his clothing. The latter is measured by the clo-value [3], which is a unit of insulation and is the amount necessary to maintain comfort and a mean skin temperature of 92°F (33.3°C) in a room at 70°F (21.1°C) with air movement not exceeding 10 feet per minute (0.0506 m/s), humidity not over 50%, with a metabolic rate of 50 kcal/m² h (58 W/m²). On the assumption that 76% of the heat is lost through the clothing, a clo may be defined in physical terms as the amount of insulation that will allow the passage of 1 kcal/m² h (1.16 W/m²) with a temperature gradient of 0.18°C between two surfaces:

$$1 \text{ clo} = 0.18 \text{ cal/m}^2 \text{ h} \quad (1)$$

This unit is the reciprocal of the overall heat flow constant h in.

$$\frac{q}{t} = h \cdot A \Delta T \quad (2)$$

Ordinary business clothing has an insulation value of about 1 clo. The best clothing has in practice a value of about

4 clo per inch (2.54 cm) of thickness [3].

All these 6 variables are of importance in man's thermal balance and it is therefore meaningless to give (comfort) values for a single variable (eg, temperature) unless values for all the other variables are established.

In one study, Fanger [4] has set up a general comfort equation, which establishes for each activity and type of clothing all combinations of air temperature, mean radiant temperature, humidity and relative air velocity which are claimed to create optimal thermal comfort. But as a criticism one should remember that many other factors, sometimes of a psychological nature, also contribute to the sensation of "comfort". It is therefore suggested that Fanger's conditions be termed a "sensation equation" rather than a "comfort equation". But nevertheless this equation allows us to compare the importance of the 6 variables among themselves, especially that of radiation, which is, after all, the subject of this study.

2.4 Importance of the radiant part of the general heat exchange

In the application of Fanger's comfort equation and diagrams, the following examples have been chosen to show the influence of radiation on men.

1st Example: A seated, nude person is in an environment of 25°C temperature, 0.2 m/s air velocity and 35°C mean radiant temperature. The radiant environment is now changed by increasing the mean radiant temperature by 5°C to 40°C (eg, by switching on an infrared heater). In order to have the same total thermal sensation, this change in radiation would have to be compensated for either by increasing the air velocity by a factor of 2.2 or by decreasing the air temperature by 3.5°C.

2nd Example: A seated nude person in an environment of 28°C air temperature, 0.5 m/s air velocity and 35°C mean radiant temperature. The radiant environment is now changed

by decreasing T_{mr} by 5°C to 30°C . In order to have the same total thermal sensation, this change in radiation would have to be compensated for either by decreasing the air velocity from 0.5 to 0.2 m/s or by increasing the air temperature to 31°C .

If we were to try to compensate for the cooler radiant environment by using light clothing of 0.5 clo, this would yield such an enormous overcompensation that we would need, for instance, an additional wind speed of 15 m/s (a factor of 30) to re-establish the original sensation of comfort. This shows how great the influence of clothing (even very light clothing) can be in protecting against radiation.

The next example will make this point even more clear.

3rd Example: A seated person is in an environment of air temperature 25°C and an air velocity of 0.2 m/s. The following mean radiant temperatures would be necessary to achieve comfort:

- $T_{mr} = 35^{\circ}\text{C}$ for a nude person (0 clo)
- $T_{mr} = 29^{\circ}\text{C}$ with light clothing (0.5 clo)
- $T_{mr} = 22^{\circ}\text{C}$ with medium clothing (1.0 clo)
- $T_{mr} = 13^{\circ}\text{C}$ with heavy clothing (1.5 clo)

3 THEORY OF RADIANT HEAT EXCHANGE

The radiant component of heat exchange is governed essentially by the same laws which are used in engineering to calculate the heat transmission from pipes, plates or any other body. From this point of view, the problem has a purely engineering aspect in addition to the ergonomic aspect mentioned above.

The wavelengths occurring in industrial irradiation lie mainly in the infrared spectrum. This can be seen in Fig 2, where intensity (energy density) is plotted as a function of wavelength. From the red-hot stove at 1 000 K down to the human body at 300 K, the radiant sources occurring in industry contribute a great part of their energy within the 1-50 μm waveband, ie, the infrared spectrum. For this reason all of the following discussion refers only to this waveband.

The radiant heat transfer between a man and his environment can generally be described by the equation:

$$H_{e \rightarrow b} = \epsilon_b \sigma F (T_e^4 - T_b^4) ; (T_e > T_b) \quad (3)$$

This relation was first derived by C Christianson in 1883 from the Stefan-Boltzmann law. The following assumptions are made in this formula:

1st Assumption: The body is considered as convex and the surrounding surfaces as concave.

2nd Assumption: The area of the surrounding surfaces $\gg$ area of the body, which is generally justified (cf the wall area of a room, for instance).

3rd Assumption: The radiation is within the infrared spectrum (no short-wave radiation).

4th Assumption: In any discussion of the heating effect of radiation it should be remembered that radiant energy is converted to heat only at a point of absorption, such as on clothing. It is therefore extremely important, as far as man

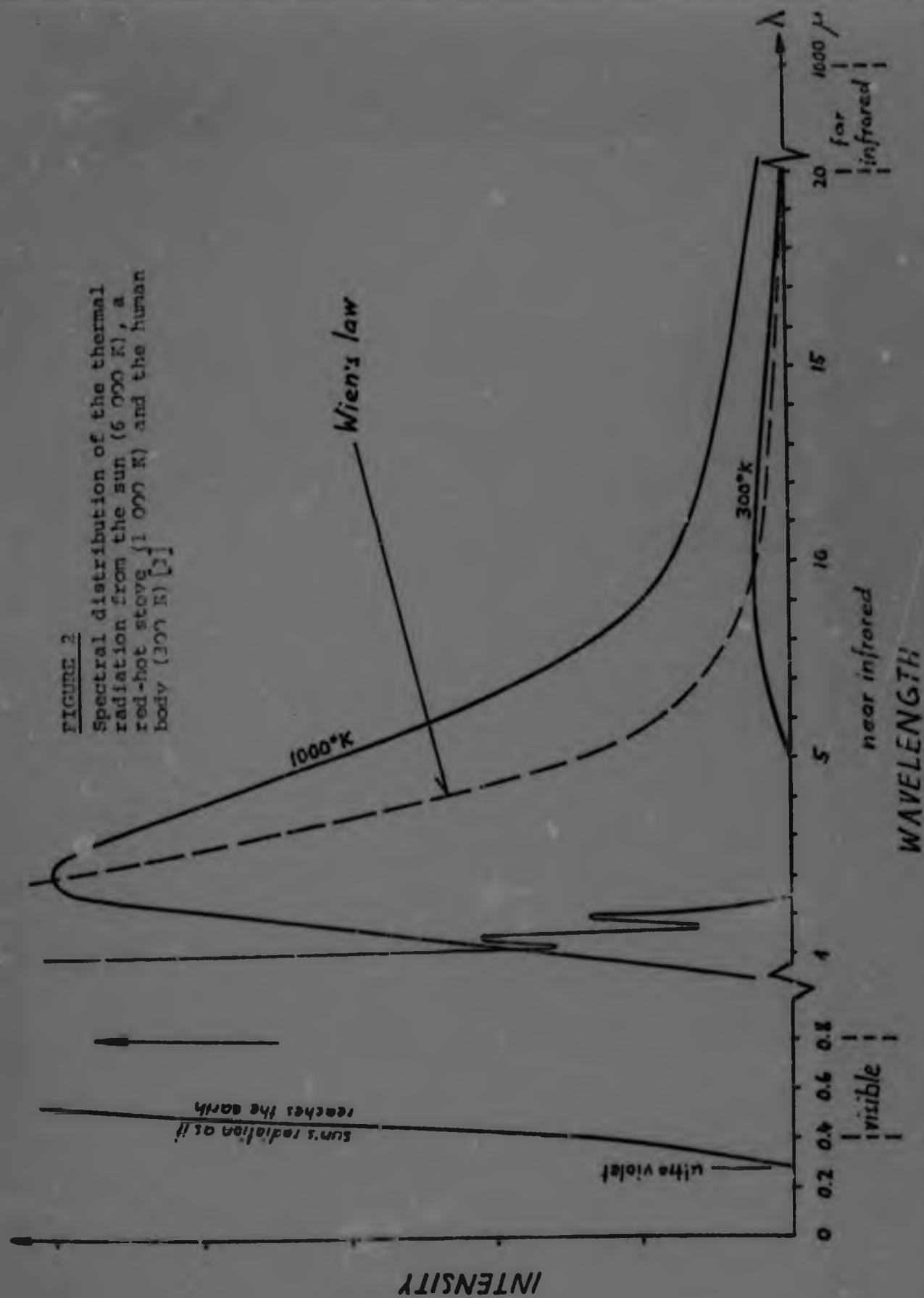


FIGURE 2
Spectral distribution of the thermal radiation from the sun (6 000 K), a red-hot stove (1 000 K) and the human body (300 K) [2]

is concerned, how near to the skin level this point is, and also what the insulation from the point towards the skin and towards the environment is. The efficiency of generation of heat by radiation at a point near the skin can be expressed by

$$H_{eff} = H I_{ext}/I_{tot} \quad (4)$$

The assumptions relating to the insulation problem must be examined in each particular case. It should be remembered that the overlying air layer is also part of this insulation. Generally, it can be said that the point of absorption lies on the very outside of any article of clothing. It was found, for instance, that in water the mean point of absorption is only approx. 40 μ m under the surface [5]. Since this distance depends only on the emissivity of the material and the emissivities of clothing and water are very similar (see II.6), the assumption of surface absorption is justified.

5th Assumption: The radiation flux is nearly isotropic, or if not, we take the mean radiant temperature to be T_e . In mines, for instance, where the environment consists of an entire rock enclosure of almost the same temperature and physical quality, we may assume that $T_e = T_{rock}$, eg, we have a nearly homogeneous environment (see Fig 3).

This situation is not found, for instance, in glass works, foundries or where warm and cold surfaces occur "passively" (windows, badly insulated walls), or where a person is exposed to radiation coming from a defined point or area such as lighting fixtures, machines or goods as well as irradiation from the sun.

It is useful in this connection to outline a few details of the way to handle this problem. Two cases must be considered:

3.1 Irradiation from non-uniform surroundings (Fig 4)

Such non-uniform surroundings consisting of n isothermal surfaces, and having temperatures $T_1, T_2, \dots, T_N$ (within the normal

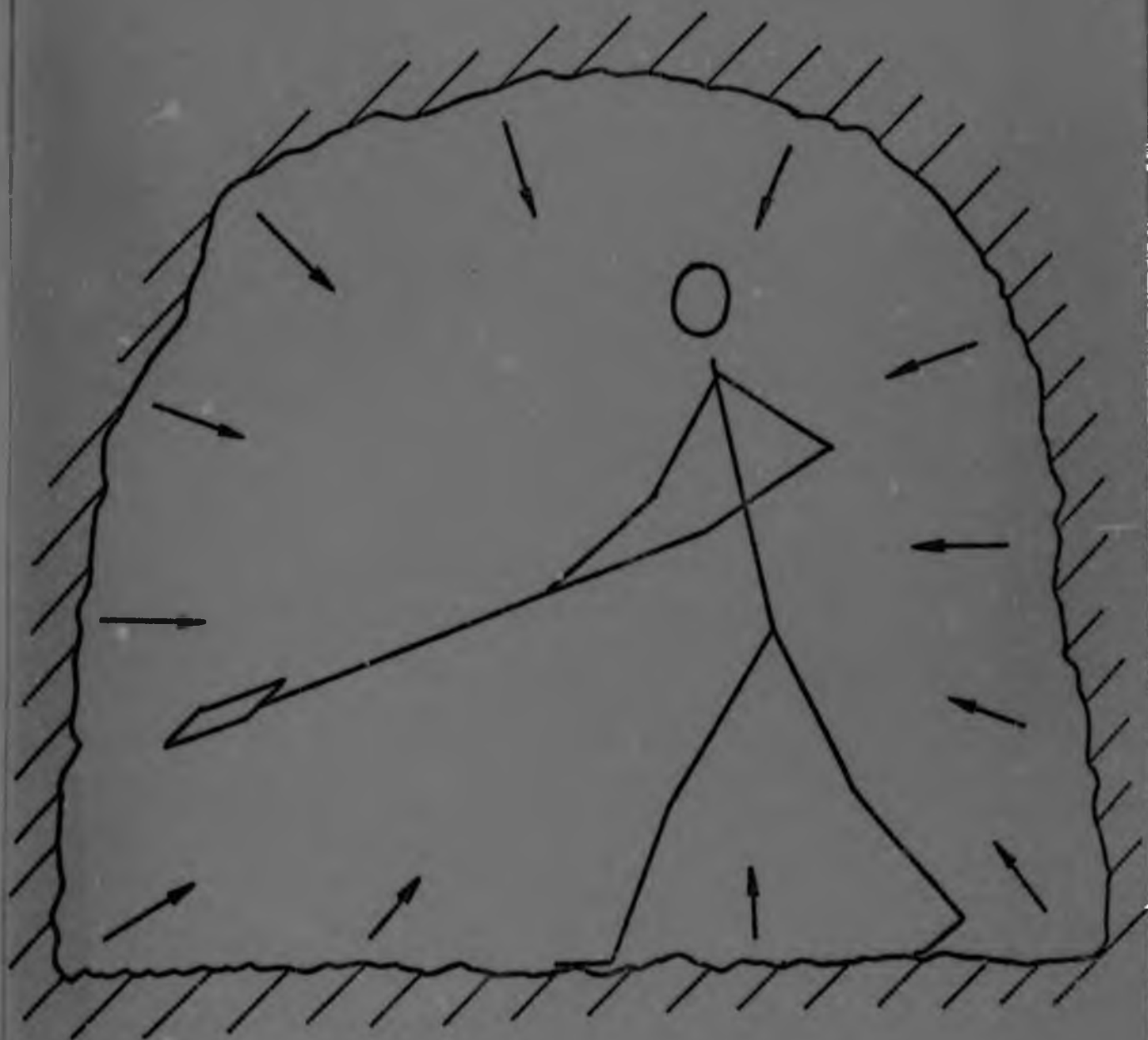


FIGURE 3

The radiant situation in a homogeneous environment, eg, in a mine

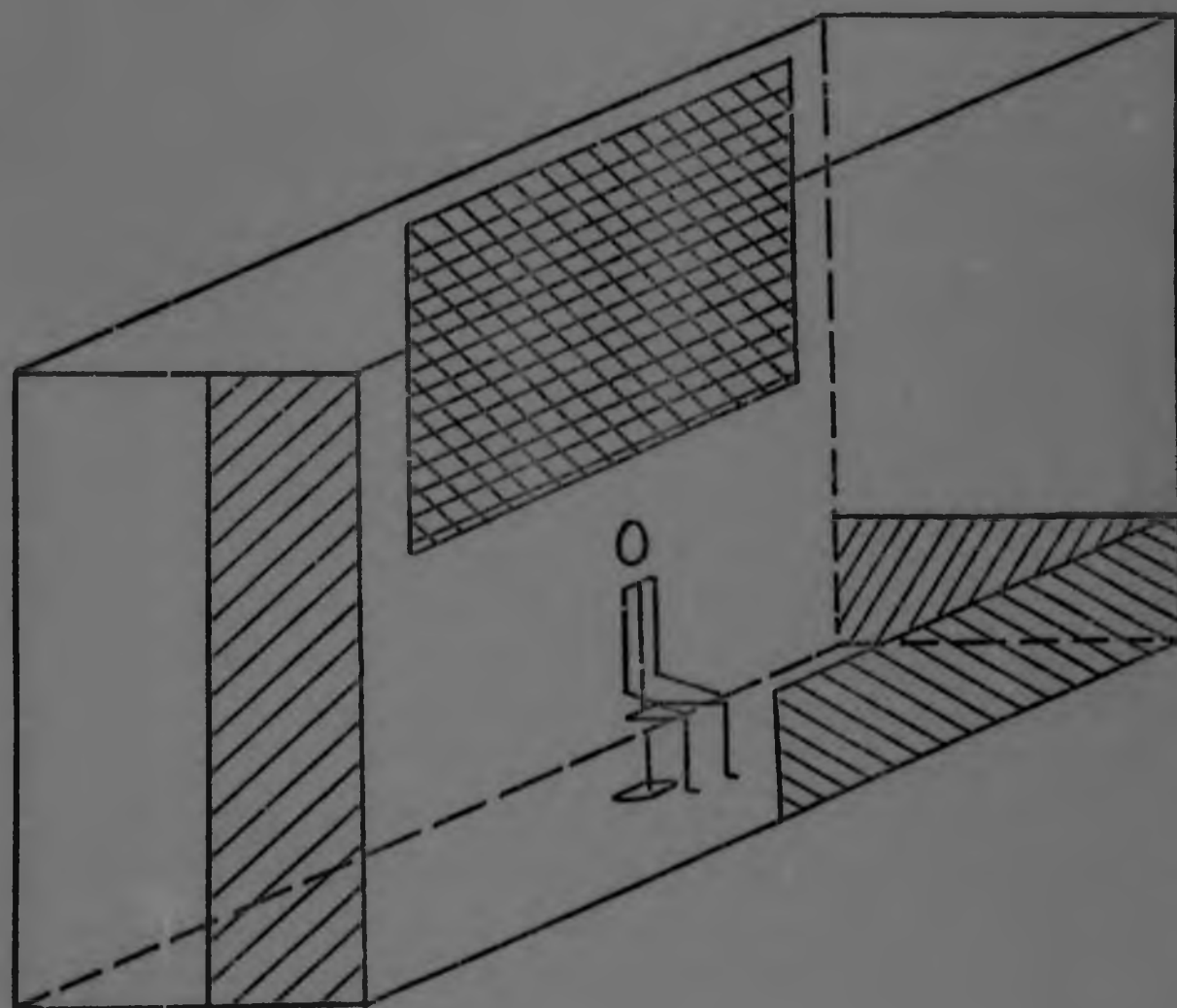


FIGURE 4

Irradiation from non-uniform surroundings

low temperature range), can be described most conveniently by the mean radiant temperature T_{mr} defined above (2.3).

In the absence of short-wave radiation T_{mr} is most conveniently determined with a globe thermometer, which is described in [6].

3.2 Irradiation from high-intensity radiant sources (Fig 5)

When a person is exposed to irradiation from a high-intensity radiant point source another method is necessary to determine the mean radiant temperature: first, the mean radiant temperature T_{umr} in relation to the unirradiated person can be determined in relation to a person as if he were not exposed to direct radiation from the heater. An exact calculation can be made with the globe thermometer, but in many practical cases one can with sufficient accuracy set T_{umr} equal to the air temperature. If the person is now irradiated with a mean radiant flux density q_{ir} , and the area of the person projected onto a plane perpendicular to the mean direction to the heater (centre of body $\rightarrow$ centre of heater) is called F_p , the irradiation upon the person will be equal to $q_{ir} \cdot F_p$ (Fig 6). (The radiation from a heater can be assumed to be largely parallel, since the distance of the subject from the heater is usually large.) Of this, $\alpha_{ir} \cdot q_{ir} \cdot F_p$ will be absorbed, where α_{ir} is the absorptivity of the outer surface of the person at the actual wavelength of the irradiation. The equation to be set up for the determination of the mean radiation temperature for the irradiated person T_{mr} is then:

$$\begin{aligned} H_{e \rightarrow b} \Big|_{T=T_{mr}} &= H_{e \rightarrow b} \Big|_{T=T_{umr}} + H_{\text{radiator} \rightarrow b} \\ \therefore \epsilon_b \sigma F [T_{mr}^4 - T_b^4] &= \epsilon_b \sigma F [T_{umr}^4 - T_b^4] + F_p \cdot \alpha_{ir} \cdot q_{ir} \quad (5) \end{aligned}$$

By rearranging Eq (5) we obtain:

$$T_{mr} = \left[T_{umr}^4 + \frac{F_p}{F} \cdot \frac{\alpha_{ir} q_{ir}}{\epsilon_b \sigma} \right]^{0.25} \quad (6)$$

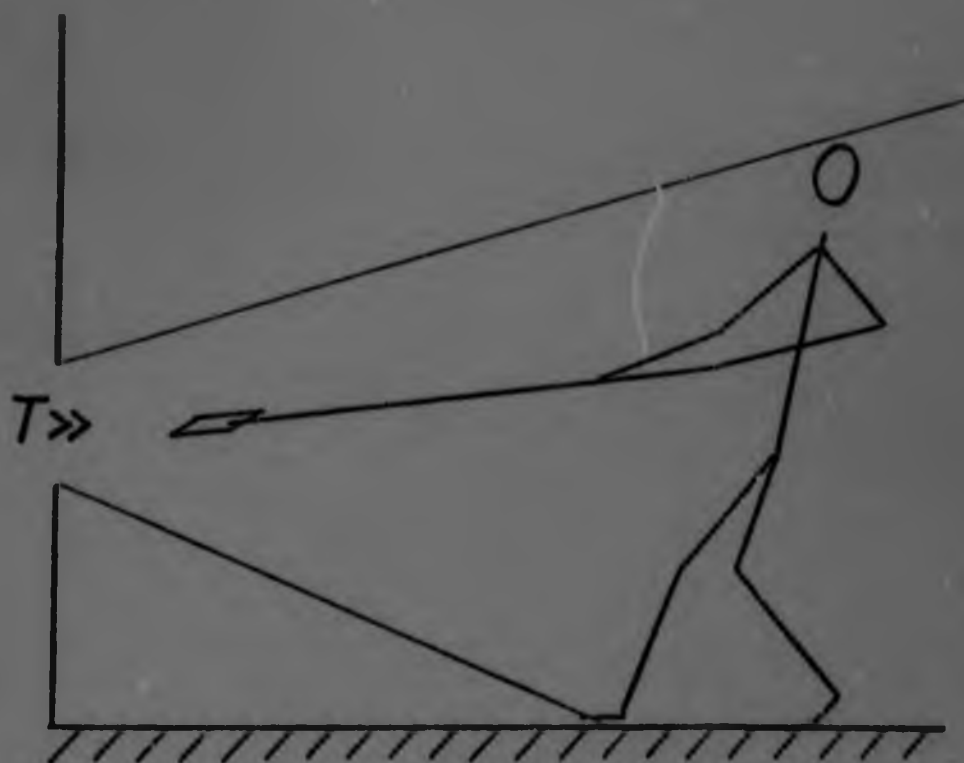


FIGURE 5

Irradiation from a high intensity radiant source

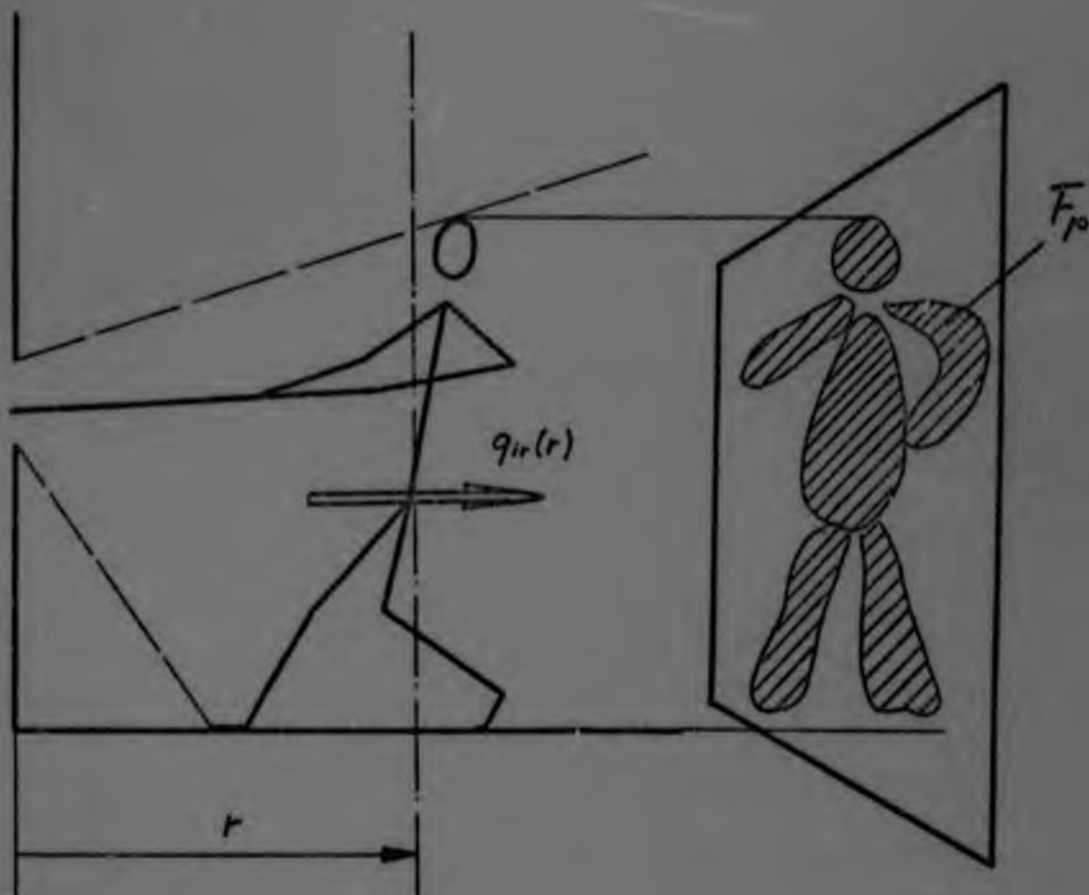


FIGURE 6

The projected area F_p , used for calculating radiant heat transfer from a high-intensity source

The introduction of $f_p = \frac{F}{A}$ (= projected area factor) makes the calculation independent of the size of the actual person. Such values are determined in [4] and plotted in diagrams from which f_p (for seated and standing persons) can be obtained for all possible directions of radiation.

4 OBJECT OF THIS WORK

In the foregoing, equations have been set down from which it can be seen what radiation data for the human body are necessary for the calculation of radiant heat transfer.

The general picture emerging from the use of these equations for calculating industrial heat stress shows that two important items are still missing: the assessment of surface area; and emissivity values of clothing.

This work was undertaken to fill in these gaps.

As far as the surface area is concerned two different definitions are required: the true geometrical area of the human body is the area of the outer surface of the skin, assuming that this surface is smooth. This area is dependent on posture, muscle tone, state of "stretch" of skin and other factors.

That area of the body which is available for exchanging radiation with the environment is described as the radiation surface area. The exact definition of the radiation surface area is given by the Stefan-Boltzmann equation:

$$q = \sigma F \epsilon T^4 \quad (7)$$

where the radiation surface area occurs as F and describes the geometrical circumstances of the radiant emission (or absorption).

The value of F naturally depends on the posture assumed. A knowledge of the radiation surface area can be very important when investigating or predicting body heat stress and the heat balance in working places exposed to radiation, as described above (2.1).

In the past, surface measurements have been mainly taken for a very few common postures, eg, standing and seated postures,

and were mostly based on only a few subjects [13]. A deeper knowledge of the radiation areas for typical working postures was therefore required.

Another factor affecting heat stress under high radiation levels is the clothing. Again the surface areas of clothed men in typical working postures, wearing typical working clothes was required. The conversion of radiant energy to heat furthermore depends on the absorption of the type of clothing (or skin), expressed by the emissivity ϵ , and this also had to be considered in this work. Naturally the heat generation by radiation as it influences a man is a function of many other factors such as surface and environmental temperatures and the point where (ie, in which layer of clothing) radiant energy is converted to heat. But these latter items may change from case to case and were therefore not examined.

The results of this work may be used in assessing the heat stress in industrial environments, where radiation will be one effect among many others. Furthermore, recommendations on the types of clothing to be worn - particularly at working places exposed to radiation - may also as a result be made.

5 SURVEY OF LITERATURE

The effective radiation area of the human body in different postures has been the subject of several investigations using surprisingly varied experimental techniques. It must be remembered, however, that the majority of these experiments were made with only a few subjects, sometimes only one.

Bohnenkamp [7], [8] at the beginning of the 1930's measured the electrical capacitance of standing subjects, claiming that this is a parameter related to the radiation area. He found a similarity between the theory of an electrostatic field around a body which determines its capacitance and the radiation field which determines its radiant heat exchange.

From this comparison, he arrived at the equation

$$F = 4\pi C^2 \quad [\text{cm}^2] \quad (8)$$

where the radiation surface area is a function of the capacitance C of the body only. C is determined by means of an electrometer, by connecting the measuring system (including the body whose capacitance is to be measured) with a battery until it is charged. The voltage of the measuring system charged in this way is V . After connecting another known capacitance C' , which was previously earthed, the voltage is decreased to the new voltage V' . Hence the capacitance of the measuring body was determined by

$$C = \frac{V' (C' + B)}{V - V'} \quad [\text{cm}] \quad (9)$$

where B represents the additional capacitance of the lead between the capacitance C' and the measuring system.

This method of determining the radiation surface area appears simple but in reality the sources of errors are serious. The main difficulty comes about as a result of the environmental conditions of such an experiment. It is obvious that this kind of experiment must take place in a laboratory with limited

dimensions. For such a large body as the human body, the influence of the surrounding walls in increasing the capacitance is considerable. In ordinary buildings, no rooms are usually large enough to keep this error negligible, as compared with the errors of the measuring method. Furthermore, it must be mentioned that such an error would be a systematic one which should be avoided under any circumstances. In spite of the fact that Bohnenkamp carried out his experiments in an especially large room in a hospital and even in a hangar on an airfield, this effect is still considerable as a few calculations may easily demonstrate.

If we take the most simple case and assume the human body to be roughly a sphere (of radius r_i) and the environmental room walls to be a concentric sphere (of radius r_a), the capacitance of this system can be calculated from:

$$C = \frac{r_i \cdot r_a}{r_a - r_i} \quad [\text{cm}] \quad (10)$$

If we assume a diameter of 0.5 m for the inner sphere representing the human body, the capacitance will change considerably as we vary the diameter of the outer sphere representing the walls of the laboratory room (see Table 1).

r_a [cm]	C [cm]
50	50
100	33.3
150	30
200	28.6
250	27.7
500	26.3
750	25.8
1 000	25.6

Table 1

Furthermore, the influence of any eccentricity of the object of measurement within the environment is difficult to estimate. In order to eliminate these errors, the apparatus was calibrated by substituting for the human body calibration bodies of varying, but basically similar shape. There is no doubt, however,

that the results of this method depend largely on the shape of these calibration bodies.

In conclusion, it may be said that this method suffers from great practical difficulties in spite of the evident appeal of the associated theory.

Bedford [9] made use of a much simpler graphical construction method. He determined the effective radiation area of a nude and of a clothed body by measuring the overall girth in a suitable number of places. Assuming an elliptical body silhouette he applied Simpson's rule to obtain the area by integration from the measurements. He found values for two subjects in both standing and crouched positions.

This method must be regarded as a very rough approach towards determining the radiation surface area. The results must therefore be judged in this light and more accurate results may not be expected from such an approximate method. The only criticism of the method must therefore be directed at the relatively time consuming nature of the procedure by comparison with the simplicity of its physical background.

Nielsen and Pedersen [10] employed a thermal method in which radiant heat transfer was determined by establishing a heat balance for the human body. They found values for one standing and one seated subject. This method is derived directly from the definition of the radiation surface area (see Eq 7) and must therefore be regarded as the best method as far as reliability is concerned. The heat loss by radiation plus convection from the human body can be determined as the difference between the heat production and the heat loss by evaporation plus or minus the change in body heat content (see 2.2). It is therefore possible to determine the heat loss by radiation and by convection separately if the mean air temperature of the surroundings, that is, the mean radiant temperature, is equal to the mean surface temperature of the subject. In the test room used by Nielsen, it was possible to vary the radiant temperature and the air temperature independently of one another without significantly influencing the air velocity.

For comparison with the experiments on a man, a parallel series of experiments was performed on a clothed thermostatically controlled dummy of the same shape and size as a grown-up man, and with the average surface temperature beneath the clothing maintained at a constant value. The heat loss from this dummy could be determined in a simple way and with a much higher degree of accuracy than is possible to obtain from experiments on a man. The clothing of the dummy was quite similar to that of the subject and covered in both cases about 90 per cent of the surface; further, since the emissivities of the unclothed areas were of the same magnitude, it was reasonable to assume that the heat loss by radiation per unit area from the dummy and from the subject would be practically the same under equivalent conditions. On the other hand the convective heat loss might be expected to be somewhat greater for the subject than for the dummy due to the small movements of the former.

When the clothing temperature is equal to the air temperature the convection heat loss is zero, and when the clothing temperature is equal to the radiant temperature the radiation heat loss is zero. For these conditions, therefore, the heat loss by radiation and the heat loss by convection, as well as the corresponding air and radiant temperatures, can be determined directly.

Once the radiant heat transfer has been determined, the other data necessary to calculate the effective radiation area are the body surface temperature T_b and the emissivity of the body surface ϵ_b . The temperature was measured by means of a number of thermocouples distributed over the entire body, in order to obtain a mean body temperature. For the emissivity of the clothed subject a value of 0.95 was taken.

The radiation surface area was obtained by rewriting Eq 3 as

$$F = \frac{H_{b \rightarrow e}}{\epsilon_b \sigma (T_b^4 - T_e^4)} ; (T_b > T_e) \quad (11)$$

It is clear that this method is enormously time consuming. However, the method has the advantage that it is based directly on the definition of the radiation surface area and does not therefore involve consideration of area similarities. The determination of the radiant heat exchange $H_{r,g}$, however, also involves calculation of heat losses by convection, evaporation and processes of metabolism. As these other items are not measured (by calorimetric means, for instance) but are instead calculated, the final radiant heat exchange is a result of so many assumptions that the advantages of the method are no greater than those of the direct method.

Guibert and Taylor [11] employed a photographic method and obtained values for 3 subjects in seated and standing postures. Fanger [4] used a very similar but slightly improved method and took measurements of 20 subjects in all in standing and sitting positions. A description of this method is given to conclude this survey of the literature. First the projected areas F_p (see 3.2) of the test person was measured from a number of directions. The experimental set-up is shown in Fig 7. The subject was placed on a vertical movable platform which could at the same time be pivoted about a vertical axis. Around the test person was mounted a system of mirrors, consisting of (i) a small, plane precision mirror which could be pivoted about a horizontal axis, and (ii) 6 large fixed plane mirrors placed in a vertical quadrant, with the subject in the centre. By turning the small mirror, the test person could be viewed and photographed with a fixed camera from 6 different angles in the vertical plane. The reflexion of the light rays by means of the mirrors is shown diagrammatically in Fig 8. By turning the platform, a total of 13 horizontal angles could be obtained, or $13 \times 6 = 78$ exposures within a quarter-spherical solid angle. It is sufficient to take measurements within a quarter-spherical angle because of the right/left symmetry of the body, and because the projected area from 2 opposite directions is the same.

The projected areas were measured by double planimetry, the negatives being projected upward onto a table with a glass top, the projected and natural sizes being in the approximate ratios

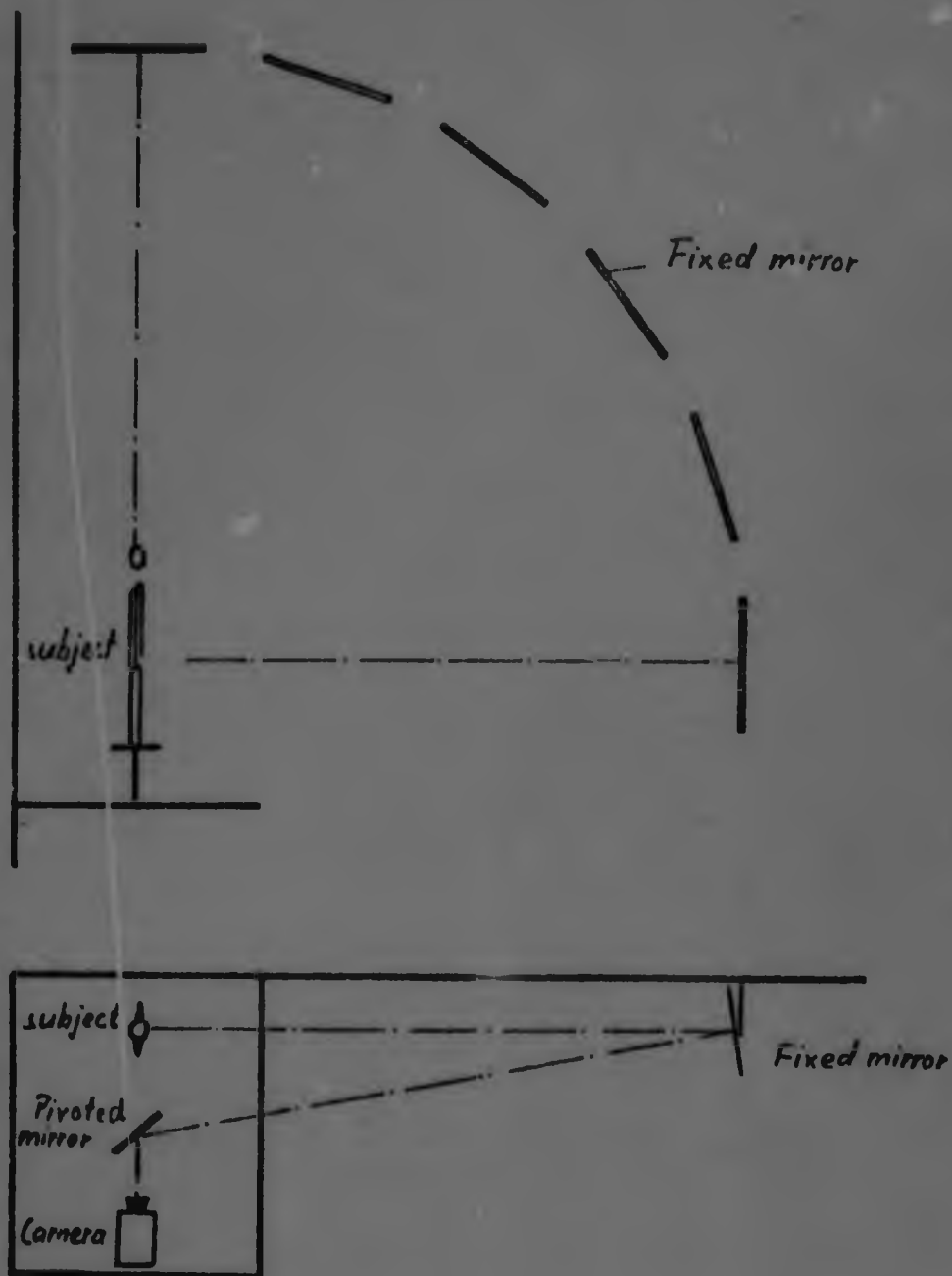


FIGURE 7

Experimental apparatus for the photo-
metric method, from side and above

of 1:5. From these projected areas, the effective radiation area was then obtained by calculation. Consider a person located in the centre of a spherical coordinate system, where any direction in relation to the person is defined by the azimuthal angle α and the altitude angle β (see Fig 8). Consider further a differential surface element dA on the sphere with angular coordinates (α, β) . The effective radiation surface area can then be determined by integration and becomes

$$F = \frac{4}{\pi} \int_{\alpha=0}^{\alpha=\pi} \int_{\beta=0}^{\beta=\frac{\pi}{2}} F_p \cos\beta d\alpha d\beta \quad (12)$$

where F_p is the person's area projected onto a plane perpendicular to the direction of dA . F is calculated for the 4 posture-clothing combinations for each subject by numerical integration of the double integral on the basis of the experimentally-determined F_p - values for 78 angles within a quadrant. Interpolation formulae for F_p between the observed values were deduced for the seated person on the basis of a detailed examination of a single subject, for which, in all, 273 F_p - values were determined.

Compared with the methods mentioned above the sources of errors are obviously very few. However, the amount of work and the time required to obtain readings are considerable. A consequence of this prolonged experimental procedure is that there is a certain danger that the test subject may change his position slightly during the photographic sequence. With this method, such a slight movement could introduce serious errors.

PART I : SURFACE AREA MEASUREMENTS

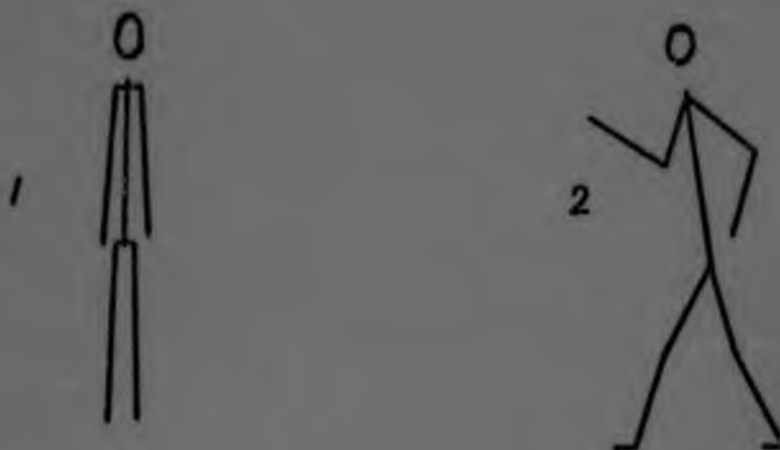
I.1 CHOICE OF POSTURES

I.1.1 Working postures

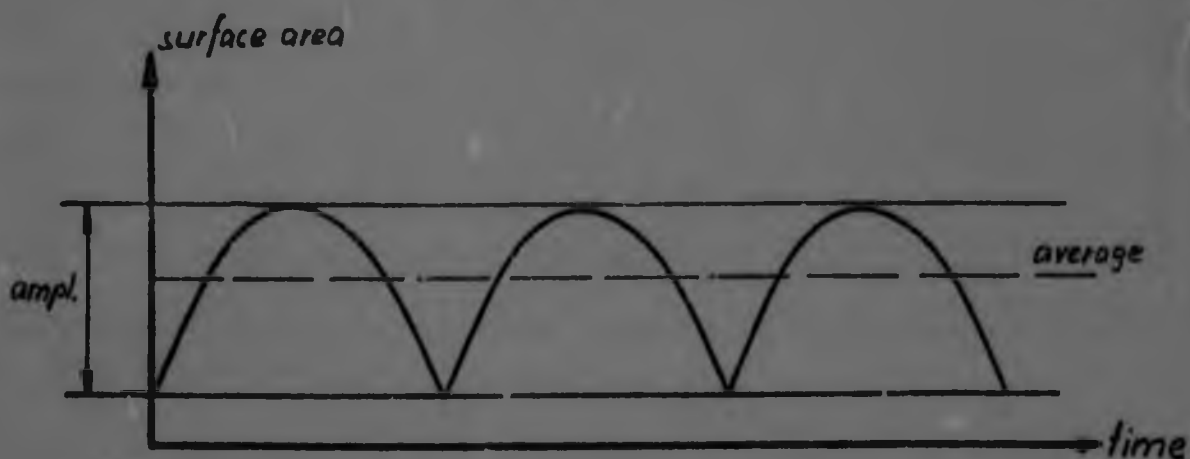
It was an important aspect of this study to select the most frequent working postures. Judging from the literature consulted, such a selection of typical working postures does not seem to have been made previously. Various postures have been intensively discussed in the large body of physiological literature, but these discussions represent a study of degrees of freedom or a study of one particular posture for the purpose of investigating the conditions of a certain job. (Many items of this kind may be found in the literature of aerospace medicine, for instance.) For material, the author had therefore to fall back on his own experience while working at 5 different industries in Switzerland as well as on observations made on numerous industrial visits in both Switzerland and South Africa and on observations from everyday life.

As will be seen later, the method of measurement employed only allows for the use of stationary postures. But as almost all work has to be done during movement and not while the body is in a stable posture, the selected postures had to be such that interpolation between them was possible in order that any activity could be described in terms of elemental postures.

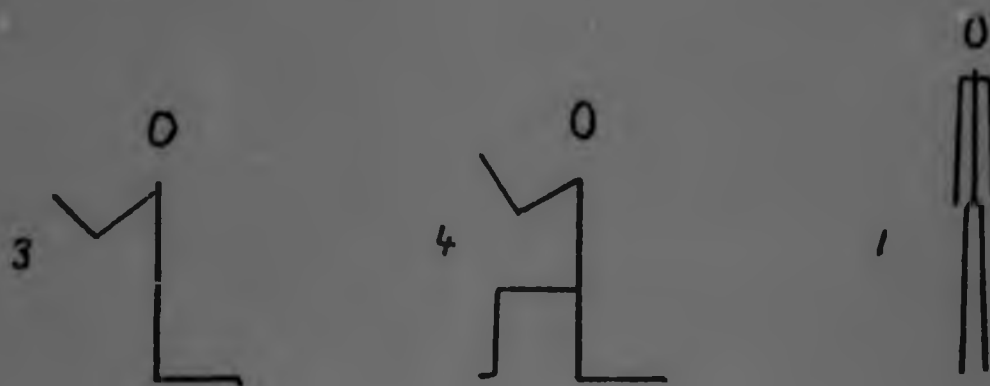
The best example of this may be the walking movement. An analysis of this movement reveals the following two typical positions:



If now a measure of surface area can be attributed to each of these two postures, the resulting average surface area can be roughly approximated by the synthesis of the two extreme positions in a harmonic movement:



Similar considerations apply in the case of the movement of standing up from the kneeling posture:



or in the case of the lifting movement:



Posture No 6 is also the typical posture for picking up light objects.

Finally the most frequent working posture, namely the sitting posture, should be considered. Here the influence of the back of a chair is certainly important, considering the fact that many activities demand a backrest and others not. But there remain many working activities which involve a continuous change between the bending-forward and the leaning-back positions. In the case of the two postures illustrated below, it should also be possible to establish an

approximate average position from a time sequence of the motions involved (work study).



All these considerations were taken into account in the final choice of typical working postures shown in Fig 9.

I.1.2 The spread-eagle posture (see Fig 10)

This posture was used for reference purposes. The way in which it was referred to in describing the working posture measurements is given in I.5. Its merit lay in its easy reproducibility as well as the fact that this particular posture yields the largest possible radiation surface area [13]. For this reason, the danger of errors arising from accidental variations in taking up this posture was proportionately lessened.

I.1.3 Detailed description of various postures

The spread-eagle posture (Fig 10): Legs apart, straight. Feet parallel with their outer edges, 96 cm apart. (This distance is chosen arbitrarily to correspond with the dimensions of the grid on which the subject is standing.)

Posture 1 (Fig 11): Standing posture. Heels together. Angle between feet ca 30° . Arms slack and hanging loosely down. Body upright. Subject looking horizontally ahead. Fingers loose in their most comfortable position.

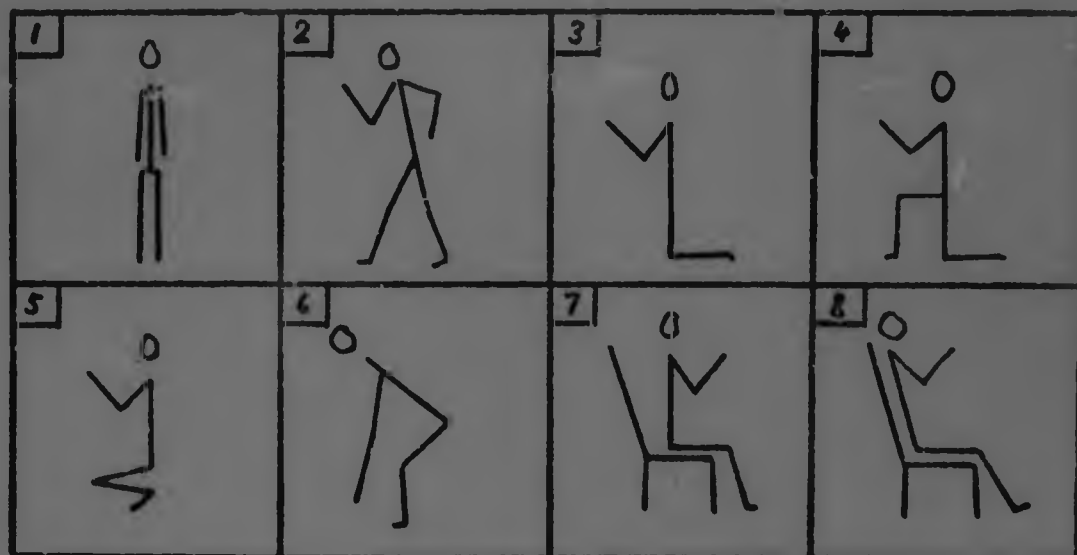


FIGURE 9

Summary of the selected working postures



FIGURE 10
Spread-eagle Posture



FIGURE 11

Posture 1 : Standing Posture

Posture 2 (Fig 12): Walking posture. Steplength (from heel to point of foot) : 96 cm (chosen for the same reason as for the spread-angle posture). The left (backward-positioned) forearm is vertical and its hand is just behind the body. The hand of the right (forward-positioned) arm is approximately at chin level. The fingers are loose as in Posture 1.

Posture 3 (Fig 13): Kneeling posture. Thighs and upper part of the body are upright. Arms and hands are both forward-positioned as in Posture 2.

Posture 4 (Fig 14): Kneeling on one knee. Shank of the forward-positioned leg and thigh of the kneeling leg both vertical. Arms and hands positioned as for Posture 3.

Posture 5 (Fig 15): Squatting posture - sitting on heels. Upper part of the body upright. Arms and hands positioned as for Postures 3 and 4.

Posture 6 (Fig 16): Lifting posture. Legs slightly (comfortably) angled so that finger tips easily touch the floor.

Posture 7 (Fig 17): Sitting, back and backrest not in contact. Upper part of the body upright. Arms and fingers positioned as for Postures 3, 4 and 5.

Posture 8 (Fig 18): Sitting, back and backrest in contact. Arms and fingers positioned as for Postures 3, 4, 5 and 7.

1.2 SUBJECTS

Twenty-three test subjects were employed for the determination of surface areas in the nude condition, and measurements were taken of a further 4 subjects in all postures, using 4 different types of clothing. All subjects were Bantu males, and they



FIGURE 12

Posture 2 : Walking Posture



FIGURE 13

Posture 3: Kneeling Postures

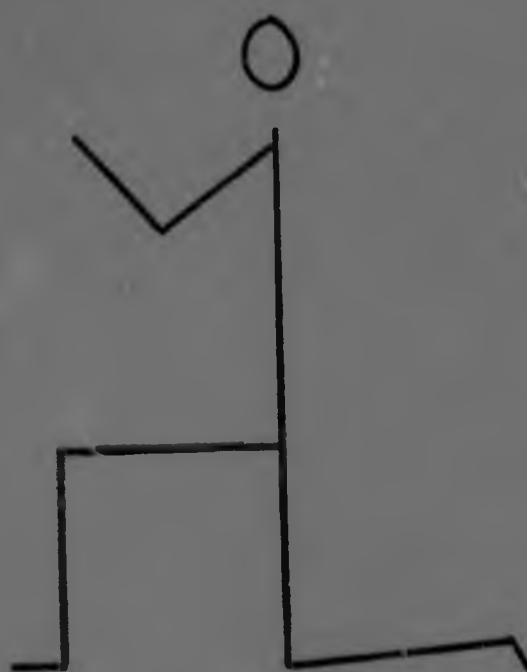


FIGURE 14

Posture 4: Kneeling on one knee



FIGURE 15

Posture 5 : Squatting Posture



FIGURE 16
Posture 6 : Lifting Posture



FIGURE 17

42

Posture 7 : Sitting, without touching
the back



FIGURE 18

Posture 8 : sitting, leaning
backwards

were average in respect of weight and height.

1.3 SELECTION OF TYPES OF CLOTHING

Four types of garment in common industrial use were investigated, namely:

1. Common track suit, without shoes
2. Overalls, without shoes
3. Mining suit, consisting of overalls, leather jacket and boots, without helmet *
4. Trousers, shirt, boots

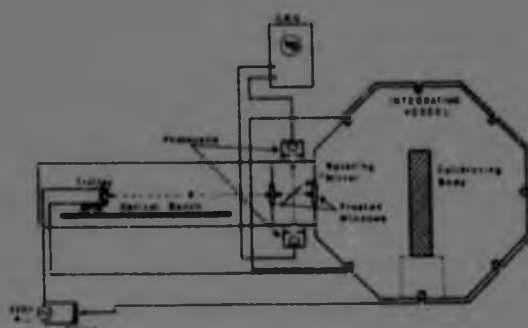
1.4 DESCRIPTION OF EQUIPMENT

1.4.1 The photodermoplanimeter (see Fig 19)

This instrument makes use of the principle that the area of a body which radiates to its surroundings is the same as the area available for absorbing light from the surroundings. An isotropic flux of white light is therefore produced in a large chamber of vertical dimension 10 ft. When a man enters the vessel he absorbs some of this light, and so decreases the light intensity at a frosted glass window in the wall of the chamber. This decrease in intensity is related to the light absorbing area by comparing the resulting intensity with that of a similar window illuminated by 4 comparison lamps. These lamps are mounted on a trolley which runs along an optical bench. The position of the trolley (which can be read off accurately from a sliding rule attached to it) thus determines

* In every type of helmet there is an insulation layer between the helmet material and the head. We must expect a helmet temperature very close to the mean radiant temperature of the environment because the thermal influence of the surroundings on the helmet is dominant compared to the influence from the head - due to this insulation. The helmet does not therefore differ much from the surroundings as far as radiation is concerned and in consequence, we may neglect it.

(A)



(B)

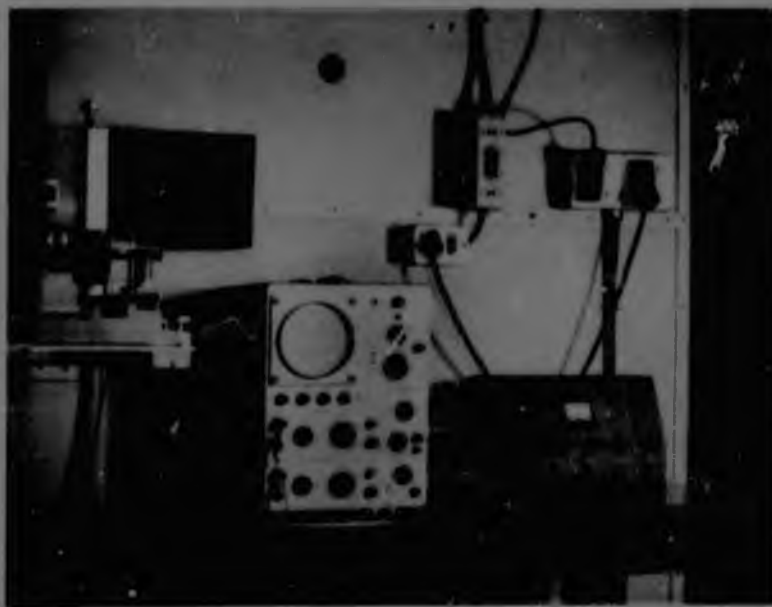


FIGURE 19

- (A) Schematic diagram of the photodermoplanimeter
(B) Recording Equipment

the light intensity at the reference window. The light intensities at the two frosted windows are compared by an electronic photometric system and are equal when the position of two ellipses on the screen of an oscilloscope coincide. Further details of this device can be seen in [12] and [13].

I.4.2 Calibration prisms*

The use of these prisms will be described later (see I.6.1). In all, 3 prisms were used, which allowed a choice of 7 area combinations, the surface areas and their respective combinations being:

I	:	0.42 m ²	} base : 0.3 m x 0.3 m
II	:	0.66 m ²	
III	:	1.26 m ²	
I + II	:	0.90 m ²	
I + III	:	1.50 m ²	
II + III	:	1.74 m ²	
I + II + III	:	1.98 m ²	

I.4.3 The chair

The chair which was used for Postures 7 and 8 had the dimensions shown in Fig 20. The seat and back of the chair were covered with a 1.2 cm thick layer of rubber foam, in order to simulate upholstery. All parts of the chair were painted with the same white paint as was used for the inside of the light chamber.

1.5 FORM OF PRESENTATION OF RESULTS

The form in which the results are given influences the experimental procedure. It is obviously convenient not to present the results of the surface area readings in absolute

* In Fig 19, one of these is described as a "calibrating body".

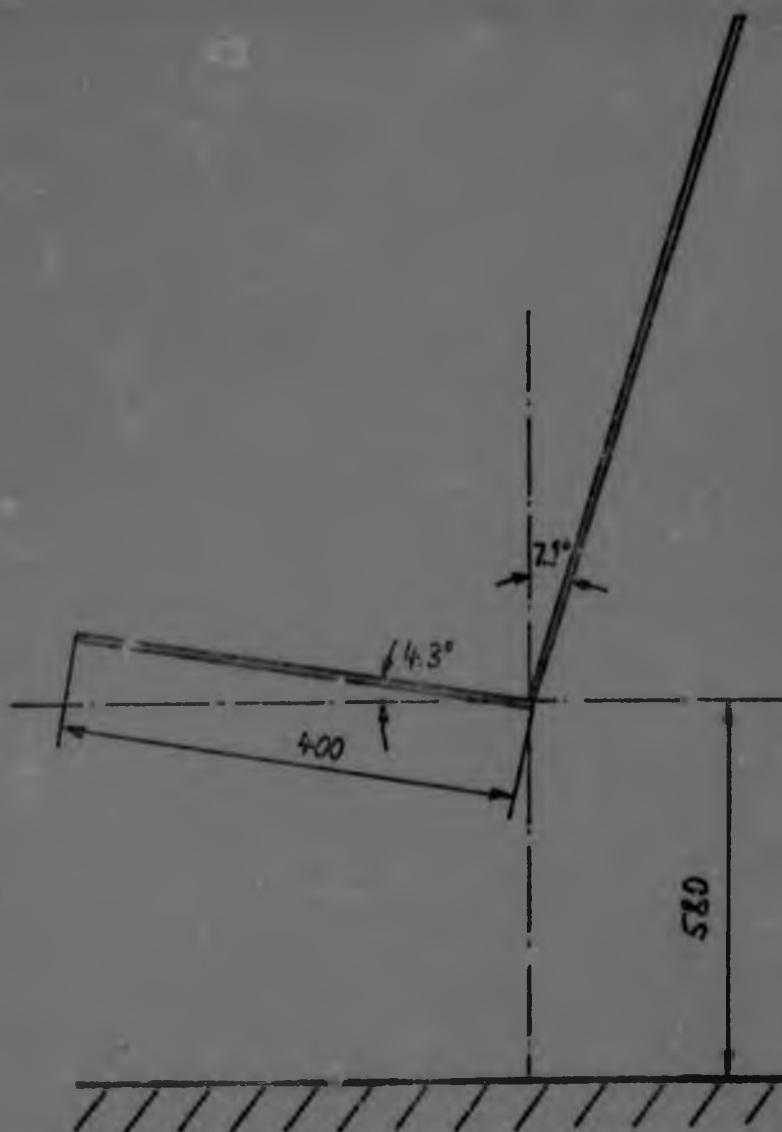


FIGURE 20
Chair dimensions

figures, but to refer them to a standard Posture. The reference posture chosen was the so-called spread-eagle posture (see I.1.2). This choice was expedient because it is already known how the true geometrical area can be obtained from the spread-eagle radiation area:

$$(\text{true geometrical area}) = 1.041 \times (\text{radiation surface area in spread-eagle posture}) \quad (13) \quad [13]$$

This may also be the reason why the literature up to the present refers mostly to the spread-eagle radiation area and it is therefore easy to compare the results of this work with those of earlier studies, and, moreover, to extend the results of earlier measurements on test subjects. It was therefore also desirable that the surface areas of the clothed subjects should be referred to the nude spread-eagle posture.

I. PROCEDURE

I.6.1 Calibration

The photodermoplanimeter was calibrated by a substitution method. A number of rectangular prisms of known areas (see I.4.2) were introduced into the chamber in place of the man. The shape of these prisms was arbitrary (in this particular case they were rectangular prisms), since it was only the surface area that was important. The only requirement that these prisms have to satisfy is that they be convex in order that their radiation surface area coincide with their true geometrical area. This is necessary to relate the reading of the photodermoplanimeter to the actual (geometrically-measured) surface area of the prisms.

The prisms have their surfaces coated with a paint with optical properties matching those of the water strain used to paint the human subject. A calibration was performed immediately after each series of measurements (which lasted not more than 3 hours) to prevent systematic errors caused by a temperature drift of the electronic measuring equipment or by dirt particles entering the chamber. If two subjects were subjected to measurement on the same day, the calibration was performed

between tests in such a way as to maintain the sequence: measurement - calibration - measurement. Three measurements were taken with each combination of prisms. All these three points (not their average) are plotted in the calibration graphs, one example of which is shown in Fig 21, so it is easy to appreciate the degree of accuracy obtained. Although the inverse square law of optics predicts a dependence on distance squared in the narrow range of areas used - approximating to that of the human subject - it was found that the distance moved by the trolley when a body is introduced is linearly dependent on the radiation area of that body. This linearity was verified in all calibration curves where each was based on three combinations of prisms (Fig 21). The entire calibration sequence consisted of one calibration with, and a second without, the chair in the chamber, because the presence of an additional absorbing body may obviously change the characteristics of the box (the white paint of the chair is not a perfect reflector). These two calibration lines are expected to converge and to intersect at the origin. This was demonstrated and verified in each case. Furthermore a slight continuous change of measured distance between the curves representing conditions with and without the chair in the box was observed, and especially after the chair had been re-painted. This is due to the continuous darkening of the chair that occurs with use. In order to calibrate the box with the chair inside, the prisms were put on the chair at the very place where the human subject sat. (See Fig 22 : the edge of the base of the prism is flush with the front end of the seat.)

I.6.2 Compensation for the area of the chair obscured by the target

Both the subject sitting on the chair and the calibration prisms cover up a part of the absorbing area of the chair. The loss of this absorbing area causes too small a surface area to be recorded. At first this problem seemed to represent an obstacle in the way of carrying out measurements with a chair in the box, as no attempt had previously been made to measure the radiation surface area of a sitting subject in the photo-

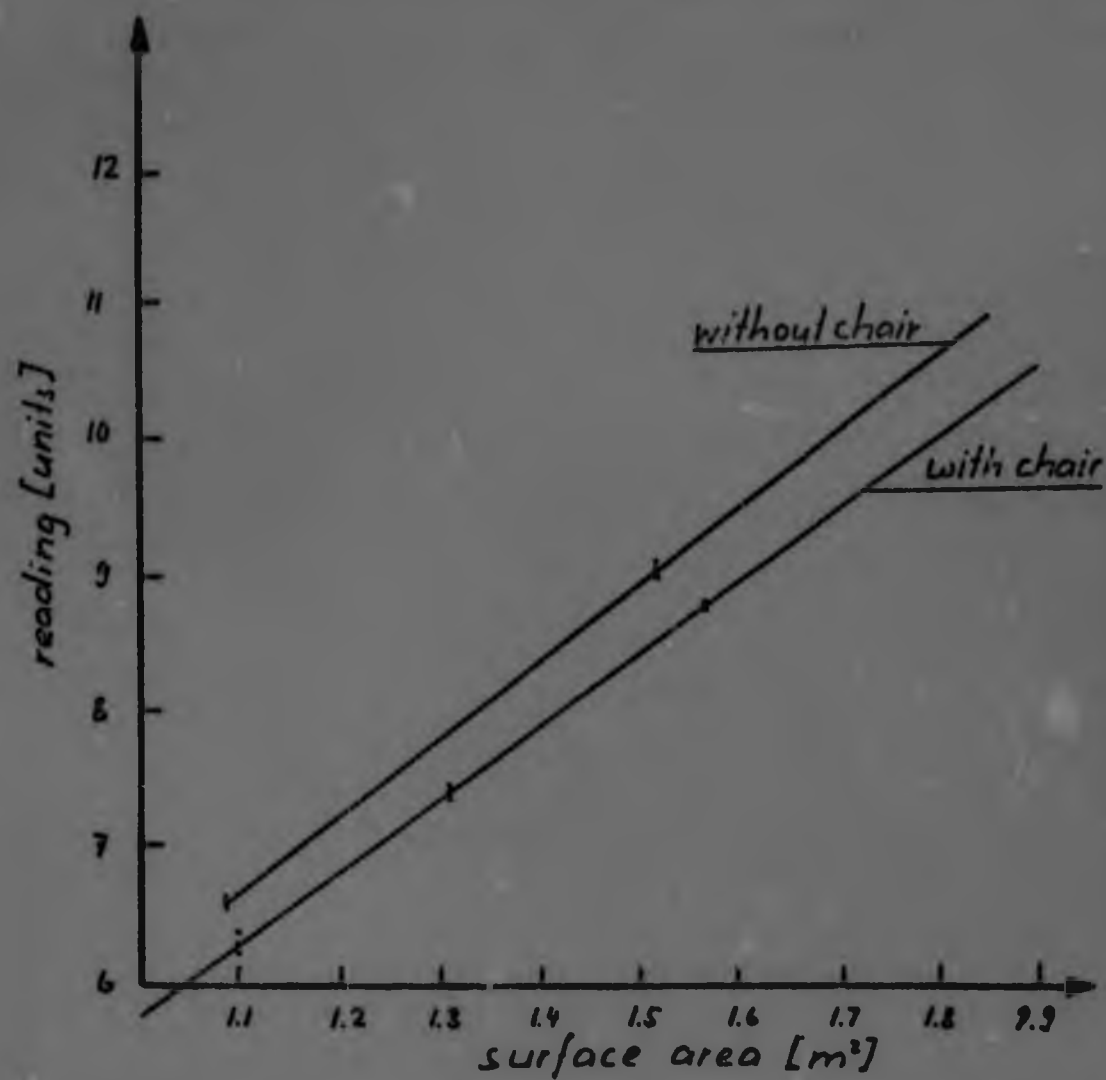


FIGURE 21

Example of a calibration graph
of the photodermoplanimeter



FIGURE 22

Calibration of the photo-lermo-
planimeter with chair

dermoplanimeter. (This apparatus had originally been designed to measure the true geometrical surface area of subjects in the spread-eagle posture. The true geometrical surface area is generally considered of more importance in physiology than the radiation surface area because it is a condition related to basal metabolic rates, oxygen consumption, cardiac output, glomerular filtration rate, heat loss by convection and evaporation and so on.) The first step in solving this problem was to keep the chair surface as reflective as possible, ie, white and clean. The chair was therefore painted with the same white paint as the inside of the chamber and the seat and the backrest of the chair were always coated with blank, new blotting paper to minimise reflection from this area. Yet in spite of this small absorption this represented a systematic error that exceeded the random standard deviation of the system. An absorption rate of 0.583 units/m² (after repainting the box: 0.669 units/m²) resulting from use of the blotting paper was recorded. (These "units" are arbitrary readings and correspond to the distance moved by the trolley.) This means, for instance, that the error resulting from the loss of the small area which is covered by the base of the prisms is $(0.3 \times 0.3) \times 0.583 = 0.052$ units (after repainting: 0.061 units) which is about 0.007 m² or approximately 0.5% of the spread-eagle posture area.

The second step in handling the problem of the obscured area was to effect a theoretical compensation: the measurements taken from the subject sitting on the chair were corrected by copying and measuring the shape of the covered area on the blotting paper and then multiplying the area obtained with the specific absorption rate of the paper. The same procedure was applied to the area covered by a prism's base. This correction was then added to the readings taken.

The change of absorption rate after repainting the box was due to the fact that in a brighter environment the paper absorbs more light.

I.6.2 Experimental procedure

Before any readings were taken, a period of 45 minutes was allowed for the various electronic devices to stabilise. During this time the subject was painted black all over and the first reading was taken as soon as the paint had completely dried. The paint used for this purpose was a matt black water stainer ("Evans water stainer-black"). Because all subjects were painted with the same paint, the amount of light they absorbed became a function of their absorbing (and therefore radiating) areas only. The operation of the photodermoplenimeter was simple. A suitable lamp current was chosen, and, with the integrating vessel empty, the position of the trolley was adjusted until the two ellipses on the oscilloscope screen coincided. The position of the trolley was then read off. The painted subject then entered the vessel and the ellipses were again brought into coincidence. The new trolley position was then noted. The difference between the readings for these 2 positions was a measure of radiating surface area.

I.6.3.1 Nude subjects

The sequence of readings taken of one subject in one posture was: Empty box - subject in spread-eagle posture - empty box - required posture. From each reading with the subject in the box, there was subtracted the immediately preceding reading of the empty box in order to ensure that this difference really represented the pure radiation area and not one affected by the presence of dirt particles which inevitably entered the box in the course of time. Each such set of readings was repeated three times and an average of the three ratios representing (required posture/spread-eagle posture) was finally determined.

Since the spread-eagle measurements could not be taken during the time the chair was in the box because of shortage of space, another procedure was chosen to obtain the required readings.

From the 18 spread-eagle readings taken for Postures 1-6 (each reading being taken three times), an average was determined

for purposes of comparison with the 8 subjects-on-chair readings. This time the ratio (required posture/spread-eagle posture) was not taken from the readings of distance moved by the trolley, but from the real radiation areas determined by the respective calibration curves, in order to take care of the different calibration characteristics obtained with and without the chair in position. For this part of the work measurements were taken of 23 subjects in each of 8 different postures. Postures 1 - 6 required 6 measurements or 12 readings each (6 readings of the empty box, 3 readings in spread-eagle position and 3 readings in the required posture). Postures 7 and 8 required 4 measurements each (because of the bigger scatter) or 8 readings (4 of the empty box, 4 of the required posture). Thus $23 \times (6 \times 6 + 2 \times 4)$ or 1012 measurements = 2024 readings were taken of the nude subjects.

I.6.3.2 Clothed subjects

For the reasons mentioned in section I.5, it was clear that the areas determined for the clothed subjects should also be referred to the spread-eagle area of the nude subject. In order to save time, the routine whereby each subject took off his clothes after each posture reading was modified, as follows. A set of 10 spread-eagle measurements was taken before the series of 8 posture measurements and was followed by a subsequent set of 5 spread-eagle readings in order to register any significant change in box characteristics. However, in all these cases no deviation between these two sets of readings was found and the average of the first set of spread-eagle measurements was therefore then taken as a basis for comparison. The rest of the procedure remained the same. For this part readings of 4 subjects in each of 4 different types of clothing were taken. The total number of measurements for the examination of clothed subjects in different postures was therefore: $10 + 4 \times 4 (6 \times 3 + 2 \times 3) + 5 = 399$, ie, 798 readings.

I.6.4 Time required to take measurements

For the sake of another person who might want to repeat on experiment, the description thereof would be incomplete if no

reference were made to the time spent in taking a series of measurements.

During the time required by the electronic equipment to stabilise, the subject was painted and dried in front of a heater. This usually took 45 minutes. Measurements on one subject in all 8 postures (nude) with 44 measurements or 88 readings in all therefore took approximately 90 minutes. Measurements of a clothed subject (a total of 72 readings) took approximately 75 minutes. (The time of changing clothes twice is included.) Calibrations involving 30 readings in all took approximately 40 minutes.

1.7 ACCURACY

In all experimental measurements it is important that the random error of the apparatus is not greater than the scatter of readings of the event. In this study the latter refers to the actual scatter of the surface area readings as a result of the many slightly different configurations associated with any one particular posture. Obviously it is important that the same subject repeat the same posture exactly. In this study interest thus attaches not only to the average of all subjects in one posture, but the scatter expressed as a standard deviation must also be considered to be an important result of the experiment, since this information enables one to estimate the range of different possible ways of taking readings to cover one posture. After all, a highly accurate and reliable apparatus was required to enable the scatter of the event to be recorded. The above-described photodermoplanimeter, when used in conjunction with the comparison technique, guarantees the utmost accuracy in this respect. However, it must be mentioned that the measuring system as a whole also includes the operator of the apparatus who may well introduce a certain random error into the system by his particular way of bringing the two ellipses on the screen into coincidence. It has been demonstrated that this part of the operation depends to a large extent on the skill of the operator. Sufficient practice in the operation of the instrument is therefore necessary to guarantee reliability of readings. In order to illustrate the

scatter of the readings and the effective scatter of the surface area, the following two series of measurements, taken on the same day, are quoted below. The spread-eagle posture, here taken as the reference, is seen to be that with the lesser scatter.

<u>Spread-eagle posture readings</u>	<u>Calibration prism readings</u>
10.910 (units)	7.025
10.865	7.020
10.845	7.045
10.900	7.000
10.870	7.015
10.855	7.030
10.865	7.025
10.910	7.035
10.810	7.020
10.895	7.015
Average: 10.876 5	Average: 7.023
Standard deviation: 0.023 68	Standard deviation: 0.011 67
$\sigma = 0.002 \text{ m}^2$	$\sigma = 0.001 \text{ m}^2$
= 0.22% of spread-eagle area	= 0.11% of spread-eagle area

The error associated with measurements on a man is significantly higher than that associated with measurements on an inert body.

1.8 RESULTS

For all types of clothing the order of the results of the 8 postures is:

$$2 > 1 > 4 > 3 > 6 > 7 > 5 > 8$$

The only change in this order was recorded with shirts and trousers (3 and 8 being then interchanged).

<u>No</u>	<u>Height</u>	<u>Weight</u>	1.) 	2.) 	3.) 	4.) 
27316	163.8cm	59.56kg	86.5%	96.3%	81.3%	83.4%
71609	167.8cm	67.50kg	85.2%	91.8%	80.7%	83.5%
66281	165.2cm	63.71kg	86.2%	93.4%	82.0%	86.5%
59803	170.6cm	67.2kg	86.3%	91.9%	81.6%	85.1%
86053	168.8cm	60.3kg	88.5%	94.8%	81.3%	84.6%
30325	168.6cm	59.45kg	87.7%	90.9%	80.5%	84.2%
31348	170.7cm	55.45kg	88.1%	94.4%	82.7%	85.7%
52807	171.4cm	61.83kg	89.2%	93.3%	80.5%	86.5%
34991	169.6cm	62.13kg	87.6%	93.7%	82.1%	84.7%
88056	159.0cm	58.95kg	87.5%	92.8%	80.1%	86.4%
17450	170.2cm	55.1kg	86.3%	92.9%	78.8%	84.7%
76848	164.3cm	51.95kg	87.2%	92.8%	82.9%	86.6%
73070	177.5cm	66.1kg	88.5%	93.3%	82.6%	86.7%
73601	163.6cm	57.72kg	88.0%	94.2%	80.4%	87.5%
90867	176.1cm	76.1kg	87.4%	92.0%	81.2%	82.9%
72990	171.0cm	56.0kg	88.8%	93.2%	78.7%	86.2%
73830	162.5cm	52.74kg	86.0%	92.4%	78.5%	81.8%
Agustino	168.0cm	72.85kg	87.3%	92.6%	80.7%	86.1%
David	164.9cm	61.6kg	88.0%	91.7%	78.7%	85.7%
92266	172.0cm	56.45kg	87.9%	92.9%	78.2%	83.3%
59919	171.0cm	67.1kg	86.2%	91.2%	77.6%	83.5%
91197	168.8cm	65.33kg	87.8%	90.0%	76.8%	82.6%
90816	172.6cm	69.05kg	87.9%	91.0%	80.9%	84.0%

TABLE 2

Radiation surface areas of 24 subjects
(nude) (8 postures) as percentage of
spread-eagle area

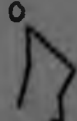
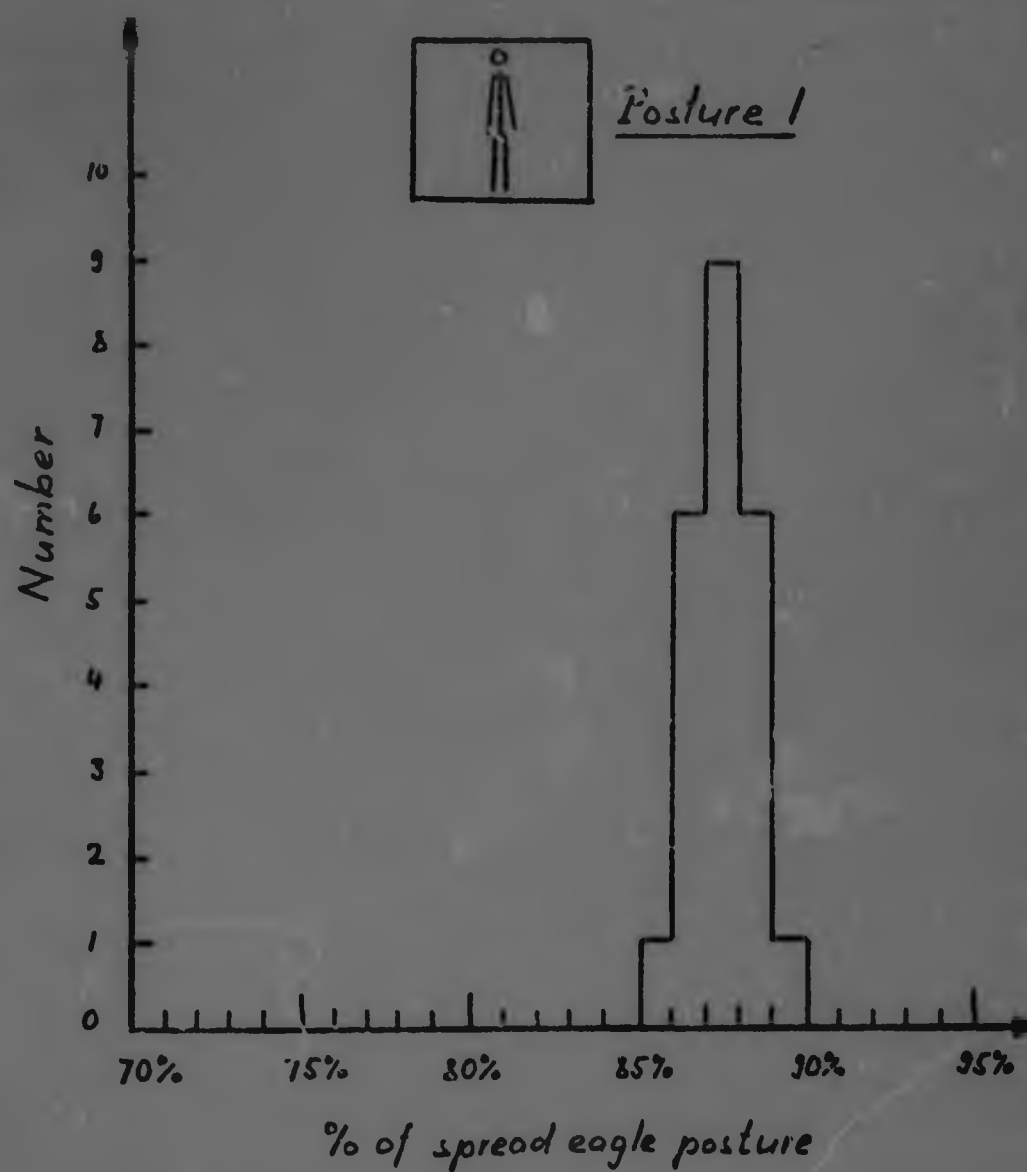
<u>No</u>	<u>Height</u>	<u>Weight</u>	5.) 	6.) 	7.) 	8.) 
27316	163.8cm	59.56kg	71.7%	78.5%	--	--
71609	167.8cm	67.5kg	70.9%	78.1%	68.6%	65.1%
66281	165.2cm	63.71kg	74.4%	78.7%	75.6%	69.9%
59803	170.6cm	67.2kg	74.0%	77.1%	71.0%	68.0%
86053	168.8cm	60.3kg	71.5%	76.4%	73.2%	66.6%
30325	168.6cm	59.46kg	74.3%	77.7%	74.1%	66.3%
31348	170.7cm	55.45kg	74.4%	78.4%	73.5%	68.2%
52807	171.4cm	61.83kg	73.6%	78.5%	71.8%	68.8%
34991	169.6cm	62.13kg	71.9%	76.7%	73.8%	69.3%
88056	159.0cm	58.95kg	76.0%	80.7%	75.4%	70.4%
17450	170.2cm	55.1kg	71.0%	77.5%	73.5%	69.0%
76848	164.3cm	51.95kg	73.1%	77.0%	75.5%	68.9%
73970	177.5cm	66.1kg	73.0%	78.0%	73.2%	67.8%
73601	163.6cm	57.72kg	74.4%	78.1%	75.3%	68.8%
90867	176.1cm	76.1kg	71.7%	77.3%	72.6%	66.7%
72990	171.0cm	56.0kg	72.1%	76.3%	73.4%	65.7%
73830	167.5cm	52.74kg	72.4%	76.3%	73.5%	65.3%
Agustino	168.0cm	72.85kg	72.3%	76.2%	72.1%	67.7%
David	164.9cm	61.6kg	73.1%	77.4%	73.1%	68.7%
92266	172.0cm	56.45kg	73.2%	75.6%	74.8%	68.6%
59919	171.0cm	67.14kg	75.2%	74.0%	73.4%	69.4%
91197	168.8cm	65.33kg	64.8%	71.1%	71.0%	64.2%
90816	172.8cm	69.05kg	72.7%	77.3%	72.5%	67.5%

TABLE 2 (CONT)

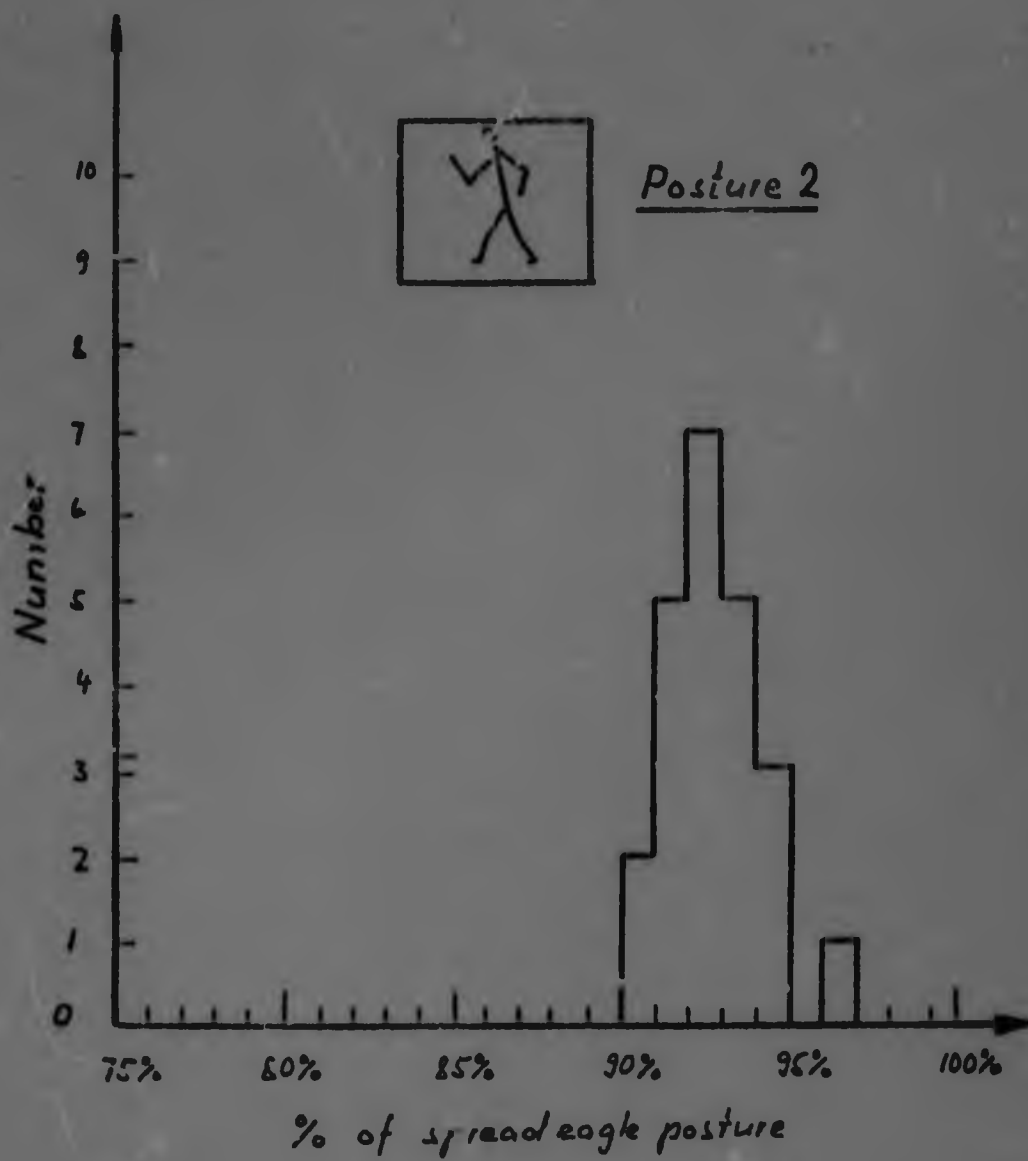


Average: 87.40%

Standard deviation: 0.986%

FIGURES 23 - 30

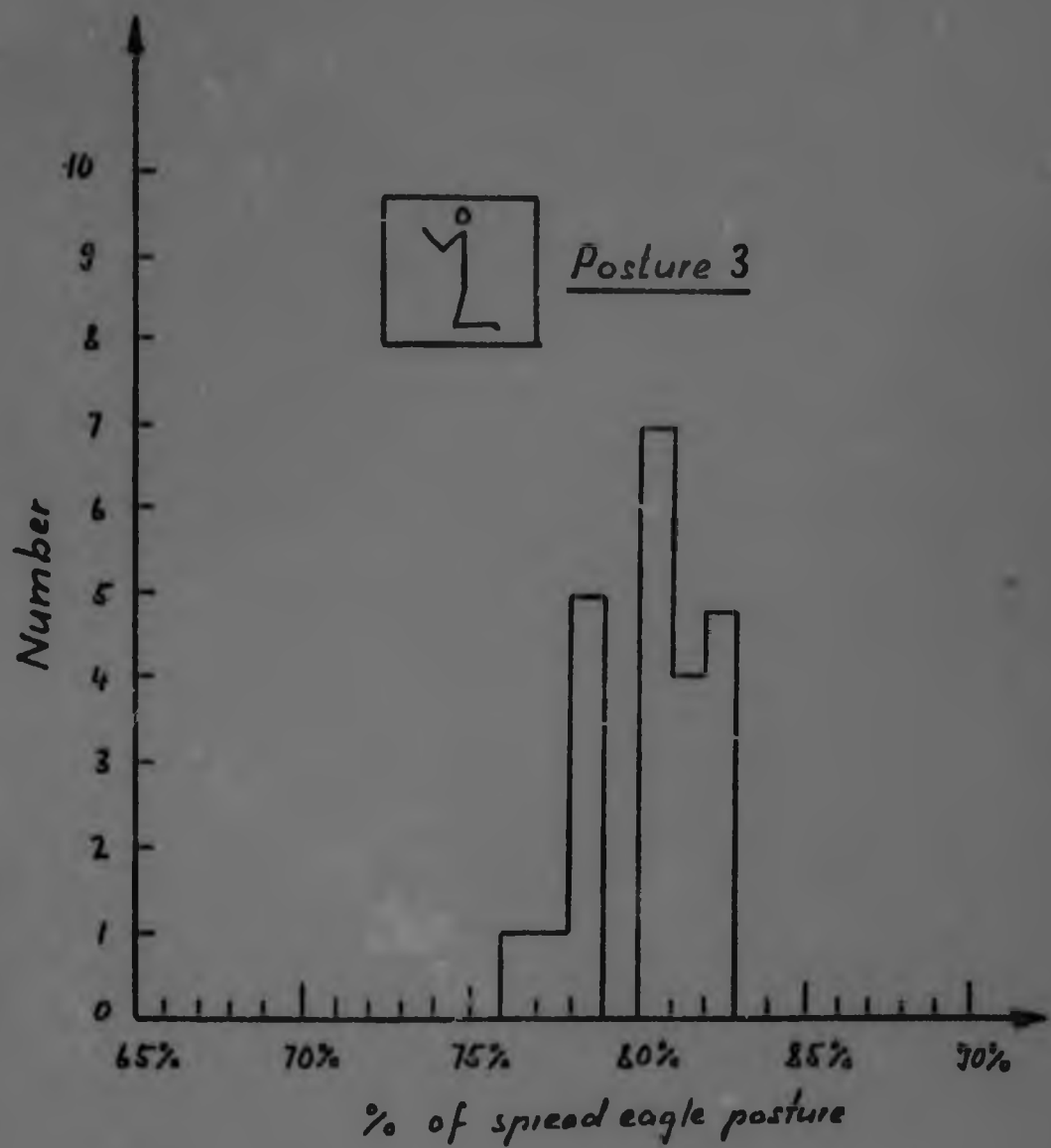
Distribution of the measured radiation surface as % of spread-eagle radiation area



Average: 92.76%

Standard deviation: 1.378%

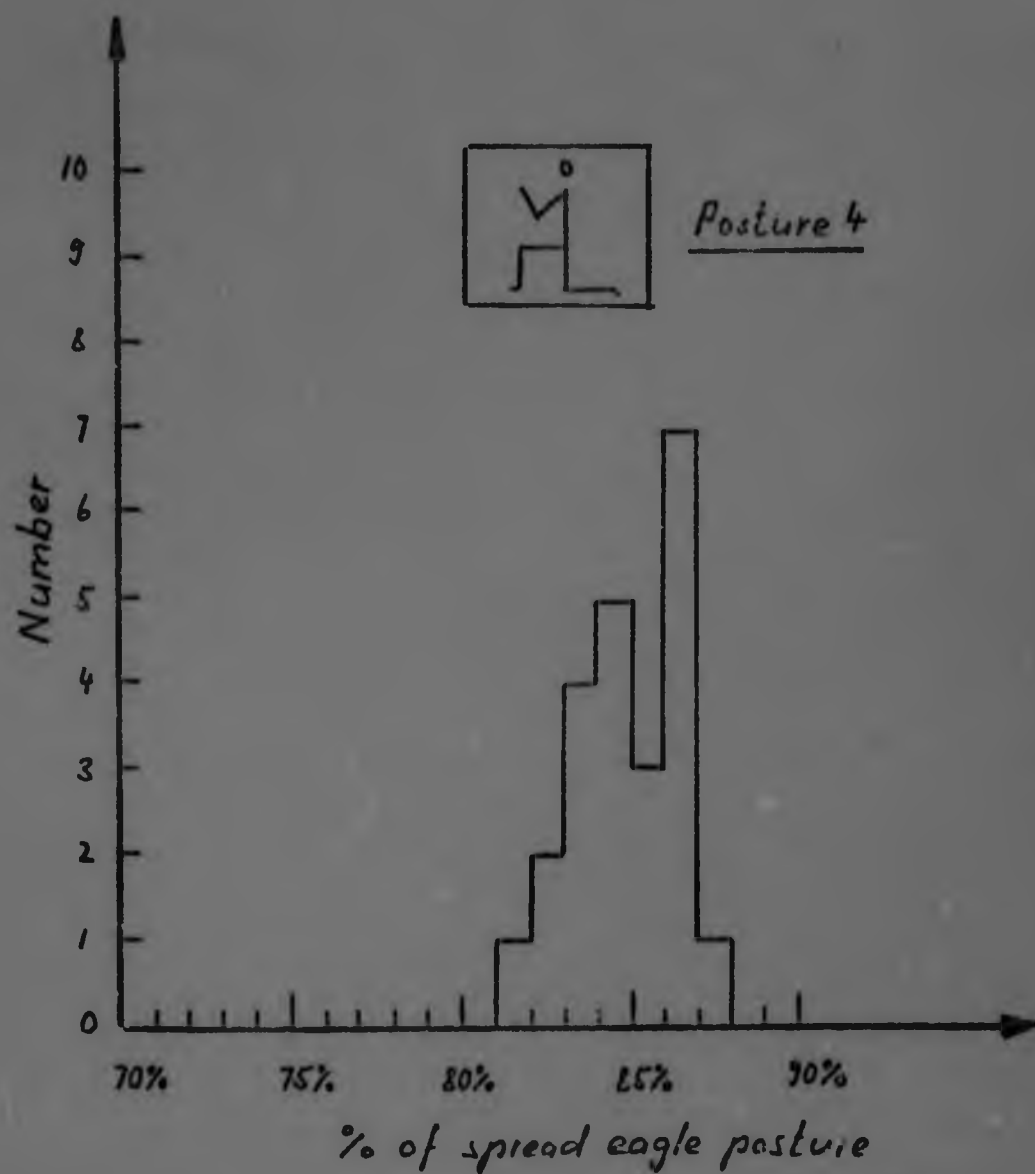
FIGURE 24



Average: 80.38%

Standard deviation 1.562%

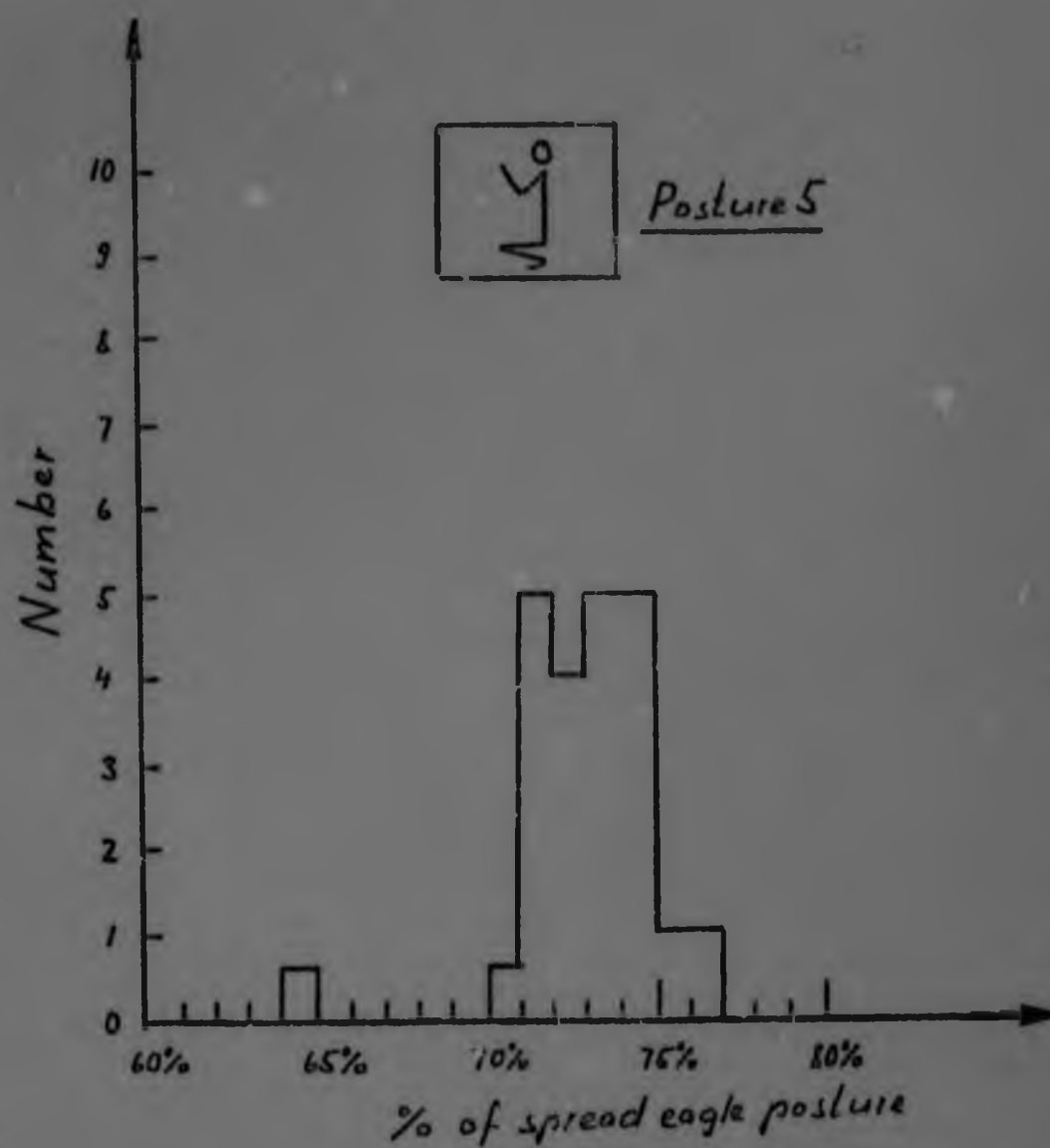
FIGURE 25



Average: 84.88%

Standard deviation: 1.529%

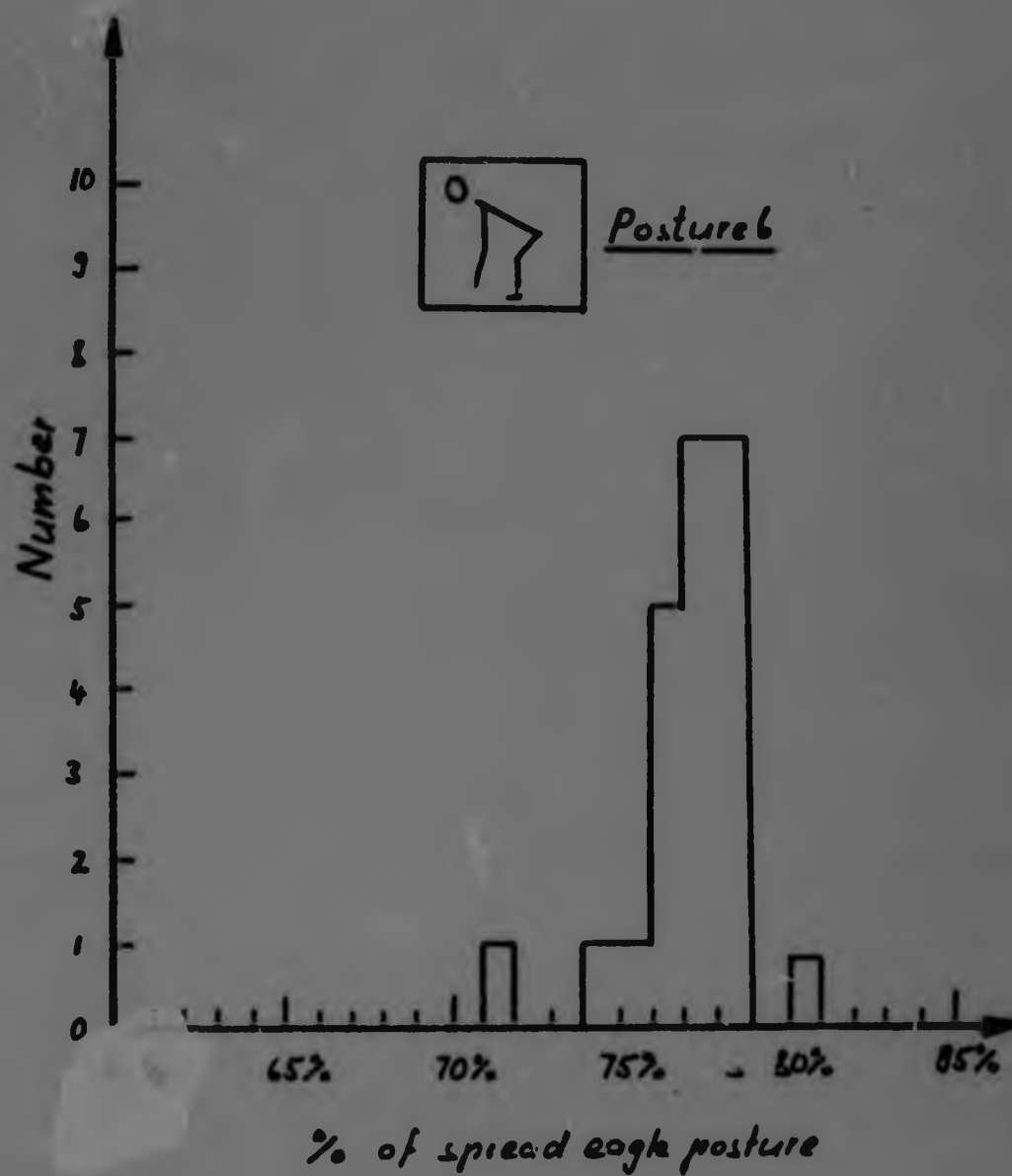
FIGURE 26



Average : 72.68%

Standard deviation: 2.147%

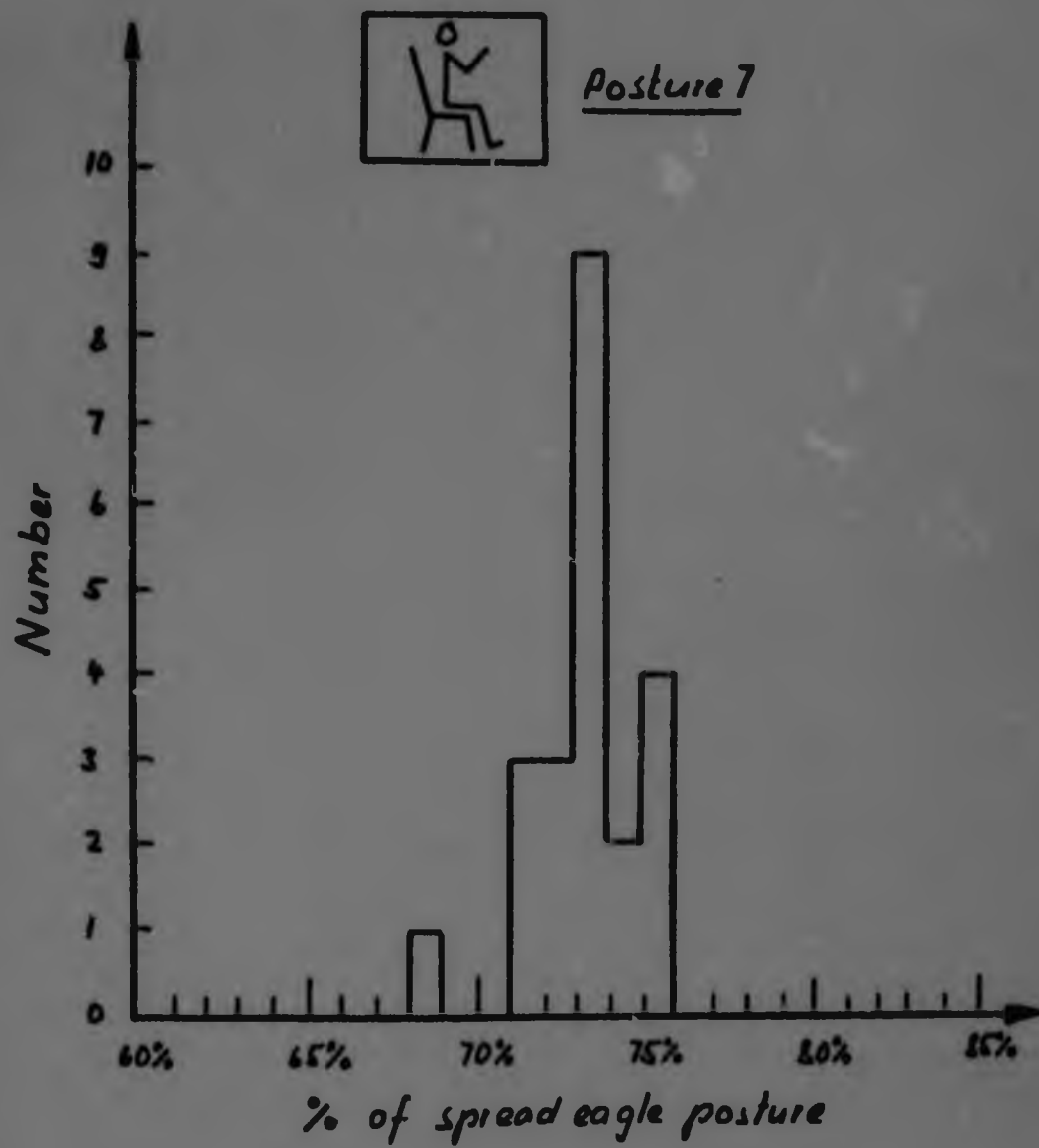
FIGURE 27



Average: 77.08%

Standard deviation: 1.824%

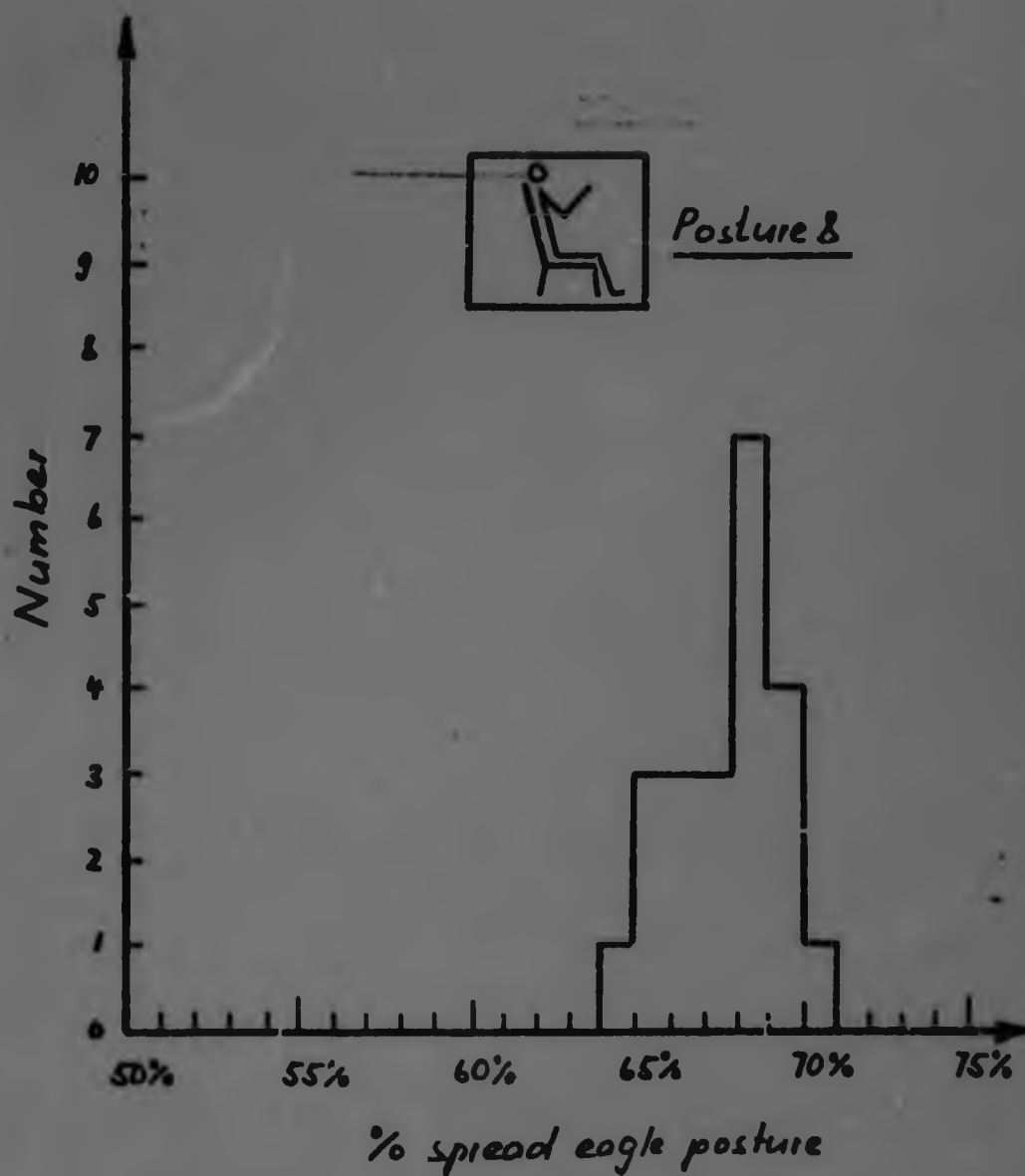
FIGURE 28



Average : 73.22%

Standard deviation : 1.611%

FIGURE 29

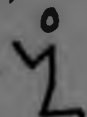
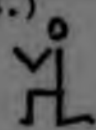
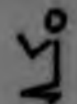


Average: 67.78%

Standard deviation: 1.590%

FIGURE 30

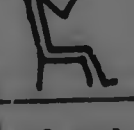
Track suit:

Subject	Ernesto	Eric	Bernardo	Michael
Height	170.5cm	157.1cm	171.0cm	164.6cm
Weight	61.24kg	60.15kg	62.35kg	59.30kg
1.) 	103.5%	100.6%	100.5%	103.2%
2.) 	106.3%	109.6%	107.3%	106.9%
3.) 	97.1%	97.2%	92.9%	94.4%
4.) 	100.1%	101.8%	96.8%	98.7%
5.) 	82.1%	90.2%	86.1%	81.9%
6.) 	94.8%	90.7%	96.5%	93.2%
7.) 	90.5%	98.3%	93.3%	86.6%
8.) 	82.4%	90.4%	81.8%	79.8%

% of nude spread-eagle area

Table 3

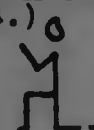
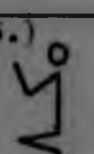
Overalls:

<u>Subject</u>	<u>Ernesto</u>	<u>Eric</u>	<u>Bernardo</u>	<u>Michael</u>
Height	170.5cm	157.1cm	171.0cm	164.6cm
Weight	61.24kg	60.15kg	62.35kg	59.30kg
1.) 	112.2%	106.6%	108.1%	106.2%
2.) 	114.4%	114.8%	109.0%	105.7%
3.) 	96.8%	97.1%	89.1%	92.1%
4.) 	100.1%	101.2%	95.3%	99.5%
5.) 	84.0%	85.9%	79.5%	81.9%
6.) 	97.6%	92.5%	90.4%	90.4%
7.) 	87.3%	92.7%	86.5%	87.9%
8.) 	79.9%	84.7%	77.0%	81.0%

* of nude spread eagle area

Table 4

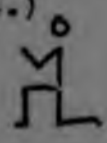
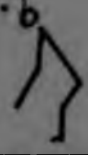
Mine-suit (Overall, leather-jacket, boots):

<u>Subject</u>	<u>Ernesto</u>	<u>Eric</u>	<u>Bernardo</u>	<u>Michael</u>
Height	170.5cm	157.1cm	171.0cm	164.6cm
Weight	61.24kg	60.15kg	62.35kg	59.30kg
1.) 	117.4%	114.8%	113.3%	102.8%
2.) 	117.4%	118.5%	118.0%	120.5%
3.) 	99.1%	98.2%	94.7%	99.9%
4.) 	102.8%	102.9%	101.1%	101.8%
5.) 	89.6%	90.3%	86.0%	88.3%
6.) 	98.3%	96.7%	96.3%	97.2%
7.) 	91.0%	95.3%	92.3%	94.6%
8.) 	84.0%	87.8%	82.5%	83.5%

% of nude spread eagle area

Table 5

Shirt and trousers, boots

Subject	Ernesto	Eric	Bernardo	Michael
Height	170.5cm	157.1cm	171.0cm	164.6cm
Weight	61.24kg	60.15kg	62.35kg	59.30kg
1.) 	112.8%	110.1%	110.5%	109.8%
2.) 	115.7%	115.9%	113.8%	118.1%
3.) 	96.8%	98.4%	92.9%	95.8%
4.) 	101.3%	102.0%	99.1%	102.5%
5.) 	85.9%	89.7%	88.4%	90.2%
6.) 	97.5%	96.3%	97.4%	97.1%
7.) 	88.8%	92.4%	88.6%	91.0%
8.) 	80.8%	84.4%	80.0%	82.2%

% of nude spread eagle area

Table 6

Average values and standard deviations:

(in % of nude spread eagle area)

Type of clothing	track-suit	overall	mine-suit	shirt+trousers+boots	nude
1.) 	$\frac{102.0\%}{\pm 1.41\%}$	$\frac{108.3\%}{\pm 2.37\%}$	$\frac{112.1\%}{\pm 5.55\%}$	$\frac{110.8\%}{\pm 1.53\%}$	$\frac{87.4\%}{\pm 0.986\%}$
2.) 	$\frac{107.5\%}{\pm 1.25\%}$	$\frac{111.7\%}{\pm 2.92\%}$	$\frac{118.6\%}{\pm 1.16\%}$	$\frac{115.9\%}{\pm 1.52\%}$	$\frac{92.76\%}{\pm 1.378\%}$
3.) 	$\frac{95.4\%}{\pm 1.83\%}$	$\frac{93.8\%}{\pm 3.35\%}$	$\frac{93.0\%}{\pm 1.83\%}$	$\frac{96.0\%}{\pm 2.0\%}$	$\frac{80.38\%}{\pm 1.562\%}$
4.) 	$\frac{99.3\%}{\pm 1.83\%}$	$\frac{99.2\%}{\pm 2.24\%}$	$\frac{102.1\%}{\pm 0.74\%}$	$\frac{101.2\%}{\pm 1.37\%}$	$\frac{84.88\%}{\pm 1.529\%}$
5.) 	$\frac{85.1\%}{\pm 3.4\%}$	$\frac{82.8\%}{\pm 2.75\%}$	$\frac{88.5\%}{\pm 1.64\%}$	$\frac{88.5\%}{\pm 1.66\%}$	$\frac{72.68\%}{\pm 2.147\%}$
6.) 	$\frac{93.7\%}{\pm 2.13\%}$	$\frac{92.7\%}{\pm 2.94\%}$	$\frac{97.1\%}{\pm 0.75\%}$	$\frac{97.1\%}{\pm 0.47\%}$	$\frac{77.08\%}{\pm 1.824\%}$
7.) 	$\frac{92.2\%}{\pm 4.26\%}$	$\frac{88.6\%}{\pm 2.42\%}$	$\frac{94.3\%}{\pm 1.94\%}$	$\frac{90.2\%}{\pm 1.50\%}$	$\frac{73.22\%}{\pm 1.611\%}$
8.) 	$\frac{83.6\%}{\pm 4.04\%}$	$\frac{80.7\%}{\pm 2.76\%}$	$\frac{84.4\%}{\pm 2.01\%}$	$\frac{81.8\%}{\pm 1.67\%}$	$\frac{67.78\%}{\pm 1.590\%}$

Table 7

Average values and standard deviations:

(in % of total nude area)

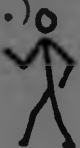
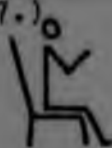
Type of clothing	track-suit	overall	mine-suit	shirt+trousers+boots	nude
1.) 	$\frac{97.9\%}{\pm 1.35\%}$	$\frac{104.0\%}{\pm 2.27\%}$	$\frac{107.8\%}{\pm 5.33\%}$	$\frac{106.1\%}{\pm 1.47\%}$	$\frac{83.9\%}{\pm 0.94\%}$
2.) 	$\frac{103.2\%}{\pm 1.20\%}$	$\frac{107.1\%}{\pm 2.80\%}$	$\frac{113.9\%}{\pm 1.11\%}$	$\frac{111.1\%}{\pm 1.46\%}$	$\frac{89.0\%}{\pm 1.32\%}$
3.) 	$\frac{91.5\%}{\pm 1.75\%}$	$\frac{90.0\%}{\pm 3.21\%}$	$\frac{94.1\%}{\pm 1.90\%}$	$\frac{92.1\%}{\pm 1.93\%}$	$\frac{77.1\%}{\pm 1.50\%}$
4.) 	$\frac{95.3\%}{\pm 1.75\%}$	$\frac{95.2\%}{\pm 2.15\%}$	$\frac{98.0\%}{\pm 0.71\%}$	$\frac{97.1\%}{\pm 1.13\%}$	$\frac{81.4\%}{\pm 1.47\%}$
5.) 	$\frac{81.7\%}{\pm 3.3\%}$	$\frac{79.5\%}{\pm 2.64\%}$	$\frac{84.9\%}{\pm 1.57\%}$	$\frac{84.9\%}{\pm 1.59\%}$	$\frac{69.7\%}{\pm 2.06\%}$
6.) 	$\frac{90.0\%}{\pm 2.04\%}$	$\frac{89.0\%}{\pm 2.32\%}$	$\frac{93.2\%}{\pm 0.70\%}$	$\frac{93.2\%}{\pm 0.45\%}$	$\frac{74.0\%}{\pm 1.75\%}$
7.) 	$\frac{88.5\%}{\pm 4.08\%}$	$\frac{85.1\%}{\pm 2.32\%}$	$\frac{90.5\%}{\pm 1.86\%}$	$\frac{86.5\%}{\pm 1.44\%}$	$\frac{70.4\%}{\pm 1.55\%}$
8.) 	$\frac{80.3\%}{\pm 3.88\%}$	$\frac{77.4\%}{\pm 2.65\%}$	$\frac{81.0\%}{\pm 1.93\%}$	$\frac{78.5\%}{\pm 1.60\%}$	$\frac{65.0\%}{\pm 1.53\%}$

Table 8

PART II : EMISSIVITY MEASUREMENTS

II.1 METHOD

The method used is based on the fact that the rate of transfer of radiant heat between a target and a radiometer used to measure the radiation depends not only on the temperature of the target but also on the temperature of the radiometer. The emissivity of the target can be extracted from the relationship between the radiometer's output and its temperature, the temperature of the target being kept constant. The method has the advantage of not requiring any actual measurement of target temperature to be made [16].

The rate of energy exchange produces an output signal ϕ in the radiometer, and in this study ϕ is directly proportional to H , that is $\phi = kH$, where k is a constant.

Thus

$$\phi = kA \sigma \epsilon_t \epsilon_r [T_t^4 - T_r^4] \quad (14)$$

If the target temperature is kept constant and

$$\phi = \phi_0 - kA \epsilon_t \epsilon_r \sigma T_r^4 \quad (15)$$

a plot of radiometer output ϕ against T_r^4 (at a constant target temperature) would therefore yield a straight line of slope

$$m_t = - kA \epsilon_t \epsilon_r \sigma \quad (16)$$

If an experiment were to be carried out to obtain such a plot for a black body surface and a target, the slopes of the resulting two lines would be $m_b = - kA \epsilon_r \epsilon_b \sigma$ (black body) and $m_t = kA \epsilon_r \epsilon_t \sigma$ (target). If the same geometrical configuration is maintained for both target and black body (A can

be kept the same), we get

$$\frac{m_t}{m_b} = \frac{\epsilon_t}{\epsilon_b} ; (\epsilon_b = 1) \quad (17)$$

All that is required, therefore, is a radiometer whose temperature can be varied, a target at a constant temperature, and a reference black body of known emissivity.

11.2 APPARATUS

A radiometer built at the National Mechanical Engineering Research Institute and improved by Mr A R Atkins of the Human Sciences Laboratory was employed [25]. The radiation detector was a commercially available thermal detector at the end of a 300 mm long barrel containing collimating diaphragms to allow only parallel rays to pass. It must be stressed that the radiometer was non-selective with respect to the wavelengths to which it was sensitive, ie, measurements were taken over the whole spectrum. However, as can be seen from Fig 2, in Chapter 3, an overwhelming part of the radiant energy occurring in industrial situations lies in the infrared spectrum. The human body, for instance, emits radiation mainly in the waveband 6-42 μm , 90% of the energy lying between these limits [14]. Therefore a radiometer measuring only within the infrared spectrum would have sufficed. By using a non-selective radiometer, however, wavelength selectivity as a source of error is excluded.

At the front end of the barrel a segmental disc chopper was employed for two purposes: first, to supply an alternating signal to the amplifier and secondly to provide a self-contained reference. When the chopper (with its mirror surface towards the sensor) was closed off, the radiometer "saw" only itself, so providing a reference zero signal. However, this mirror had no permanently highly-reflective surface in the relevant waveband and therefore to some extent it "saw" the radiation from the chopper. Another stationary mirror of identical construction was therefore introduced (see Fig 31). The radiometer now alternately "sees" either itself reflected off the chopper

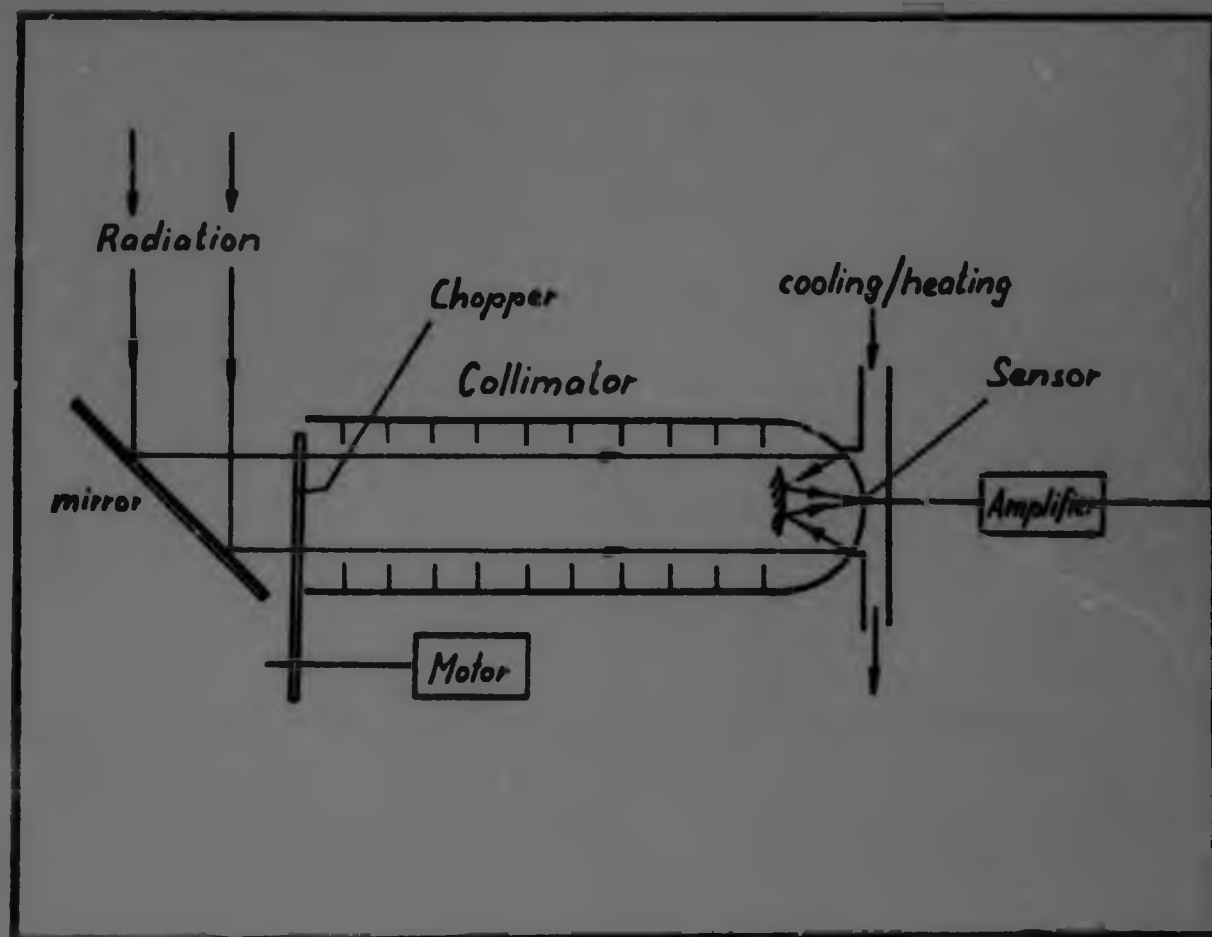


FIGURE 31

Schematic diagram of the radiometer

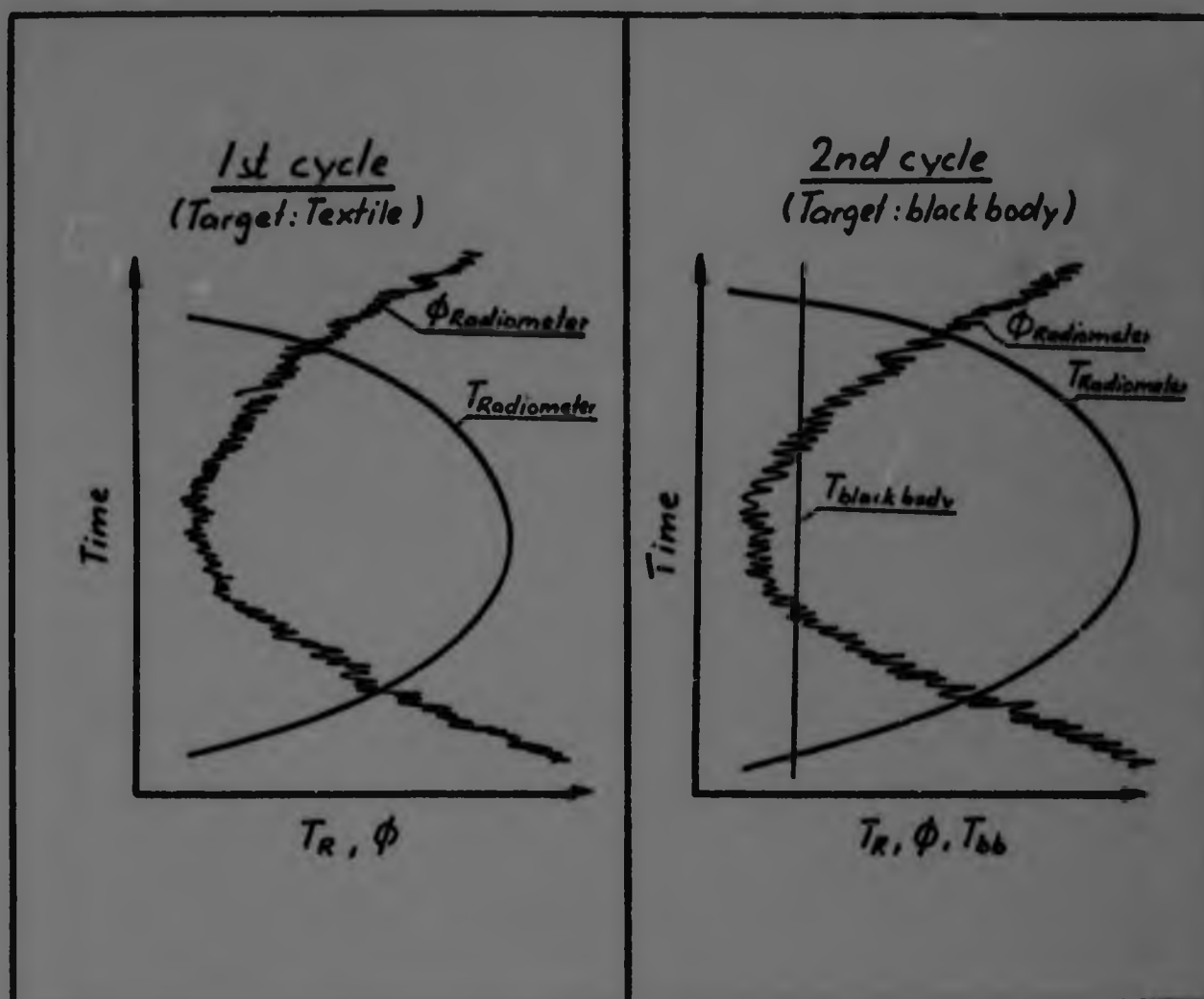


FIGURE 32

Radiometer and temperature output with textile (left) and black body (right) as target

or the target reflected off the mirror. Provided the mirror and chopper are at approximately the same temperature and age equally, the effects of the chopper temperature are thus eliminated.*

The temperature variation of the radiometer was obtained by a water circuit in connection with an electronically programmed heating/cooling device. The maintenance of a constant target temperature was greatly facilitated by the availability of a constant-temperature environment in the climatic chamber of the Human Sciences Laboratory, in which all measurements were made.

The black body used took the form of a conical cavity of approximately 11 cm depth and 40° apex angle. Its aperture was reduced to 6 cm by means of a circular diaphragm. The cavity was painted with matt black paint and immersed in a well-stirred water bath controlled by a mercury contact thermostat.

11.3 PROCEDURE

Each measurement involved two heating/cooling cycles of the radiometer, one with the textile to be investigated, and one with the black body as target. The output plot of the 3-channel graphical recorder showed the temperature and radiation output of the radiometer during the first cycle and in addition, the black body temperature during the second cycle (see Fig 32). From these two plots the graph of radiometer output for target and black body as a function of the radiometer temperature could be plotted (Fig 33).

This diagram was the basis for calculating the target's emissivity according to Eq 17.

*Since the above was written, it has been found that the Research Department of the Heating and Climate Section of Messrs Sulzer Brothers at Winterthur, Switzerland has independently developed a new radiometer with a chopper mirror of very high and practically constant reflectivity, as a result of which the effect of variation in mirror temperature on output measurement cannot be detected. There is therefore no need to reflect radiation from the target back off the mirror (in order to compensate for temperature - dependent reflecting qualities of the mirror). This improvement obviously simplifies the apparatus considerably. 77

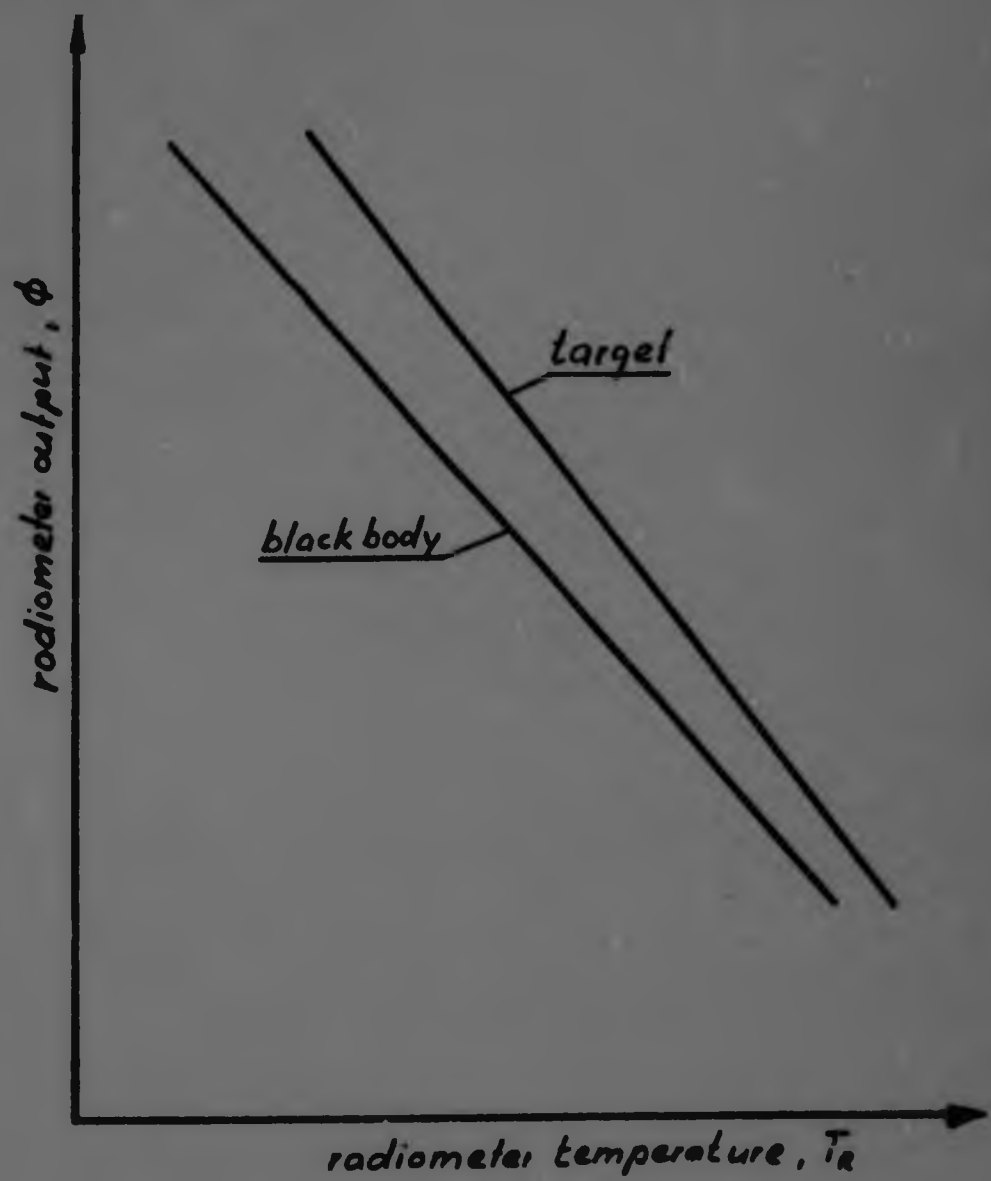


FIGURE 33

Radiometer output as a function of
radiometer temperature
Two targets: textile and black body

11.4 TIME REQUIRED TO TAKE MEASUREMENTS

Each cycle lasted 62 minutes, and before each cycle, the water circuit had to be cooled down, which took approximately 30 minutes. Two cycles (target and black body) were necessary to obtain one emissivity value. 10 to 15 values were considered satisfactory for obtaining a statistically correct value within set limits of confidence.

11.5 SELECTION OF TARGETS

A common canvas overall was taken as a typical specimen of an ordinary clothing textile, and it was assumed that neither the texture nor the colour had a dominant influence on its emissivity. Another target was the material of the special suiting with a metallic coating, as used sometimes by firemen (see Fig 34). These two targets are felt to cover the large range of target materials likely to be found in working garments.

11.6 RESULTS

Overalls	:	$\epsilon = 1.02 \pm 0.111$ (s.d.)
Metal-coated textile	:	$\epsilon = 0.74 \pm 0.108$ (s.d.)

Results of other authors

Paper	:	$\epsilon = 0.93 - 0.94$ [15]
Water (wet clothing)	:	$\epsilon = 0.95 - 0.96$ [15]
Oil paints, 16 different colours (to show that colour has no influence	:	$\epsilon = 0.92 - 0.96$ [15]
(Black) Bantu skin (excised)	:	$\epsilon = 0.997 \pm 0.006$ [14]
(White) Caucasian skin (excised)	:	$\epsilon = 0.997 \pm 0.001$ [14]



FIGURE 34

Textile material of protective clothing
into which thin aluminium ribbon is woven

11.7 SOURCES OF ERROR

A considerable uncertainty attaches to the radiometer output signal, which is subject to random drift as a result of the extremely high amplification employed. The drawing of a line through the scattered recorder output data is therefore influenced by a certain amount of subjective estimation. Since errors of this kind are random errors, the only way to prevent them is to repeat the experiment until a statistically acceptable average value can be found.

Other possible sources of error are discussed elsewhere [16], but it is found that none of them would result in an error in emissivity, but only in an extension of the confidence limits, a situation which again can be improved by taking a sufficient number of measurements.

PART III : DISCUSSION AND CONCLUSIONS

III.1 CORRELATION BETWEEN BODY SURFACE AREA AND BODY SIZE

As a rather large set of percentage posture area values (expressed as a function of the spread-eagle posture) was collected, one might expect a certain coupling between these values and some of the most important body data. It was found, however, that neither the body size (height), nor the weight, nor the actual radiation surface area, had a significant influence on these percentage values.

In order to illustrate this assertion, the following graphs were plotted:

For posture 1, nude:

Percentage of spread-eagle posture against height
(Fig 35)

Percentage of spread-eagle posture against weight
(Fig 36)

Percentage of spread-eagle posture against radiation
area (Fig 37)

For posture 7, nude:

Percentage of spread-eagle posture against height
(Fig 38)

Percentage of spread-eagle posture against weight
(Fig 39)

Percentage of spread-eagle posture against radiation
area (Fig 40)

It is obvious that the type of clothing has no positive influence on an eventual correlation between these percentage values and the body data.

Radiation surface areas (in % of spread eagle posture)
as a function of height and weight and spread eagle area

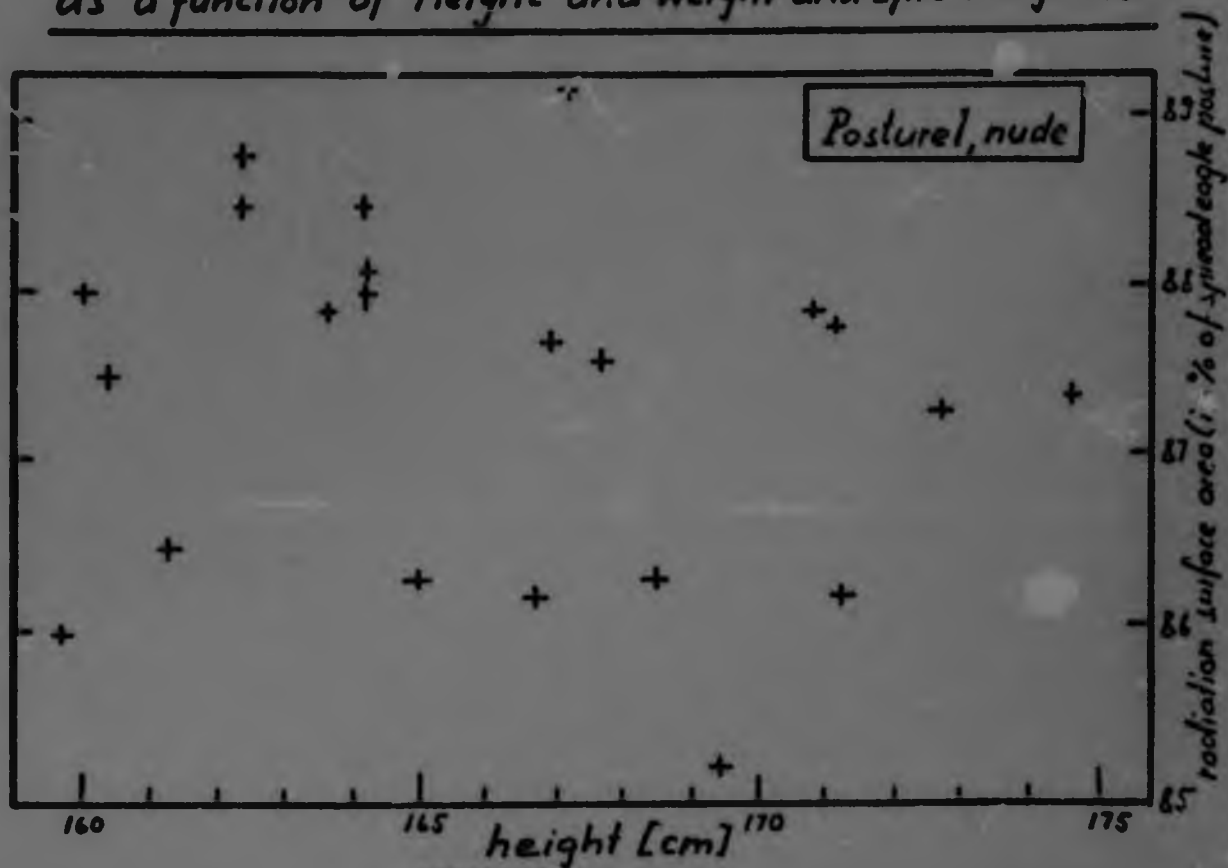


FIGURE 35

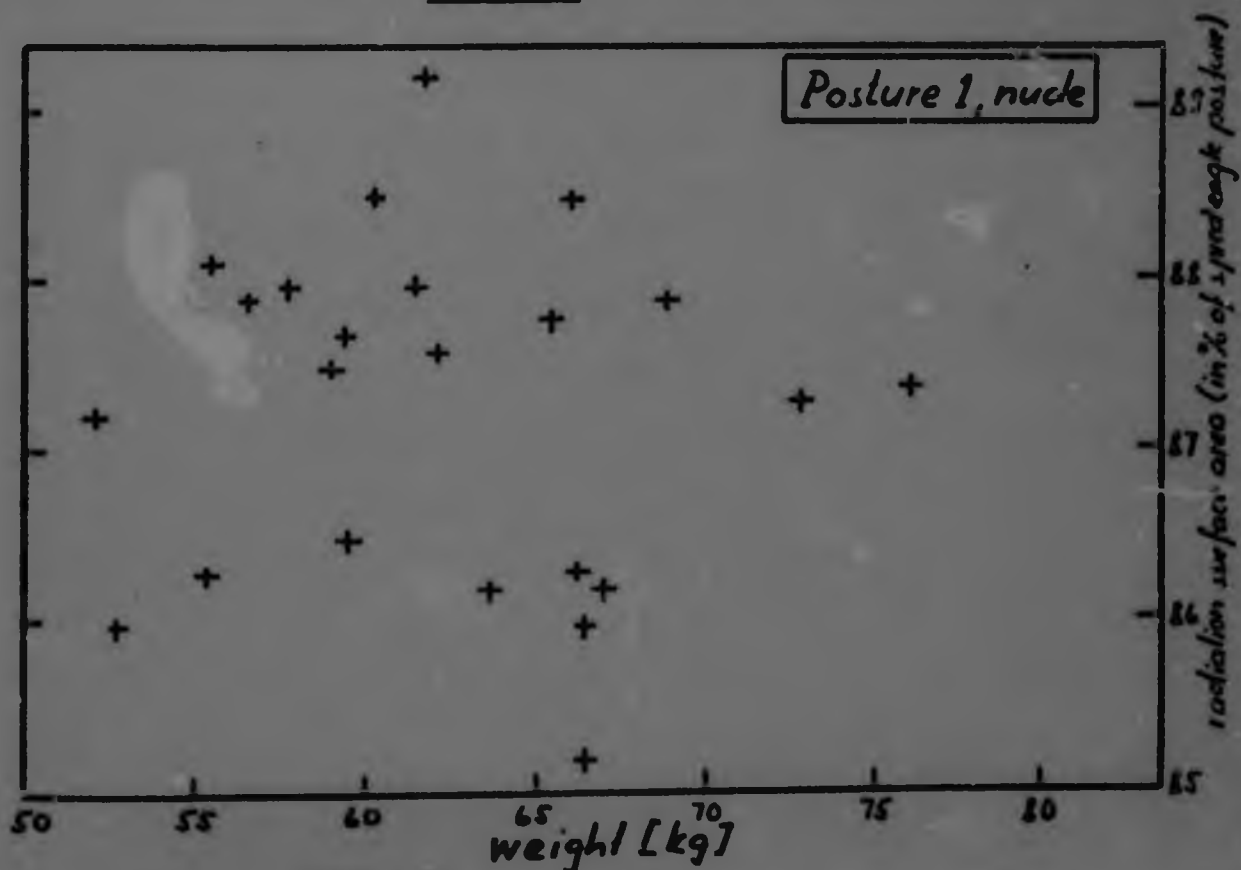


FIGURE 36

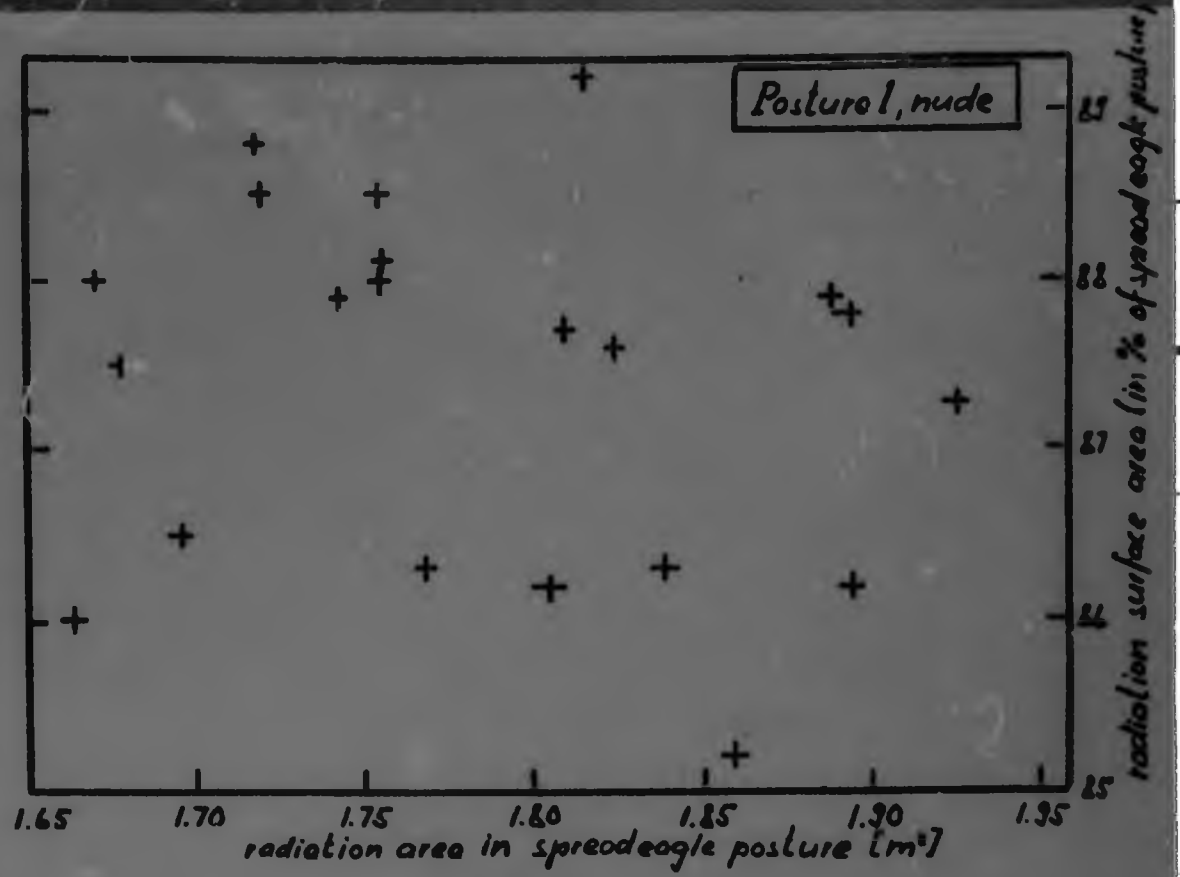


FIGURE 37

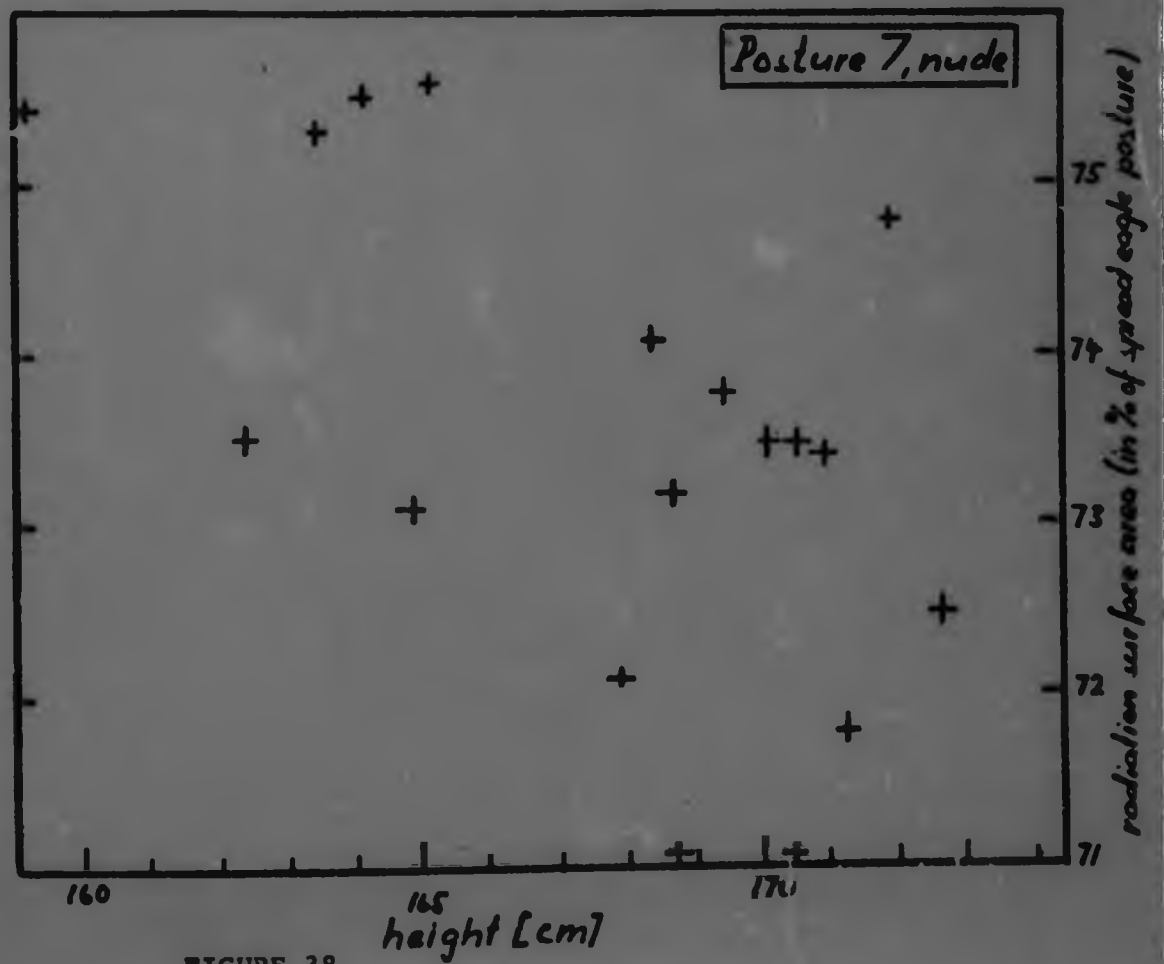


FIGURE 38

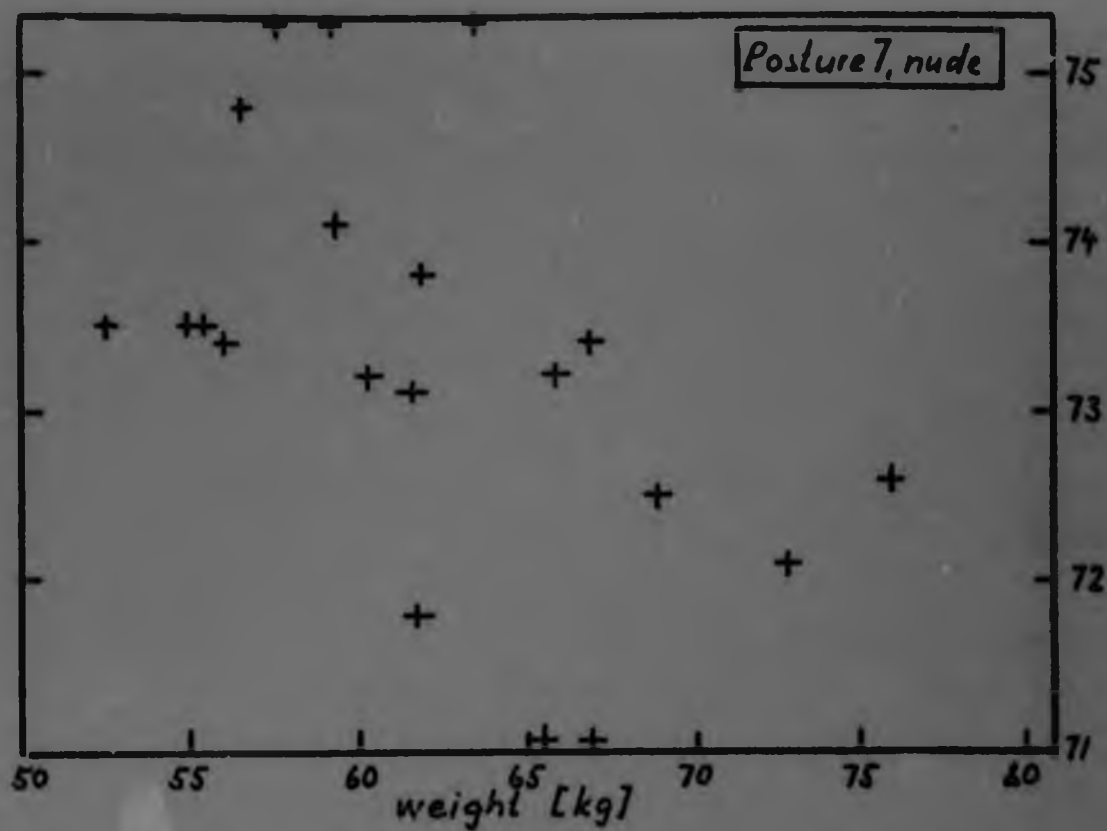


FIGURE 39

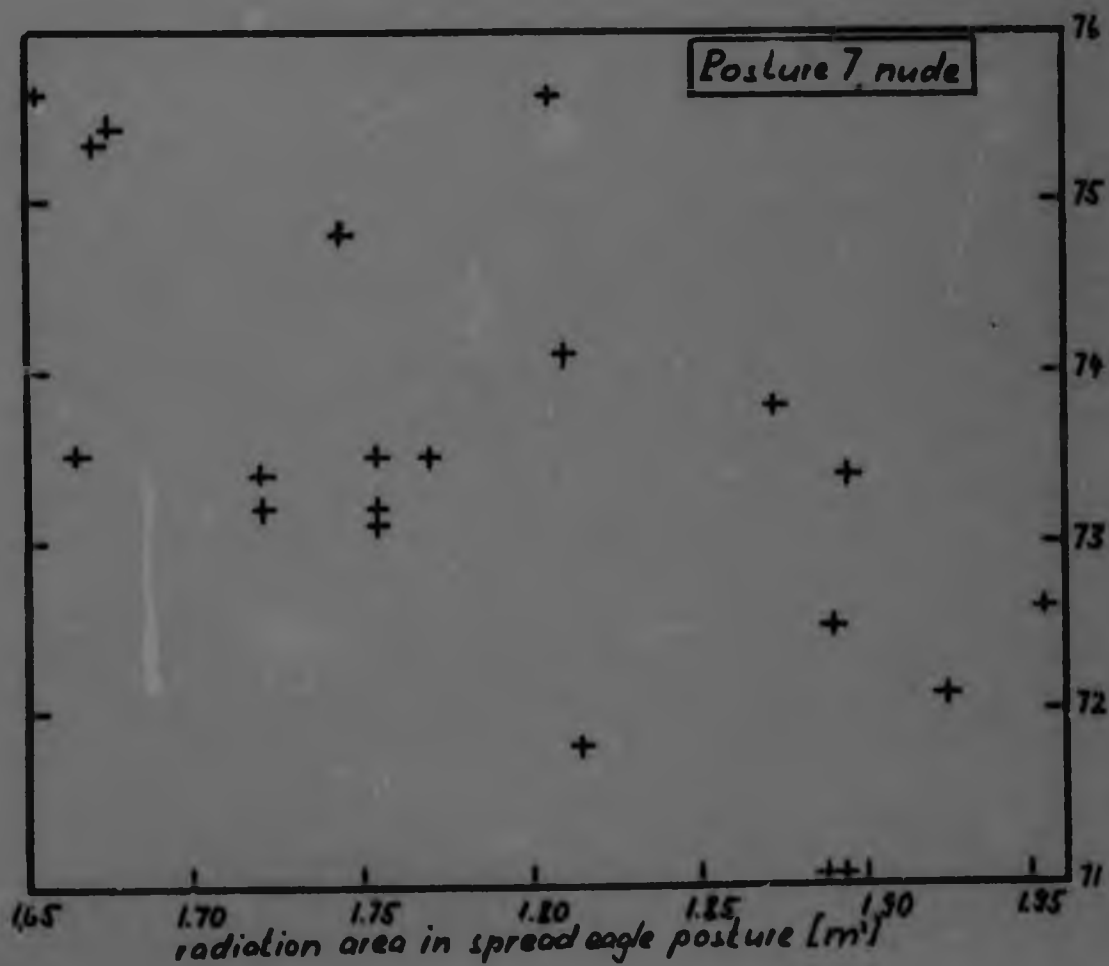


FIGURE 40

III.2 COMPARISON WITH RESULTS OF OTHER AUTHORS

The radiation surface area has been the subject of several investigations and these involved the use of various experimental techniques. But, as mentioned in the survey of literature (5) almost all of these experiments were carried out for only the two most important postures, namely, the seated position and the standing position. For that reason we are able to compare the results of the present study with those of preceding experiments, at least for these two postures. It must be remembered, however, that the majority of those experiments were made with only a few subjects, and often a precise description of what "seated" and "standing" means is not available. A criticism of their methods and the reasons for the deviation from the present results are also given in the chapter referred to.

For reasons of comparison it was necessary to transform the values obtained in this experiment into the convenient form of the effective radiation factor f_{eff} :

$$f_{eff} = \frac{F}{F_{tot}} \quad (18)$$

This form of presentation is also that most commonly used in the literature. The percentage values arising from the present experiment however are not expressed as F/F_{tot} but as F/F_{se} , where F_{se} = radiation area of the (nude) subject in spread-eagle posture. But since we have $F_{tot} = 1.041 F_{se}$ (see Eq 13), we obtain:

$$f_{eff} = \frac{F}{F_{tot}} = \frac{F}{F_{se}} \frac{1}{1.041} = \frac{F}{F_{se}} 0.960 \quad (19)$$

A comparison of percentage values of the total area (true geometrical area) is now possible, and is shown in Table 9.

Investigator	Standing	Seated
Present results (nude subjects)	82.2%	70.2%
Fanger <u>et al</u> [4] (photographic)	72.5%	70.0%
Bohnenkamp [8] (capacitance)	82%	-
Bedford [9] (graphical)	82%	72%
Hardy & Du Bois [17] (graphical)	73%	-
Nielsen & Pedersen [10] (thermal)	66%	60%
Guibert & Taylor [11] (photographic)	76%	70%

Table 9

The results of Bohnenkamp, who employed an electrical method (capacitance) and Bedford, who applied an approximate method (graphical), agree surprisingly well with the present results. The photometric methods of Guibert & Taylor, as well as that of Fanger, however, seem to give results which in both cases are apparently too low. The fact that both the results arising from use of the photographic methods are equally low as compared with the other 3 results (Fanger, Bohnenkamp and the present results), and the fact that although the methods of the latter investigators differ from one another, the results coincide very well, increase the probability that the photographic method yields results which are too low.

The conclusion emerges that the present results fit well into the picture which has existed up to now. But the present results adduce the new fact that they are based on tests of a considerably greater number of subjects. The demonstrated agreement of the present results lends confidence when assessing the accuracy of new results for the 8 working postures, for which no comparison is available, except as follows: the influence of the clothing can be described by means of the clothing area factor

$$f_{cl} = \frac{F_{clothed}}{F_{nude}} \quad (20)$$

for a certain posture. The factors f_{cl} for seated and standing subjects are given in Table 10.

Investigator	seated	standing	clothing
Present results	1.26	1.17	track suit
Fanger [4]	1.11	1.19	uniform

Table 10

III.3 DISCUSSION OF THE HIGH EMISSIVITY VALUES OF CLOTHING AND SKIN

It has already been mentioned that the emissivity does not depend on the colour of the material - in the present case, skin and textile. This can be explained by reference to Fig 2, where it will be seen that sunlight distributed between the wavelengths of 0.2 and 3 μm contributes practically nothing to the thermal emission within the infrared waveband. The emissivity of a surface depends on its nature (physical composition) and on the topography of its surface. In what follows it will be shown that smoothness of the surface is a factor of overwhelming importance as far as the emissivity of a surface is concerned. A description of the surfaces of an ordinary textile and of the skin will show why the emissivities of these surfaces are so high.

The following emissivity values, which demonstrate the strong effect of the smoothness of the surface, are taken from [18]:

<u>Copper</u>	<u>ϵ</u>
polished	0.04
etched and scratched	0.09
rolled	0.64
matt	0.22
rough	0.74

<u>Iron</u>	<u>ϵ</u>
pure, polished	0.06
freshly rubbed with emery	0.24

wrought, polished	0.28
wrought, smooth	0.35
cast, freshly turned	0.44
cast, oxidized	0.63
rough, oxidized, cast	0.98

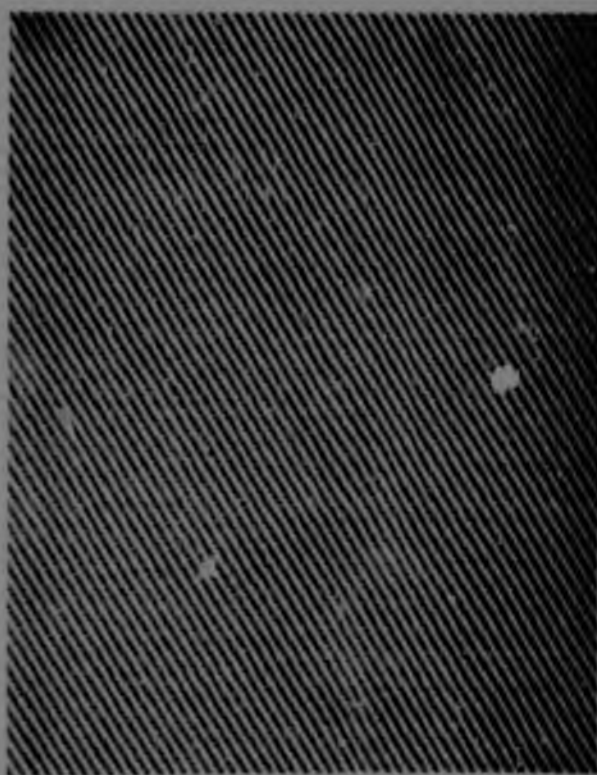
It is a well-known fact that the surface of an ordinary textile is usually very unsmooth, not only from the point of view of the texture but also from that of the fibrous nature of the yarn. This can be seen from a close-up view of the canvas (Fig 41).

The surface of the skin is also not smooth but is densely patterned with ridges, furrows, hair follicles and pores. Superimposed on this system of irregularities is a further roughness of cellular dimensions, caused by the constant sloughing of dead cells from the surface. Fig 42 is a micrograph made by Sarkany and Caron [19] of an aluminium-shadowed replica of the skin surface clearly showing roughness of the same dimensional order as the wavelength of the radiation involved.

Another possible explanation of a high skin emissivity lies in the high water content of the skin. Water has a high emissivity even in very thin films, although the quoted values generally lie between 0.95 and 0.97 [15], that is, appreciably lower than that found for the skin. If the water content of the skin is a reason for its high emissivity, then dehydration of the skin should result in a drop in emissivity. It was in fact found that with dehydration to the stage where skin became brittle and glossy (about 10% water content by weight), the emissivity of a specimen of Bantu skin dropped from 0.997 to 0.919 [14].

III.4 APPLICATION OF THE MEASURED DATA

In what follows an attempt is made to combine the measured data into handy and illustrative graphs, for use in estimating the radiant component of the heat exchange. A practical example



1cm

FIGURE 41

Close-up view of the canvas texture

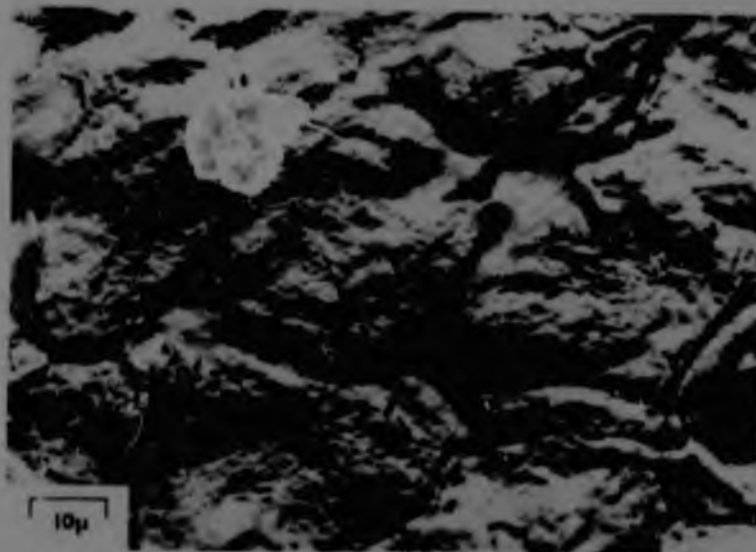


FIGURE 42

Aluminium shadowed replica of the
skin surface [19]

involving calculation of the situation near a submerged-arc furnace is also given.

Eq 3 can be rewritten as

$$R = \epsilon_b \cdot \sigma \cdot \frac{F}{F_{\text{tot}}} (T_e^4 - T_b^4) \quad (21)$$

so as to relate the rate of radiant heat exchange to the unit of the total (nude) body surface. (It should be remembered that Eq 3 was obtained subject to certain assumptions, as mentioned in the appropriate chapter.)

Recalling that results are expressed in terms of $\frac{F}{F_{\text{tot}}}$ instead of $\frac{F}{F_{\text{se}}}$, and since we have $F_{\text{tot}} = 1.041 F_{\text{se}}$, we obtain

$$R = \epsilon_b \cdot \sigma \cdot (T_e^4 - T_b^4) \frac{F}{F_{\text{se}}} 0.960 \quad (22)$$

The influence of clothing and posture on radiant heat transfer can now be shown by substituting the experimentally-determined values into this formula.

The first four graphs (Figs 43-46) show the influence of posture (nude men), assuming a range of emissivities between 1.00 and 0.90.

The expected real radiant heat transfer per unit of total body surface area is plotted as a function of the transfer, calculated according to the Stefan-Boltzmann law. The shaded areas indicate the range of emissivities between the limits of 0.9 and 1.0. A curve showing the experimentally-determined skin emissivity is also drawn in.

In the next set of 8 diagrams (Figs 47-54) the influence of clothing is shown for each of the eight postures investigated. From these graphs it can be seen that any clothing increases the effective body area. One would therefore expect an increased radiant heat exchange, but this is generally not so; this heat exchange also depends very strongly on the temperature of the surface of the subject, on the temperature of the nude skin and on that of the clothing. Although exposed to

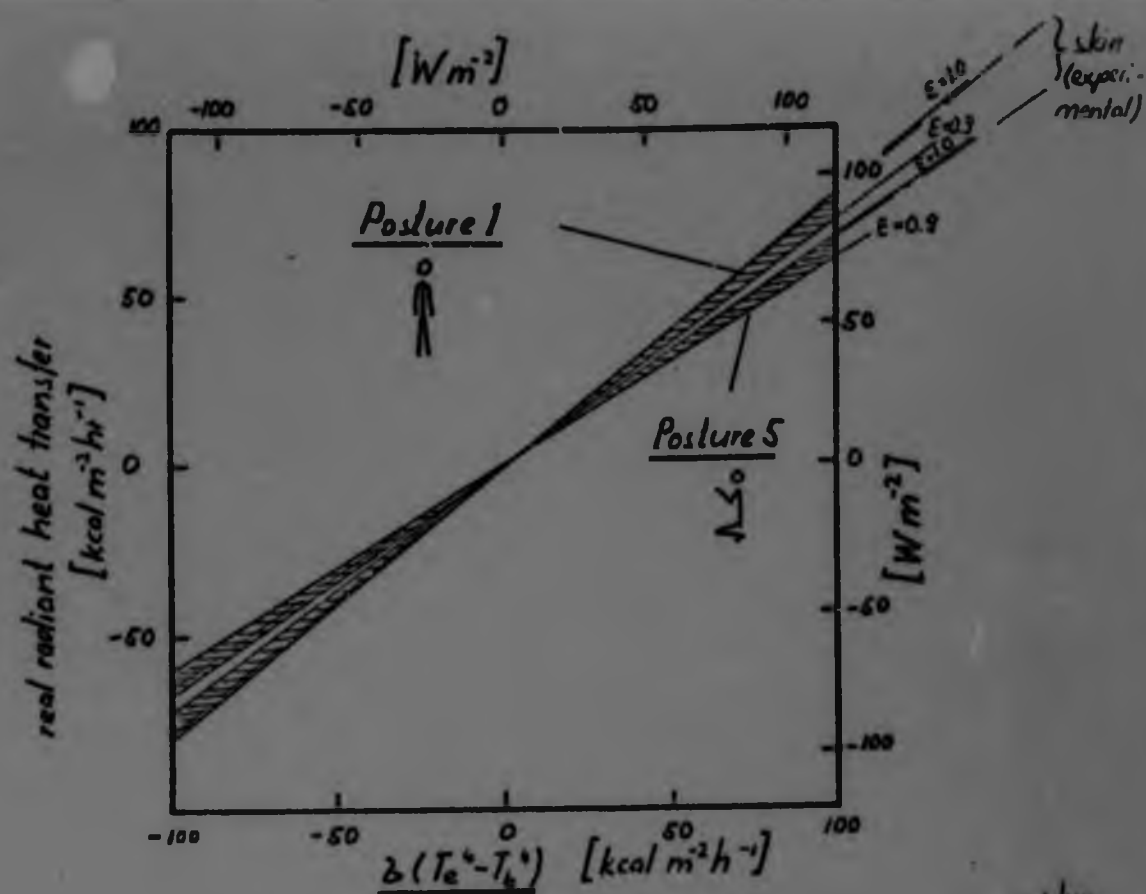


FIGURE 43

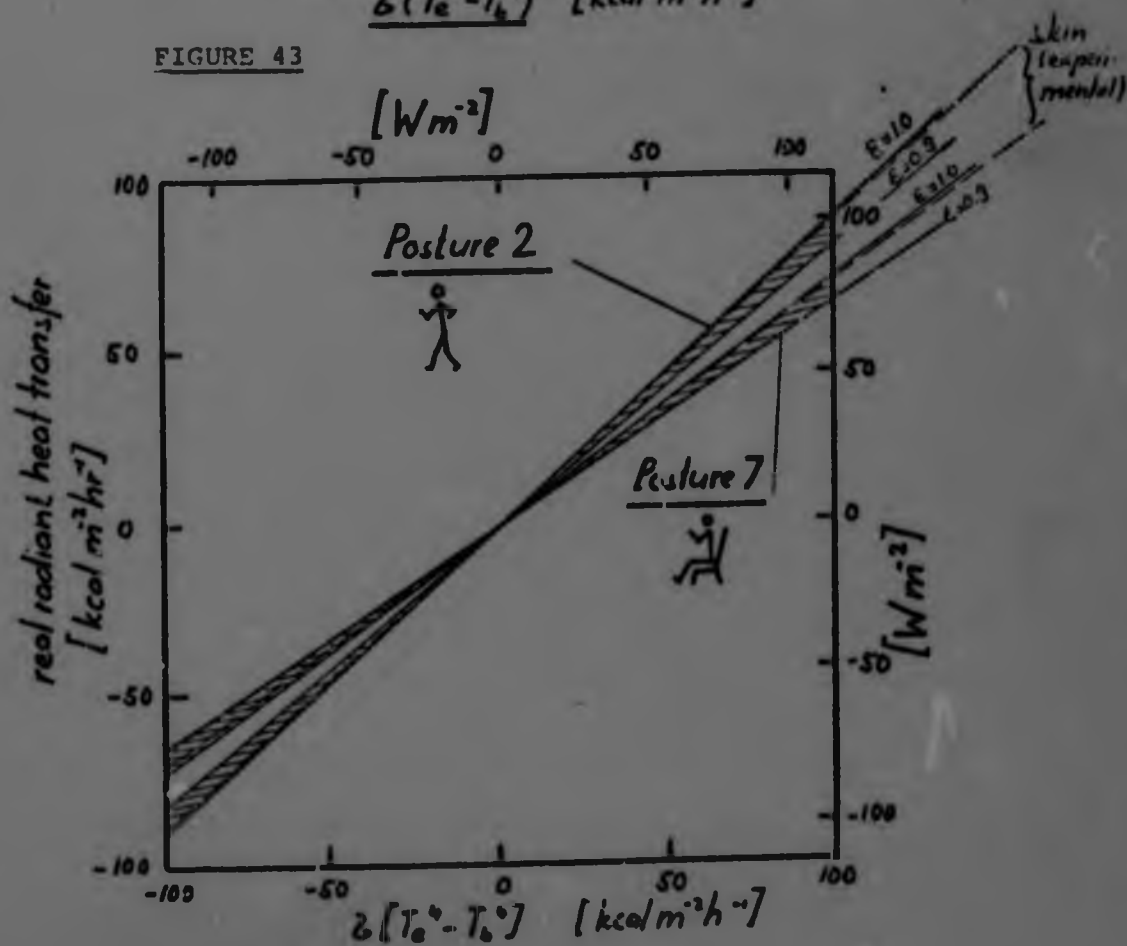


FIGURE 44

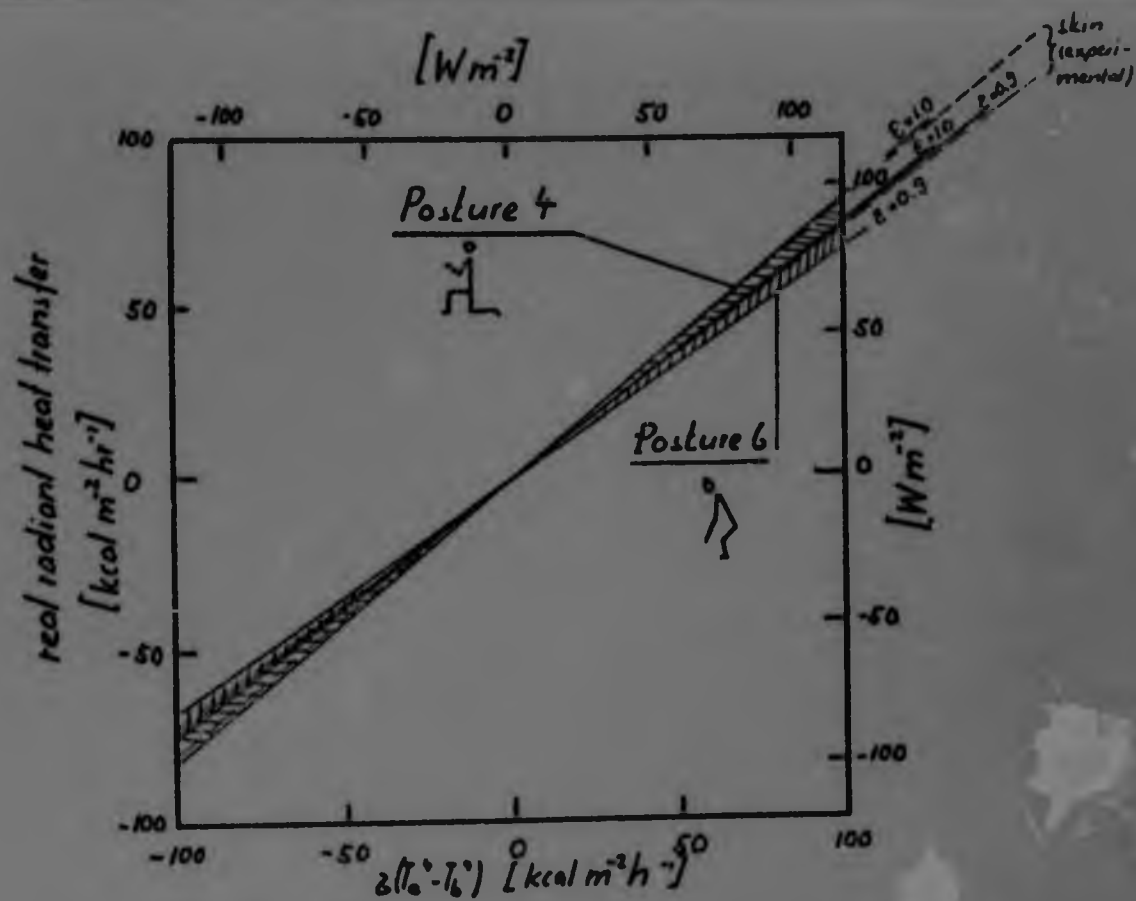


FIGURE 45

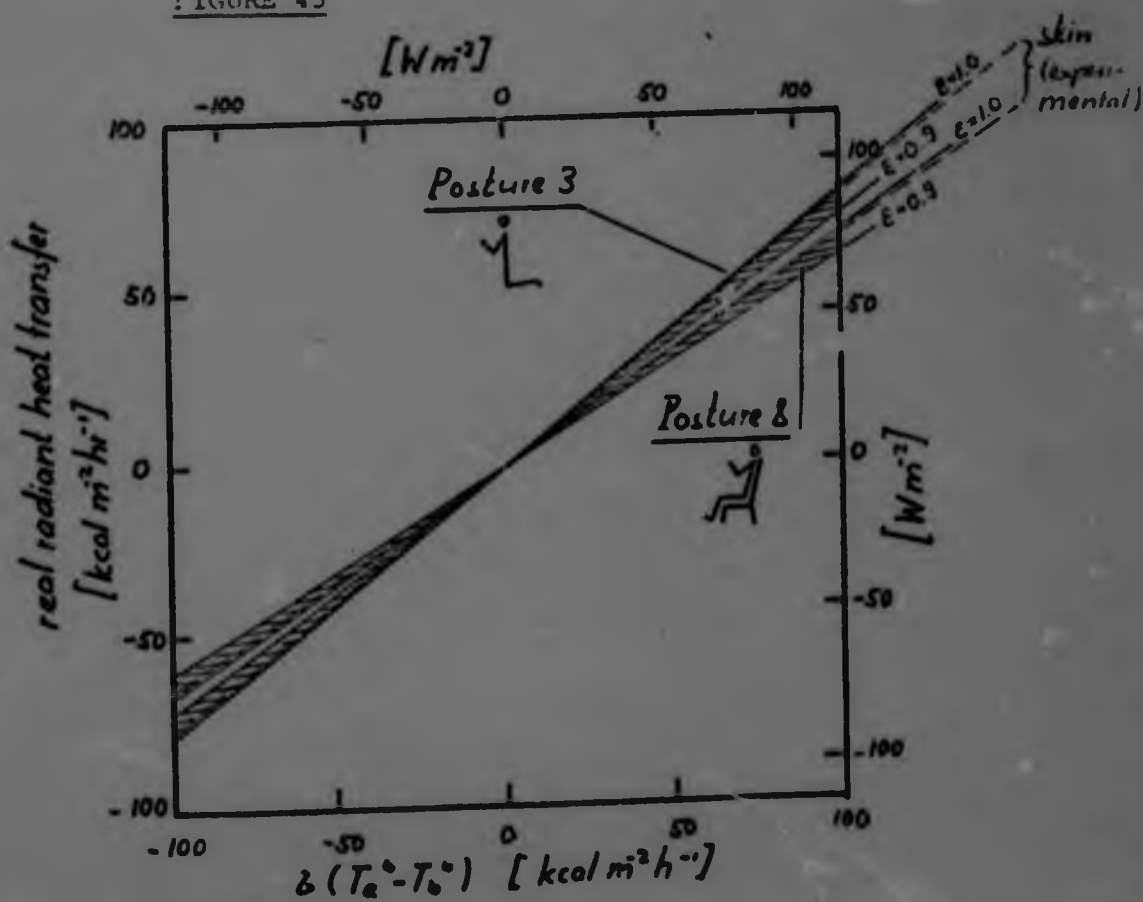


FIGURE 46

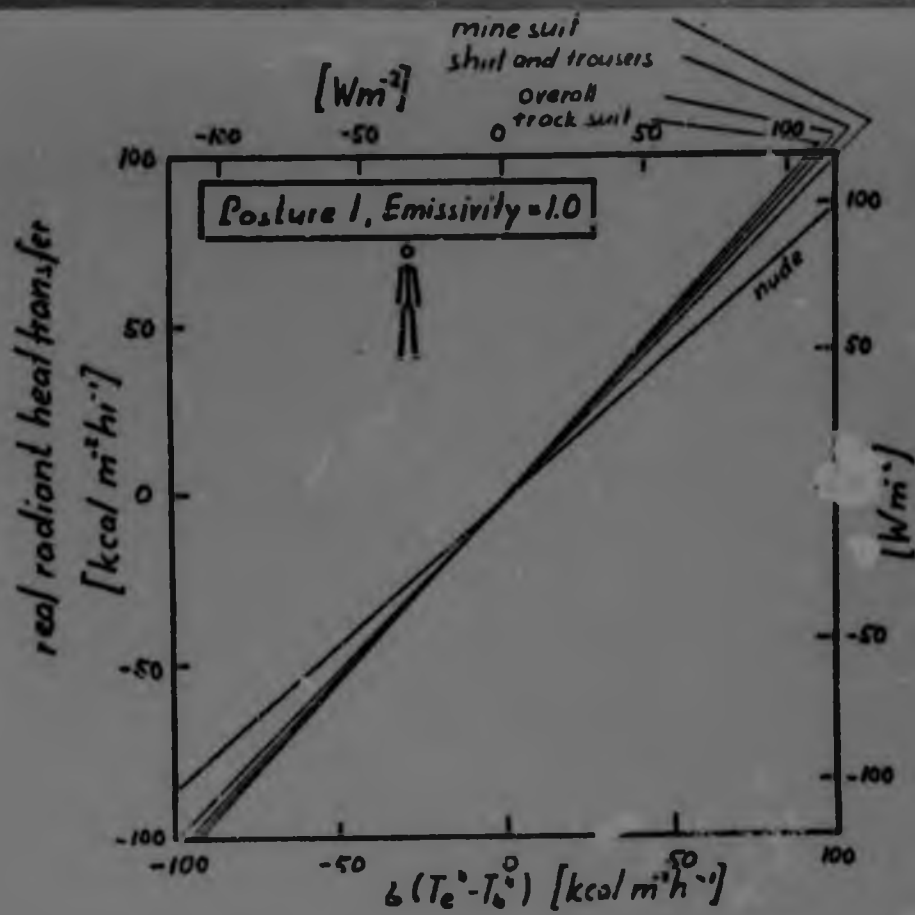


FIGURE 47

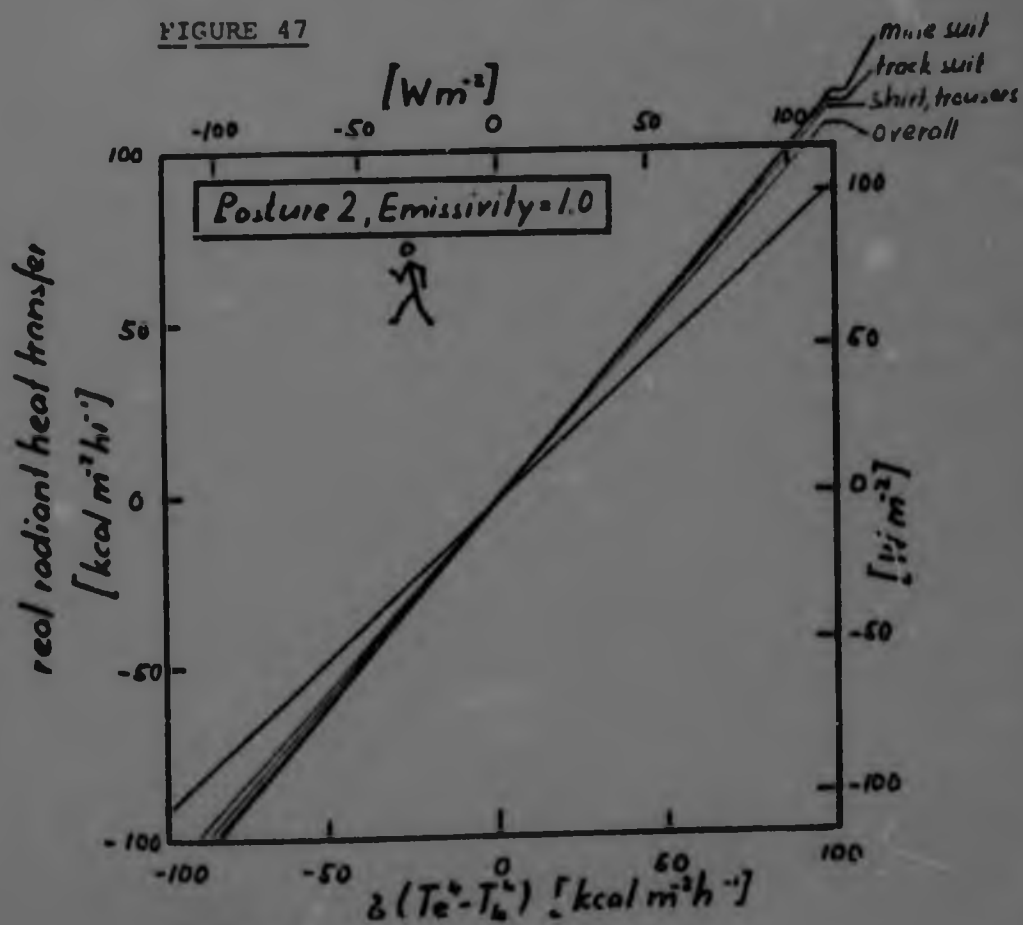


FIGURE 48

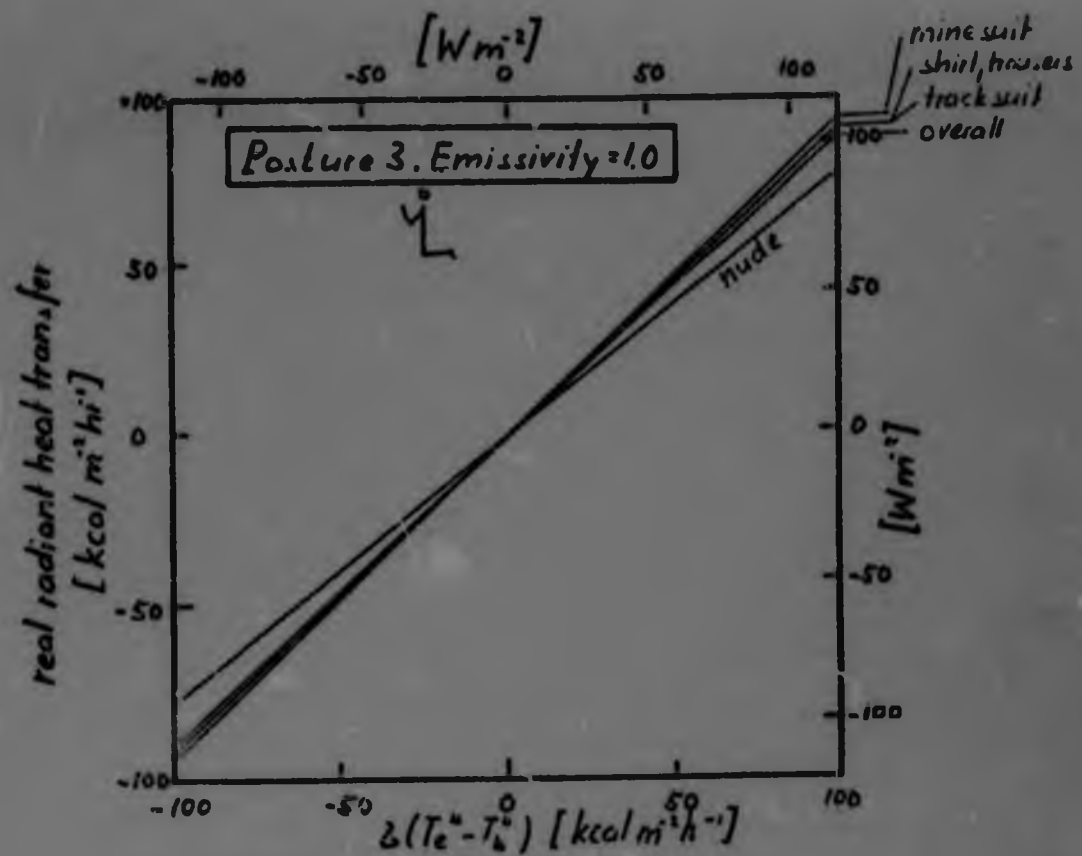


FIGURE 49

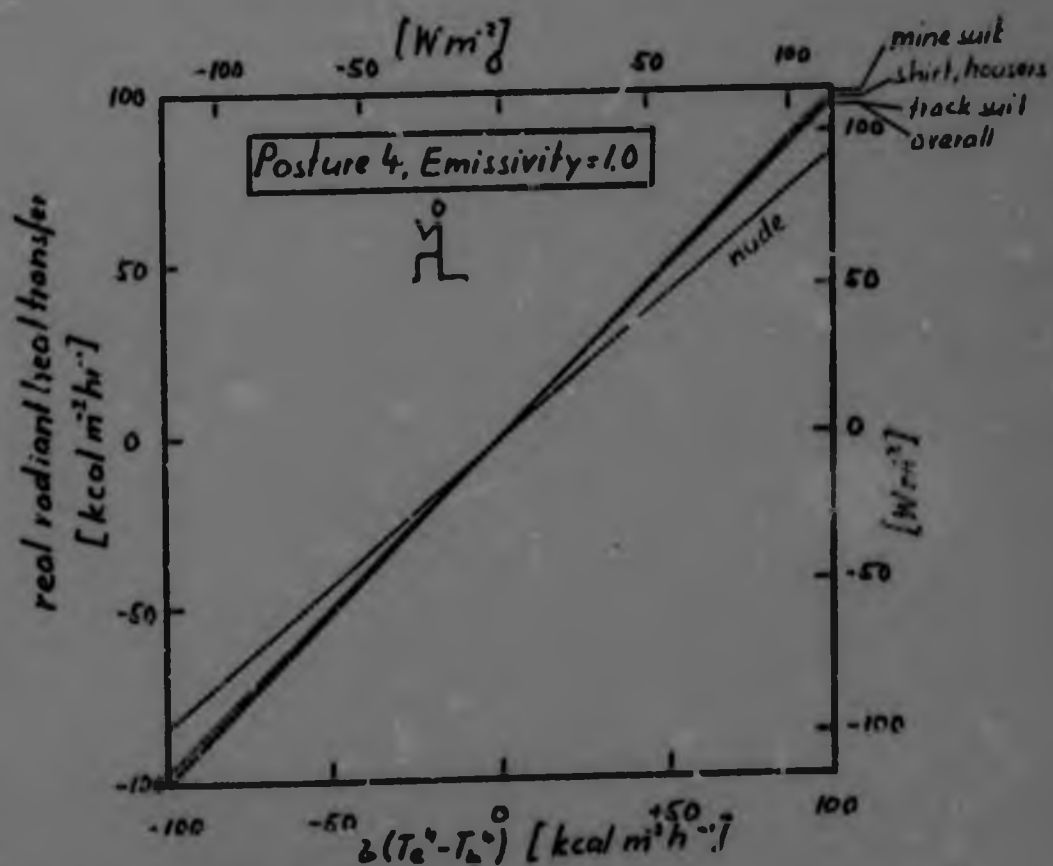


FIGURE 50

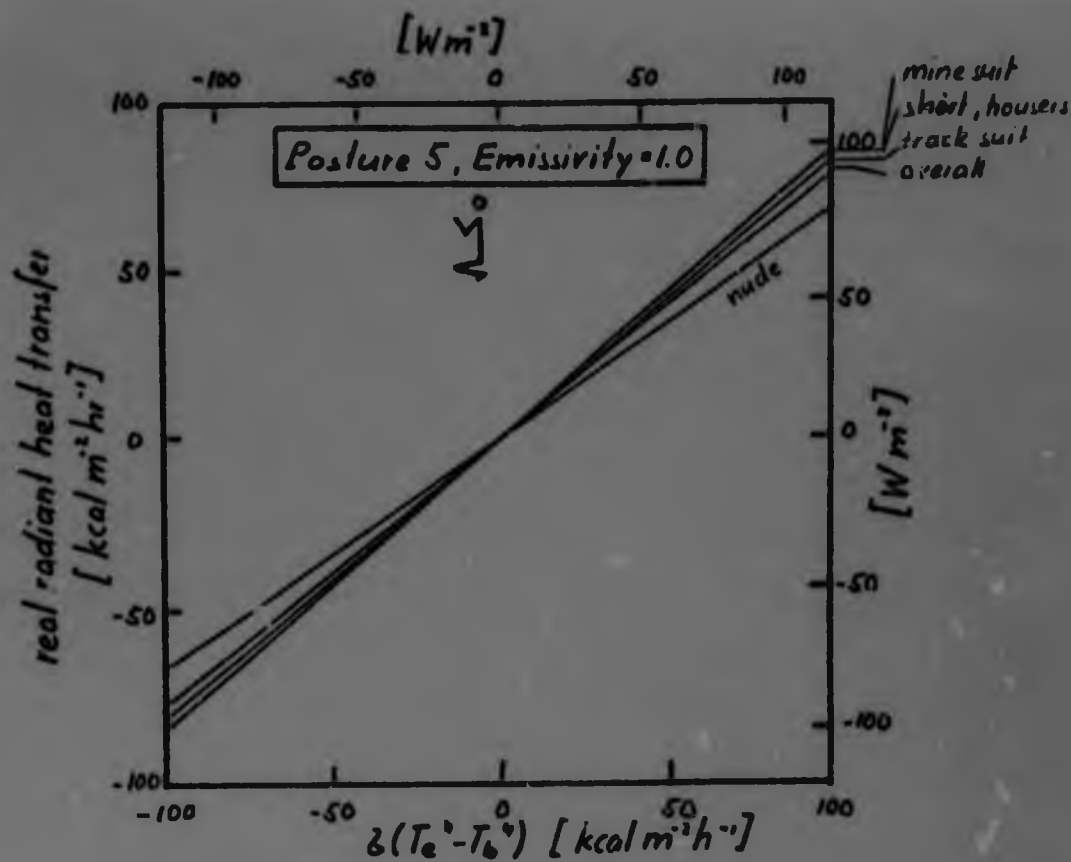


FIGURE 51

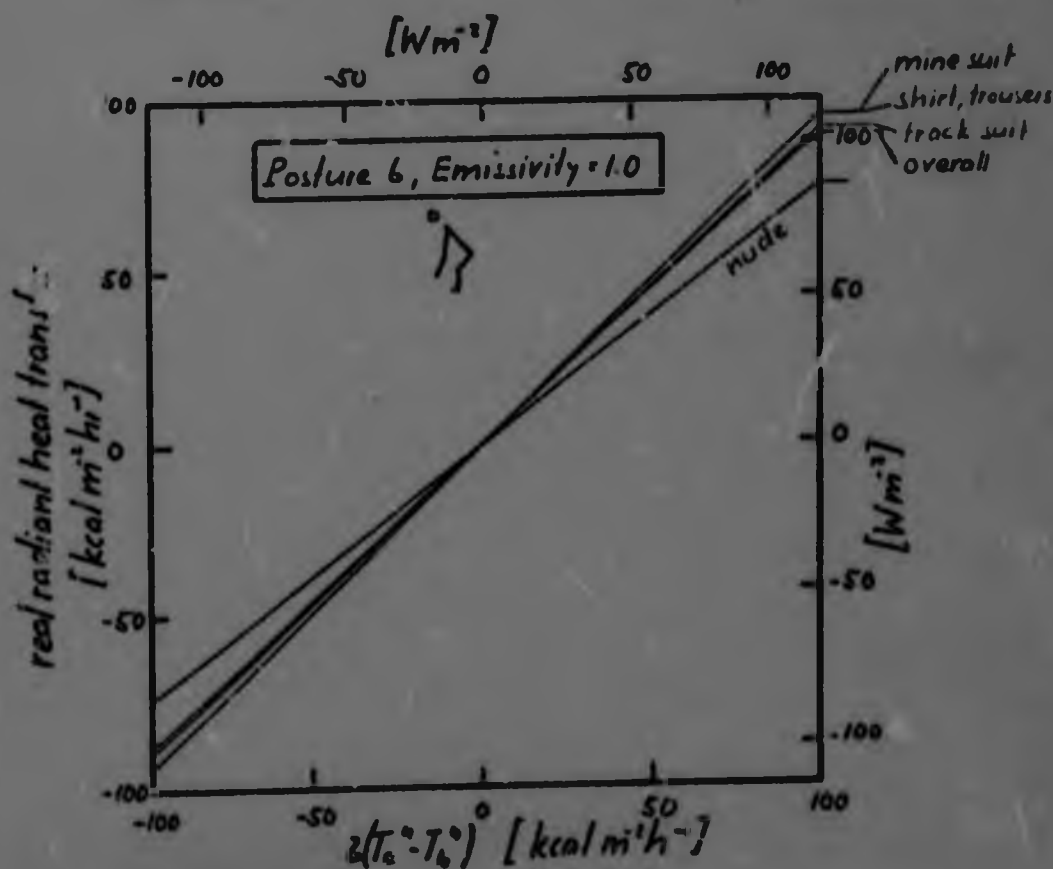


FIGURE 52

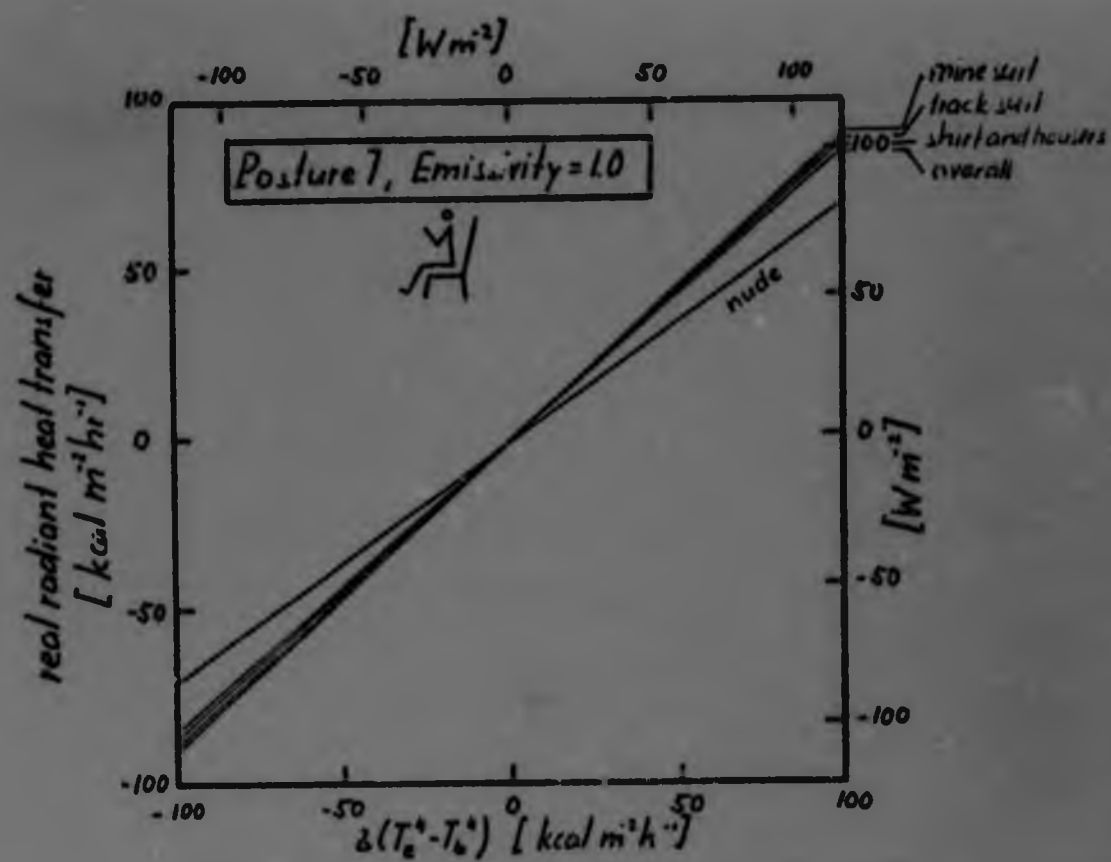


FIGURE 53

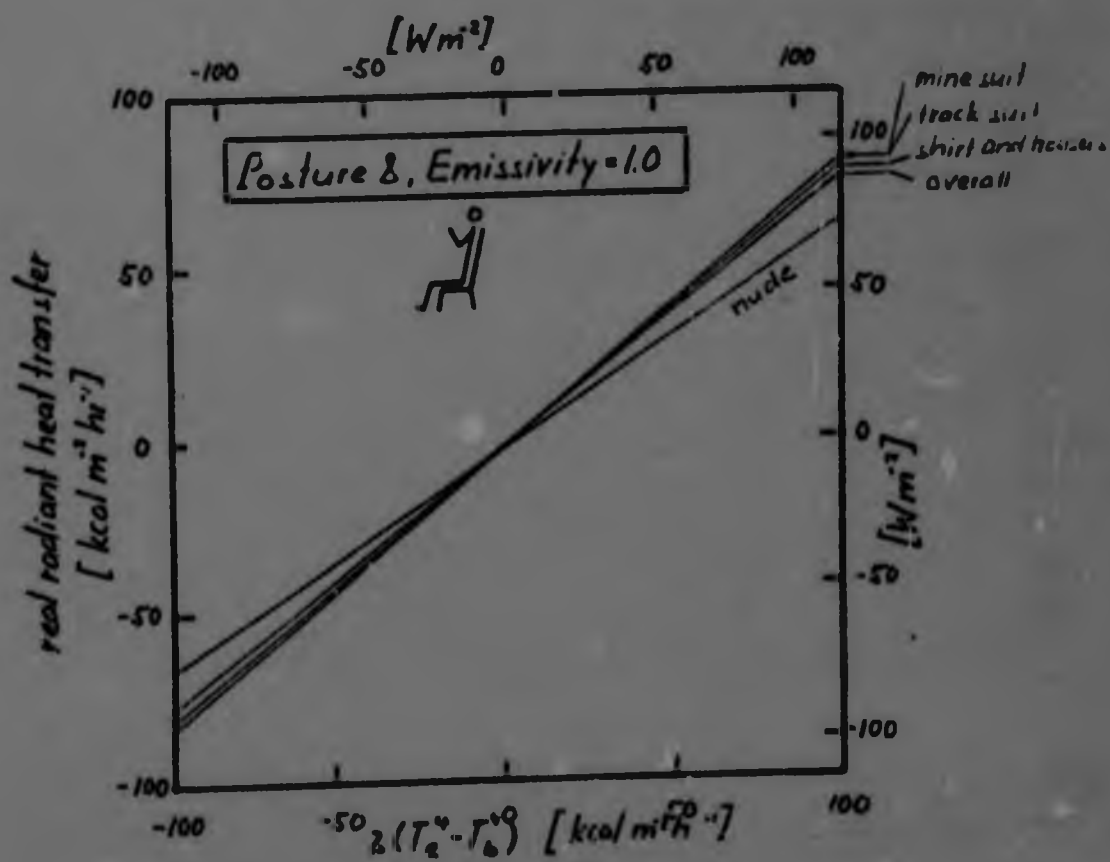


FIGURE 54

the same radiation, each behaves very differently. Whereas the skin tries to maintain a more or less constant temperature (within limits) due to the action of the underlying blood vessels, the temperature of the clothing (outer surface) may rise to high values under irradiation from a heat source, or fall to low values in a cold environment. Generally, it can be said that the temperature of clothing normally lies somewhere between skin temperature and environmental temperature. Therefore it can not be concluded that an increased area due to the clothing also results in an increased heat transfer. A high temperature environment will even partly compensate for this increased area and yield a lower heat exchange due to the high surface temperature of the clothing, and vice versa. In these 8 diagrams, an emissivity value $\epsilon = 1$ has been shown, taking into account the fact that emissivities of clothing are usually very close to unity. The consequences of an emissivity variation between 0.9 and 1.0 can also easily be estimated from Figs 43-46. If the emissivity of certain clothing (and naturally its temperature) is known, then the graphs of Figs 47-54, in which an emissivity of 1 is shown, make it easy to determine the real radiant heat exchange, simply by reading off values for $\epsilon = 1$ and multiplying them with the known emissivity. It should be mentioned, however, that the measurement of clothing temperature is very difficult.

To close this discussion of applications of the measured data, a practical example is given:

Morrison et al [1] have shown that the radiant heat load on labourers when near submerged-arc furnaces is 405 kcal/m² h of the radiation area of the clothed man. The conditions were: the mean radiant temperature was determined to be 160°C and that of the mean body surface (including clothing) to be 52°C. The clothing is described as loose fitting, with gloves and bulky aprons, which were necessary wear under such extreme environmental conditions. The emissivity of the entire body (skin and clothes) was assumed to be $\epsilon = 1$.

Provided that a man wore clothing consisting of the special high reflecting textile which was measured in the present study, he

could therefore decrease the radiant heat load by 26% or 105 kcal/m²h. A decrease of the same amount by decreasing the mean radiant temperature would have required a new mean radiant temperature of + 16°C instead of 100°C, provided that the surface temperature of the clothing remained the same. This shows that such a protecting suit does not protect as much as would appear from its optically reflecting and shiny appearance.

A few further exercises may demonstrate the influence of posture. The heat load of 405 kcal/hm² of radiation surface of the clothed subject referred to is naturally independent of the type of clothing. Based on our new knowledge of the relationship between the total body surface area (nude) and the radiation area of the clothed body for 4 different types of clothing we are now able to determine the radiant heat exchange rate per unit area of the total nude body surface area. This is actually the essential quantity that determines how much the man is physiologically stressed.

The following assumptions are made: the environmental and body surface temperature conditions remain the same ($T_{mr} = 100^{\circ}\text{C}$, surface temperature = 52°C); the posture is assumed to be Posture 1 (standing); the emissivity of the surface is assumed to be 1; the heat generated by radiation is assumed to be equal to the heat that affects the man physiologically. This latter is actually incorrect because there is always an insulation layer between the point of absorption and the skin level, but we have good reason to assume that these insulation conditions are more or less the same for all 4 types of clothing, which is generally not far away from reality (the variations are usually between 0.5 and 1.5 clo). The following figures are therefore rather to be regarded as a relative comparison between the different type of clothing than between the actual magnitudes of radiant heat affecting the subject. All figures should be divided by a certain factor to allow for the effect of the insulation. But since this factor is more or less the same for all types of clothing, a comparison (which is actually the final aim of this exercise) is possible.

According to the equation:

$$\frac{\text{radiant heat generation rate}}{\text{radiation surface area (clothed)}} \times \frac{\text{radiation surface area (cl)}}{\text{total body surface area (nude)}} = \frac{\text{radiant heat generation rate}}{\text{total body surface area (nude)}} \quad (23)$$

We obtain the results in Table 11.

Posture	(radiant heat generation rate/total body surface area (nude)), kcal/m ² h	difference to nude subject, kcal/m ² h
nude	405	0
track suit	396	-9
overalls	421	+16
mine suit	436	+31
shirt and trousers	430	+25

Table 11

The influence of posture can be shown in a similar way. Suppose we are looking for the radiant heat generation rate per unit area of the total body surface area (nude) for various postures in an environment similar to the one described above. We assume that a mine suit is worn in all postures, that the emissivity is 1 and that the temperature conditions of the environment and the body surface are the same. Furthermore, the same restrictions as to the insulation between the point of absorption and the skin level hold.

For the different postures we obtain the results shown in Table 12.

Posture	(radiant heat generation rate/total body surface (nude)), kcal/m ² h	difference to posture 2, kcal/m ² h
1 (standing)	436	-25
2 (walking)	461	-0
3 (kneeling)	381	-80
4 (kneeling)	397	-64
5 (squatting)	344	-117
6 (lifting)	377	-84
7 (sitting)	366	-93
8 (sitting)	328	-133

Table 12

By comparing this Table with Table 11, we see the important influence of posture on the quantity of the radiant heat transfer. Naturally the posture cannot always be chosen to accord with the best radiation surface area, and certainly not in cases similar to that discussed. But in many other cases improvements can and should be made, as for instance when a man has to operate a very hot machine (glassblowing); a seated position instead of a standing one could contribute to a decrease of the radiant part of his heat load.

Note: All original laboratory records are deposited
in a file at the Human Sciences Laboratory of
the Chamber of Mines of South Africa, P O Box
61809, Johannesburg.

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