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THE COLLEGE OF AERONAUTICS

CRANFIELD

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METHOD STUDY OF HOT WORKING CONDITIONS

by

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MEP

1. Introduction and Historical Note

A convenient dichotomy of the technology of Work Study in everyday use[1] is

(a) Method Study
(b) Work Measurement

This applies to most current work conditions and techniques although the work sampling techniques of ratio delay and memomotion do not fill conveniently into either. The usual chart methods and photographic techniques used in method study stem from the practice of the Gilbreths so that some practitioners equate method study with motion study[2]. Such a view would necessarily restrict method study to movement at normal temperatures and leave outside the study of work conditions which are the interest of the ergonomist. In everyday practice no rigid division of the study of industrial work situations can be made and an eclectic approach is required even in the big organisations employing specialists. The term 'ergonomist' is used in the sense that the technician concerned has a wider interest and training than that needed for motion study. Such a use stems back to F.W. Taylor whose use[3] of the term Time Study (as opposed to the modern 'time study') implied

(a) the study of work and experimentation to develop the best method of performing a job which was then standardised

(b) the division of a work cycle into elements, the timing by stopwatch of these when performed by a selected, suitably trained andhighly motivated worker. The addition of allowances for rest, necessary delays etc. and the establishment of a time to be used as a basis for planning and control and the setting up of a wage incentive scheme.

(c) The analysis of all such established times so that a system of synthetic times can be used for forward planning.

Such a programme comprises what is now accepted by practitioners to cover Work Study. The genius of the Gilbreths tended to concentrate the attention of later practitioners to the motion study aspect of the first part but Taylor did not make any such a restriction in his experimental approach. His experiments on metal cutting and work physiology, started at Midvale Steel Co. and continued at Bethlehem Steel Co., were part of

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this programme of what is now comprehended within Method Study. The contributions of Taylor to work physiology were important both in insight and in the fact that they stimulated interest and started a tradition which is especially strong in Europe[4,5] in centres such as the Max Planck Institut für Arbeitphysiologie at Dortmund.

In industry in U.S.A. and Gt. Britain the spread of knowledge of the tenets of motion study, the increased use of powered devices and of electronic control and feed devices (automation) has resulted in the position that, except for isolated cases and for non-repetitive work, there is no industrial work which would be described by physiologists as physically exhausting in normal temperature conditions. This does not imply that physical strain is not present in the form of bad posture (especially caused by bad seating) and from the use of machine controls designed without attention to human restrictions which require relief by change of posture or, better still, eradication by better design[6]. Rather has the restriction on human output, or the conditions in which it is found, shifted from that of physical effort which can be attacked by Gilbreth motion study into such fields as motivation and morale, inspection processes requiring vigilance, multi-machine minding and conveyor belt (machine paced) processes and lastly hot processes in which considerable physical effort may be exerted. In all these fields, Gilbreth techniques have a limited or no application and increased productivity can only be achieved from such work by applying psychological, physiological and statistical techniques to them.

Before coming to the main purpose of this paper it will be noted that considerable increases of productivity have been achieved in all the fields noted.

(a) Motivation and morale. The Hawthorne Investigation was an example and later work, such as that from the Tavistock Institute has made claims in this connection. The writer does not necessarily accept such claims at their face value as frequently no attempt is made in such instances to control the technical aspects of production, overall production being taken as a morale index - this is considered to be fallacious in many contexts.

(b) Inspection processes have been studied since the work of Taylor at Simonds Manufacturing Co. in 1883. Some notable advances have been made recently by psychologists in Gt. Britain deriving from the pioneer work of the Applied Psychology Unit at Cambridge.

/(c) ...

(c) Multi machine minding processes and conveyor belt processes are susceptible to statistical analysis using queuing theory[9] and various statisticians in U.S.A., U.S.S.R. and Gt. Britain are working on these problems. Conrad has reordered conveyor belt working[10] using a rational approach to this type of problem.

This paper is concerned with the method study of hot working environments which are not susceptible to present study methods. The writer wishes to call attention to the pioneer work in industry of Prof. G. Crowden and Dr. T. Bedford in this field which has been the inspiration for deriving a 'system' for the routine use of work study technicians.

2. Physiological Effects of Hot Conditions

Hot working conditions differ from normal temperate conditions in that physiological strain will result whether the worker is working or not. The object of method study of hot conditions must be the statement (and measurement in the broadest sense) of those conditions and the redesign of the work-place and work to reduce the effects on the worker to a minimum.

The conditions which result in decreased efficiency of the worker through heat stress derive from

(a) environmental conditions of radiant heat, and air humidity, temperature and speed

(b) internal heat (metabolic rate) generated by the worker especially in exerting physical effort

(c) clothing worn which interferes with body convection and radiation processes

(d) mental activity of the worker

(e) individual physiological and psychological tolerance of the heat stress and degree of acclimatisation.

In order to discuss heat stress it is necessary to examine the effect of increased heat on the body and this will be done for conditions in which pain or burning of the skin does not occur. The human being retains relatively constant temperature conditions within certain internal regions of the body, notably the brain and viscera, by autonomic nervous control which affects the heart rate and the distribution of the blood flow. A large part of the body, notably the extremities of the limbs (such as the feet), is not controlled at such constant conditions and is subject to temperature fluctuation within everybody's experience. The effect of increasing heat in the environment results in increasing differential heating of the body tissue (especially the limbs) a redistribution of blood flow towards the surface of the body, increasing oxygen consumption from breathing and an increase in sweating. In physiological laboratory work the effects of heat on the body are generally measured by changes in rectal temperature, skin temperature, pulse rate and sweat loss. The response of human subjects to various test conditions is shown in Figs. 1 and 2 derived from Kuno[11]. These figs. and other studies show

(a) the quickness of sweating response to exposure to high temperature depends on the degree of stress

(b) sweating rates differ between various areas of the body. In general at low heat stress conditions sweating occurs mainly on the legs but increase of temperature results in recruitment from all areas but chiefly on the chest and upper areas which are the main sources at high stress conditions.

(c) the onset of sweating in an area results in decreased skin temperatures.

(d) rectal temperature and heart rate increase with exposure

(e) mental activity inhibits sweating and therefore may add to heat stress although authorities differ in view on this

(f) physical effort (increased metabolic rate) adds to heat stress.

The increases of body temperature, sweating and pulse rate which are typical for the worker in hot conditions compared with temperate, are not 'unhealthy' per se. The body tolerates such increases up to levels which differ between individuals and accommodation takes place within a short period of time in which the capacity to sweat is increased; Fig. 3a shows the decreases in heart rate, rectal and skin temperatures with the passage of time of exposure to heat [12] and Fig. 3b the increase in sweat loss[13]. Individual differences in response to the same conditions are large and reports for two of Eichnas subjects [14] show this.

Data at end of work in an
environment of 96°F saturated

Subject	Duration (hrs)	Rectal temp°F	Heart rate	Resp. rate	Sweat loss gr/hr.	Condition
WIL	4	103.5	132	36	1240	Tired walking easily
HOF	1.3	102.0	171	12	2425	Can't breathe all in

The physiological response for a particular individual will vary with age; Weiner and Lind[16] have investigated age differences for fit mine rescue personnel of different age groups but much work has to be done in this area. The work of Eichna[14,15] has shown that under conditions of non-radiant heat the main determinant of tolerable work levels is wet bulb temperature. Fig.4 shows that only small differences in wet bulb temperature exist between tolerable and impossible work conditions; large variations in dry bulb temperature at these levels of wet bulb temperatures having small effect.

A question frequently raised by work study technicians is what physiological conditions can be used as a basis for rest allowances in time study. The writer's view is that individual differences between workers are large and that for workers engaged on hot work both acclimitisation and selection of the worker has occurred so that the level tolerated by such workers is higher than for other workers. Only rough indications can be given therefore for rest allowances and the conditions in which they are taken based on statistical average values. Such allowances should preferably allow the workers physiological state to return to a safe level in a similar manner to that first established by F.W.Taylor in his pig-iron leading experiment with 'Schmidt' under temperate conditions: the work of Muller[17] in the realm of muscular effort is important here as it has been shown that the stress (or rather the physiological effect) varies with the way the rest is split up and that Taylor's practice of compelling rest after each work cycle results in the lowest physiological stress. Brouha has shown[18] that hot conditions affect the recovery that is obtained after heavy work Fig.5.

Various figures are available for 'safe' limits of sweating; a limit discussed later is 1 litre/hr. for fit young men working for 8 hours. This figure results in a higher limit than would be suggested by psychological considerations discussed later and it is suggested that 1/4 litre/hr. should be regarded as a maximum industrial figure. For short term (not day long) exposure higher values could be tolerated.

At high sweat levels, unbalance of the body water and salt levels occurs without replacement of water or salt takes place. The intake of water by drinking corresponds closely with sweat and urination loss but salt is also needed as it is lost in sweating and the eating of salt tablets increases the toleration of hot conditions.

Under conditions of extreme radiant heat the skin temperature may rise to values of 45°C and above at which pain nerves are affected and special conditions exist in the breathing passages. It is not intended to discuss these conditions which are partially covered in references 38 and 39.

3. Psychological Considerations

It is a useful convention in discussion to use the terms mind and body but, in practice, psychological and physiological performance or behaviour must be regarded as two aspects of the overall behaviour of the human organism. Psychological behaviour such as the making of judgments of distances, weights and velocities or in reaction to stimuli such as warning signs on gauges is affected by the physiological state of the body. Psychological behaviour is very important where safety, timing and attention is concerned and deterioration of performance often occurs before physiological danger levels.

In considering the effect of heat on psychological behaviour comment is required on the methodology involved. An investigator can ask workers what they consider to be the effects of heat but such reports are a notoriously unreliable indication of performance deterioration. When the numbers involved are large such a method is valid in obtaining such useful temperature scales as 'effective temperature'[26] by which the feeling of equivalence between saturated air at various temperatures and zero air speed is made with unsaturated air at other temperatures and air speeds. However, for most cases in industrial production better indications of the effect of heat stress are obtained by tests such as those used by Mackworth[19]. These tests, some results of which are shown in Fig. 6, show that performance begins to fall off at conditions of 95°F dry bulb/85°F wet bulb which is much below the physiological level of 1 litre/hr. sweat loss which young fit workers can tolerate. An important finding of Mackworth is that performance also falls off at temperatures below a certain level when the subjects begin to complain of feeling cold. Reaction times lengthened as temperatures increased and this is suggestive that accident rates should increase with increased temperature. A multiple reaction time experiment carried out for Fraser and Jackson[20] has been found to give useful indications of the deterioration of psychological performance. All such laboratory tests have face validity but if possible some validation is required for practical cases although this may be difficult to obtain.

4. Overall Industrial Effects

A main difficulty in all research work under industrial conditions is to control the large number of variables (causal factors) that occur. The extension of laboratory work to factory conditions is difficult and any results obtained must be scrutinised carefully to remove bias in interpretation. If data be gathered from a large number of sources over a long time period it is often taken that effects due to various causal factors such as work place design, worker skill etc. will be randomised and therefore cancel each other so that the effects of such factors as heat stress (a. assignable cause) can be determined. Such an assumption requires close scrutiny in all cases.

The work of the I.H.R.B. investigators between the wars is worthy of study in the present context of heat stress. Dr. H.M. Vernon showed[21] as early as 1919 that production varied with monthly average temperature and Vernon and later workers such as Dr. T. Bedford and Eric Farmer showed the effect of heat on production and accident rate in a number of trades including coal mining and glass manufacture[22,23].

Some of the accident results are shown in Fig. 7. An alternative explanation of such curves could, in certain cases, be that there was a substantial correlation between temperature and the accident potential of the work apart from the effect of heat on the worker, but the results shown would be expected from the explanations of laboratory tests.

5. Heat Stress Indices

5.1. General

In deriving a basis for the method study of hot conditions certain indices are required for the strain (effect) on the worker of hot working conditions. Current tables of C.R. (fatigue) allowances used for hot conditions are not helpful in this context for reasons which will appear from this paper. Extracts from three typical tables are given below (24) from the four given in that reference.

SOURCE A	C		D			
When work must be	Freezing below 30°F	0-5%	Humidity			Air
done under trying	Normal $55-70^{\circ}$F	0		N	Exc	Moving
conditions of heat,	High over 85°F	5-10%	Below 30°F	20	25	-
cold, dust, fumes,	High humidity conditions		$30-35^{\circ}$F	5-10	6-12	-
noise, vibrations,	raise allowances towards		$55-75^{\circ}$F	0	5	2
bad light danger	maximum circulating air		$75-100^{\circ}$F	15-40	-	50
etc. add up to 15%.	conditions reduces allow-					
If 15% is found to	ances towards minima.					
be insufficient,	Good ventilation	0				
consider if and how	Poor ventilation	3				
conditions can be	Fumes and/or dust	3-8				
improved.	Use of respirator	8-15				

The terms and the values used in these tables are not in accord with factors known to effect heat stress and it is suggested that such tables be abandoned in favour of a more rational description using certain heat stress indices if a rationalised system based on scientific concepts be required.

Various measuring instruments for temperature have been used by physiologists working in this field[40,41] and have been discussed by F.E. Smith in relation to certain indices[26]. The most widely used index is probably the 'effective temperature' scale originally determined by Yaglou (Yagoglou) for persons clothed in pants only and modified by Drs. Vernon and Bedford to take into account radiant heat conditions. This is shown in nomogram form in Fig. 8. It has been used successfully by Dr. Bedford in controlling shipboard conditions in the Royal Navy. A temperature value on the 'effective temperature' scale is that of the temperature of saturated air at zero air velocity which gives an equivalence of feeling with the measured conditions of non-radiant heat. For conditions of radiant heat, Dr. Bedford introduced the use of the globe (black bulb) temperature reading which replaced the dry bulb temperature required in the original scale. Effective temperature will continue to be used but a difficulty arises in the present context as degrees at various points of the scale are not equivalent and the scale must still be related to effects on the worker and environmental conditions which it is required to alter in order to reduce heat stress.

An extremely useful index is the Predicted Four Hour Sweat Rate (P4SR) developed from a statistical analysis of laboratory experiments conducted by McArdle and his colleagues at the National Hospital, London.[27] This index is determined from a nomogram Fig. 9. There has been verification of this by work at the Tropical Research Unit, Royal Navy in Singapore[28]. The calculation of the P4SR index requires the following quantities to be known:

(a) black bulb (globe) temperature

(b) dry bulb temperature

(c) wet bulb temperature

(d) air speed

(e) metabolic output of the worker

(f) clothing condition - values for two conditions are given viz. that of pants only and overalls over pants.

The nomogram gives a predicted value for the sweat flow when the worker is immersed in the hot environment for 4 hours continuously and from this the probable increase of rectal temperature can be determined. This nomogram has been determined empirically and no regression equation is known for it.

Another useful index, recently developed by Belding and Hatch[29] depends upon engineering concepts of body heat gain. It stems from the development by Haines and Hatch[30] of mathematical equations for

(a) the heat gain of the body from metabolism, radiant heat and convected heat sources (E_{REQ})

(b) the evaporative capacity of the wetted skin of the body (E_{MAX}).

$$\text{The Belding and Hatch Index} = \frac{E_{REQ}}{E_{MAX}} \times 100$$

with the restriction $E_{MAX} \leqslant 2400$ BTUs/hr.

This index is confined to clothing conditions of pants only but otherwise requires the same factors to be known as with P4SR. Its main advantage in the writer's view is that its mathematical form allows mathematical expressions to be developed as a method study basis. It can be determined from the nomogram shown in Fig. 10.

The writer has proposed P4SR as a rational basis for the allocation of fatigue (C.R.) allowances in time study[31] and by extension the Belding and Hatch Index can be used in a similar manner. Such a use requires the determination of objective measurements of the work situation and is more realistic than current fatigue (C.R.) allowance tables as important interaction factors of environmental heat and metabolism are taken into account. The main difficulty in such an application is the determination of a mean basic sweat value throughout the rest and work periods. Probable values of indices that can be taken for an acceptable sweat value is 1 litre for a period of 4 hours for use with P4SR and from heat gain considerations a mean Belding and Hatch Index of 40: these values are proposed tentatively and require validation in industrial situations as many complicating factors arise which are not accounted for in the indices. It is suggested that the main object of work study should be the reduction of stress by method study and in the case of hot working conditions this implies the redesign of the working environment. In some cases even after redesign, heat stress will still occur in which case rest from the hot conditions will be required following a basis such as that proposed.

5.2. Effect of Various Conditions on P4SR.

The measurable quantities enumerated above which are needed for the determination of P4SR have been assigned arbitrary values by the writer to derive curves of P4SR on a systematic basis[31] from the nomogram. Extracts from these are presented in Fig. 11 for conditions where radiant heat is present and it is suggested that in everyday practice practitioners could use such arbitrarily determined charts for use in time study and method study rather than derive values from the nomogram. These curves show the importance of the determination of all the variables especially metabolic rate, wet bulb and black bulb (globe) temperatures which do not normally receive attention by technicians. Eichna's results[15] have already been commented upon as showing the importance of wet bulb temperature on heat stress but the other variables are obviously important.

The use of measured quantities in determining P4SR values is the obvious approach favoured by an engineer to determine the human stress index value but the black bulb, wet bulb and dry bulb temperatures are not independent. Consequently in a method study approach to the redesign of the environment, as opposed to an assessment of the heat stress, it may be necessary to make a restatement of the variables used. This has been done in Fig. 12 in which mean radiant wall temperature and air moisture content have been maintained constant (instead of globe temperature and wet bulb temperature) and these values are compared with a lattice from Fig. 11 - one condition (120°F., 80°F. D.B. and 70°F. W.B.) being made common between the two lattice sets.

5.3. Belding and Hatch Index (B.H.I.)

This index is a rationalised approach to assessing heat stress based on mathematical formulae deduced by Haines and Hatch[30] to calculate the heat gained and lost by the body from the various heat sources. It has been assumed that the skin is completely wetted at a temperature of 95°F and that evaporative cooling of the skin occurs. A further simplifying assumption has been made that the gain of heat of the body derives from

(a) metabolism of the body

(b) heat gained from radiating heat sources in the working environment

(c) heat gained or lost by forced convection of the air flowing past the body.

When equilibrium is attained the heat gained from the three sources is balanced by the heat lost. The Belding and Hatch Index (B.H.I.) is the ratio of heat gain (E_{REQ}) to the evaporative cooling capacity (E_{MAX}) multiplied by 100. This has been reduced to nomogram form, Fig. 9. The mathematical equations for these quantities are

$$\underset{\text{(BTUs/hr)}}{E_{REQ}} = \underbrace{M}_{\text{Metabolism}} + \underbrace{15.5 \times 1.73 \times 10^{-9} (T_W^4 - T_{SKIN}^4)}_{\text{radiant heat gain}} + \underbrace{2\sqrt{V}\,(T_a - T_{SKIN})}_{\text{convective loss or gain}} \qquad \ldots\ldots\ldots\ldots(1)$$

and

$$\underset{\text{(BTUs/hr)}}{E_{MAX}} = 10.3\, V^{.4} (42 - VP_a) \qquad \ldots\ldots\ldots\ldots(2)$$

where M is body metabolism in BTUs/hr

T_W is the mean radiant temperature of environment (°F absolute)

T_{SKIN} is assumed skin temperature ^{o}F absolute ($95^{o}F = 554.6^{o}F$ absolute)

T_a is ambient dry bulb temperature (^{o}F absolute)

VP_a is vapour pressure of air in mms.Hg (N.B. 42 is this value at $95^{o}F$)

V is air velocity in ft/min.

The writer has compared values of this index with P4SR values for assumed arbitrary conditions[32]. This comparison is shown in Fig. 13 which shows the same general trend but that B.H.I. is more sensitive to changes in dry bulb temperature than is P4SR at lower values of wet bulb temperature.

The Haines and Hatch equations involve a simplification of the body conditions and are intended to be for only one clothing condition which is rather atypical of most working clothes, viz. wearing only pants. Nevertheless for engineers required to take action without being able to afford money or time for extensive experimentation. This index allows a relatively simple method study approach to hot working conditions[35]. This approach is helped by the mathematical form of the index, the partial differentiation which, with respect to <u>independent variables</u>, gives

$$\frac{\partial\left(\frac{BHI}{100}\right)}{\partial\ T_a} = 2\sqrt{V} + \left(\frac{BHI}{100}\right) 10.3\ V^{.4}\frac{\delta VP_{SAT}}{\delta T_a}\left(\frac{RH\%}{100}\right) \quad \text{(for constant RH\%)}$$

$$\frac{\partial\left(\frac{BHI}{100}\right)}{\partial\ V} = \frac{\frac{T_a - T_{SKIN}}{\sqrt{V}} - \left(\frac{BHI}{100}\right)\frac{4.12}{V^{.6}}\left\{42 - VP_{SAT}\frac{RH\%}{100}\right\}}{E_{MAX}}$$

$$\frac{\partial\left(\frac{BHI}{100}\right)}{\partial\ T_W} = \frac{.107\left(\frac{T_W}{100}\right)^3}{E_{MAX}}$$

$$\frac{\partial\left(\frac{BHI}{100}\right)}{\partial\ (RH\%)} = \frac{\left(\frac{BHI}{100}\right)10.3\ V^{.4}\left(\frac{VP_{SAT}}{100}\right)}{E_{MAX}} \quad \text{(for constant } T_a\text{)}$$

These equations allow the calculation to be made for the necessary changes in T_a, V, T_W, and R.H. % to change B.H.I. a given amount when

$\dfrac{\partial \frac{BHI}{100}}{\partial\ T_a}$ is written as $\dfrac{\Delta \frac{BHI}{100}}{\Delta\ T_a}$ as a first approximation.

If the environment cannot be changed by redesign then, on a supposition of the worker tending to work at a constant B.H.I. value, the metabolism (physical effort term) must decrease by an amount given by (36)

$$(-\Delta M) = \Delta T_W \quad .107 \left(\frac{T_W}{100}\right)^3$$

in the case of radiant heat relative to a fixed base etc. Such an approach may be helpful in considering seasonal or diurnal variations in conditions such as those shown in the work of Vernon (ref. 21).

6. Method Study Approach

The approach of Taylor and Gilbreth to the study of work was essentially that of redesigning work conditions to reduce the physiological strain on the worker and to minimise unproductive operations and movement. In hot working conditions there is an obvious need for the latter but the physiological stress on the worker can only be partly relieved by applying Gilbreth's techniques in hot conditions.

Heat stress arises in the worker from a number of factors which have been commented on already. For the purposes of method study it is convenient to accept the basic approach of Haines, Hatch and Belding that the human body acts as an inert mass gaining or losing heat from

(a) metabolism

(b) convection

(c) radiation

and subject to evaporative cooling of the skin.

In order to reduce physiological heat stress it is necessary to minimise each one of the sources of heat gain and to maximise the evaporative cooling subject to limitations imposed by chilling. Each one of these factors will now be examined in more detail.

6.1. Metabolism

The body generates internal heat in chemical changes necessary for life. When muscle action occurs either in maintaining posture, in moving the limbs or in doing external work, the glycogen of the muscles is broken down into lactic acid and carbon dioxide, which is released with the generation of some heat. The muscle potential for further work is restored by an oxygenated blood supply to the muscle converting the lactic acid back to glycogen with the formation of further heat (approximately twice that formed in the breakdown of glycogen). The heat generated in this process (the metabolism) varies with the intensity of the work and the training of the worker. Prof. Crowden[33] showed that the metabolism (expressed here in terms of oxygen consumption) depended upon the training of the worker, Fig. 14, and this must be remembered in considering the acclimatisation of all new workers. The metabolic rates of different types of work obviously vary but a useful indication of expected levels is given by Spitzer[34]. The rate can be determined by determining oxygen uptake by the lungs but this requires skilled technicians to take measurements and has limited application for practical purposes in the writer's view. Muller[17] has made useful contributions in this field for workers engaged on heavy work and those interested in the physiological aspects are referred to his papers. In the case of method study the general practice of the Gilbreths is applicable for the reduction of metabolic rate although physiologists do not necessarily accept all the Gilbreth rules. Movement should be generally reduced and especially bending from the waist to pick up objects should be avoided by prepositioning work.

6.2. Convection

Heat is gained or lost by the body when air, hotter or cooler than the body surface, passes over it. This heat transmission is somewhat complicated but Haines and Hatch[30] have derived the expression below (for a worker clothed only in pants) in order to estimate this quantity.

$$\text{Convected heat gain (BTUs/hr.)} = 2\sqrt{V}\,(T_a - T_{SKIN})$$

The value of T_{SKIN} taken by Belding and Hatch is 95°F. which is assumed constant. In practical cases variation of skin temperatures occur over the body and under hot conditions values up to 97°F. occur frequently and such a value can be easily substituted in the equation.

The air speed V is the speed relative to the body and therefore in working conditions involving for instance walking (e.g. fettling openhearth steel furnaces) adjustment will have to be made for wind direction and body movement An accepted time study pace of 3 m.p.h. = 264 ft/min. which is seen to be large in the present context.

T_a is the dry bulb temperature of the air which is that normally spoken of as 'temperature' in present fatigue (C.R.) allowance tables. This temperature will often vary from point to point in the work space. It should be obtained when the thermometer is shielded from radiation effects and some relative air movement to the bulb should be present. In some cases now known in industry temperatures are often taken with the bulb unshielded and to some extent the temperatures obtained are higher than the real dry bulb temperature.

It is a common misconception that blowing air onto a worker is always beneficial. The equation above shows that the body can gain heat from this practice under certain conditions determined by interaction of the convection term with the convective cooling term discussed below.

The main difficulty in using such an expression for the convected heat term is that clothing interferes with convection and further experimental work is required to estimate this effect for practical clothing conditions.

6.3. Radiation

In many industrial processes e.g. glass making, tyre moulding and open hearth furnace fettling, the main source of heat gained by the worker's body comes from radiation effects.

In the developed theory of radiation every body is considered to emit and absorb radiation following the Stefan-Boltzmann law. The amount of energy radiated per unit area varies with the temperature and other conditions of the radiating surface. Such energy is emitted at various wavelengths which for industrial cases occur mainly in the infrared region ($> .8\mu$). Fig. 15 shows typical radiant energy distributions at different temperatures for a 'black body' which shows the temperature has to be very high before any radiation is 'seen'.

The 'black body' conception in heat transfer theory is useful. A black body (not to be confused with colour) is one that emits the maximum possible radiation at a given temperature. It will be seen from Fig. 15 that

(a) an increase in body temperature causes a decrease in the wave length (towards the visible part of the spectrum) at which maximum emission occurs.

(b) an increase in temperature causes increased radiation at all wavelengths

(c) the total energy emission rate is given by the area under the curve.

As visible radiation extends from approximately .4μ (violet end of spectrum) to .8μ (red end) it will be appreciated that considerable radiation occurs in the infra-red region. This radiation causes heat effects but may not otherwise be detrimental to the eyes; examination of the heat tolerance of the eyes is a matter for further examination. Such radiation will be generally absorbed before the retina.

The actual radiant energy emitted from hot surfaces in the industrial environment is dependent upon the area of the emitting surface, its temperature and the emissivity coefficient. The latter is numerically equal to the absorptivity coefficient of the surface and is the ratio of the emissive power of the body to that of a corresponding black body. The emissivity coefficient of actual surfaces does not remain constant with changes in temperature but the following seem to be generally true.

(a) highly polished metals have low emissivities

(b) the emissivity coefficient of most substances increases with increase in their temperatures

(c) most non-metals have high emissivities

(d) the emissivity of any surface varies widely with the condition of the surface.

Typical emissivity coefficients (from Hottel, ref. 42,)are

Surface	at °F.	Emissivity Coefficient
Aluminium, highly polished	440, 1070	.039, .057
Oxidised aluminium	390, 1110	.11 , .19
Rolled plate brass, natural surface	72	.06
Brass oxidised by heating at 1110°F	390, 1110	.61 , .59
Iron and Steel: metallic surface (or very thin oxide layer)		
Iron freshly emeried	68	.242
Smooth sheet iron	1650, 1900	.55 , .6
Iron and Steel: oxidised surface		
Rolled steel sheet	70	.657
Cast plate, smooth	73	.8

Surface	at ^{o}F	Emissivity Coefficient
Tin, bright, tinned iron sheet	76	.043, .064
Linseed Oil layer on aluminium foil:		
Aluminium foil	212	.087
Aluminium plus 1 layer oil	212	.561
Paints, lacquers, varnishes: Snow white enamel varnish on rough iron plate	73	.906
Black shiny lacquer, sprayed on iron	76	.875
Aluminium paints and lacquers: 10% Al, 22% lacquer body on rough or smooth surface	212	.52
26% Al, 27% lacquer body on rough or smooth surface	212	.30
Aluminium paint after heating to 620°F.	300,600	.35
Asbestos board	74	.96

The energy radiated behaves in a similar manner to light waves as to directionality and therefore the energy absorbed by any surface subject to radiation will depend upon the incidence of the waves. It follows therefore that radiation can be screened from the workers in a manner which is being increasingly practised in industry.

The workers clothes and skin have high absorption coefficients approximating to 1 and therefore the radiation effect on the standing worker is given by considering his clothes and skin as a 'black' body. The heat gain is therefore

$$= 1.73 \times 10^{-9} \left(T_W^4 - T_{SKIN}^4\right) \text{ BTUs/hr}$$

for an unclothed worker.

T_W is an integrated mean temperature of the working environment taking into account incidence effects in a manner given by Hottel[42].

In practice a convenient method of determining both T_W and heat stress factors is with the use of the black bulb (globe) thermometer. This gives an equilibrium temperature established between radiant energy impinging on the globe and convected energy following the empirical equation

$$T_W{}^4 \; = \; T_G{}^4 + .103 \times 10^9 \sqrt{V} \;\; (T_G - T_a)$$

where

T_W = mean radiant temperature in $^oF.$ absolute

T_G = black bulb (globe) temperature in $^oF.$ absolute

T_a = ambient dry bulb ' ' ' '

V = air speed in ft./min.

Such an equation applied to the working environment obviously involves simplifications as, for instance, posture (crouching compared with standing erect) in a given environment would involve different radiant energy incidence. The globe (black bulb) temperature needs to be determined after twenty minutes exposure as stabilisation requires that time. This time requirement means that the globe thermometer can only be used when the radiant energy is constant and of a time duration with a minimum of twenty minutes. For durations below twenty minutes, thermopile instruments can be used and readings taken at discrete points to integrate radiant temperature spherically.
This equation is not simple to solve directly and nomograms are available for easy solution. The writer has given values[36] to allow easy solution. Globe temperature enters into all the heat stress indices now used (viz. effective temperature, P4SR and Belding and Hatch Index) so that it has been considered useful to calculate mathematically the required changes needed in either T_W, T_a or V to alter T_G a given amount and this has been done in the equations quoted earlier.

The means open to the technician to reduce the body heat gain from radiant heat sources are three

(a) reducing the temperature of the radiating source by suitable insulation

(b) reducing the emissivity coefficient of the radiating source

(c) use of suitable screens between the workers skin and the radiating source.

6.3.1. Insulation. Processes require a certain working temperature which usually cannot be altered. Insulation of the apparatus saves fuel and this results in another practical saving in that the process can be placed in commission quicker from a cold start than when insulation is not used. Insulation can be either of the conductive type using typically asbestos derivatives, glass fibre etc. or reflection insulation using high purity metal foils (usually aluminium). It is not intended to consider the relative merits of these forms in detail but an important practical point to note is that the foil weight will be lower for the same surface temperature.

6.3.2. Surface Emissivity. The emissivity coefficient of the apparatus surface must be considered. If surfaces are not suitable for insulation the use of aluminium paints (see the previous Table) might be considered as these have low emissivity coefficients. The low emissivity coefficient of high purity metallic foils is worth consideration when surface finishes are considered.

6.3.3. Screens. The simplest form of screen is of wood or metal but this absorbs a large amount of heat and is impracticable for many operations as it impedes the workers. Protective clothing is a portable form of screen which is effective in decreasing the radiation effects on the worker although it may interfere seriously with convective cooling. This clothing may be of two types

(a) conduction insulation such as the well known asbestos suiting

(b) reflection insulation using aluminium foil.

This latter type was originally developed in Germany but is increasing in use and can wholly or partially cover the worker. Miss Slade[37] has reported its use in steel making shown in Fig. 16. It will be appreciated from the previous Table that the heat absorptivity of bright aluminium foil is only some 4 - 5 per cent, the rest being reflected (absorptivity = 1 - reflectivity). In such protective clothing convection cooling is prevented without special measures are taken and therefore exposure times may still have to be limited.

6.4. Evaporative Cooling of the Skin

The body loses heat to the atmosphere by convection and radiation under some circumstances but the chief mechanism is the evaporative cooling caused by moisture absorbed into the atmosphere. This is dependent upon the relative vapour pressure of the moisture at the skin and the atmospheric vapour pressure. A difficulty arises in practice in formulating a reasonable estimate of this cooling because the skin temperature varies greatly over the surface at temperatures below 70 - 80°F dry bulb, being low on the extremities.

At conditions where heat stress occurs the skin temperature does tend to be the same all over the surface and for calculation purposes Haines and Hatch[30] and Belding and Hatch[29] have assumed a value of 95°F. which might be low in many instances especially if the skin be subjected to direct radiation.

In addition the evaporation process is subject to interference by clothes especially if these are non porous (or porous but clogged by grease and sweat.)

Verbal reports from the Institute of Preventive Medicine, Leyden suggest that the Haines and Hatch formulae accord well with calculations using measured rectal temperatures of clothed workers and it is assumed that clothes do not affect the overall picture but merely delay body temperature increase (and decrease).

It follows from the equation for evaporative cooling capacity (E_{MAX}) that such cooling will always take place when the air temperature is below 95°F (saturated) but that it is obviously desirable to maintain low humidity for maximum effect. In practice no air humidity control is exercised in most workshops so that the air moisture content at the work place varies with that in the outside air. The atmospheric conditions at the work place is therefore subject to diurnal and seasonal variations which must be taken into account in any redesign of the workplace.

7. Sequence of Heat Stress Study

In order to study a worker in a hot working environment the following steps are suggested.

1. Make a ratio delay, memomotion or stopwatch study of the work cycle to determine the relative time spent in each working position in which the heat stress index will be different.

2. Determine for each working position with different heat stress index (a) black bulb (globe) temperature: 20 mins. exposure is required and this may be difficult to obtain. Alternative means by thermopile instruments etc. are described by Morpurgo[40].

(b) dry bulb temperature taking care to shield the thermometer from radiation

(c) wet bulb temperature: it is important to maintain a steady airflow over the wet bulb in order to get a true reading.

(d) air speed relative to the workers body, taking into account his movements.

(e) an estimate of metabolic output using Spitzer's tables[34].

3. Calculate a time integral of the heat gain[30], heat gain index[29] or predicted 4 hour sweat rate[26] using data from 1 and 2 above.

4. Apply Gilbreth motion study techniques in order to shorten the work cycle and reduce the metabolic load for the work cycle.

5. Recalculate 3 for the shortened work cycle with reduced metabolism calculated from 4. By examination of this recalculation decide on the particular work positions in which the chief heat gain occurs.

6. Using the formulae for the heat index given above calculate the required changes in T_W, T_a, V and R.H. to reduce B.H.I. by a given amount.

7. Decide on which of the factors in 6 to alter to reduce the stress. In some cases where T_W varies widely during the cycle it may be advantageous to reduce one or more of the other three independent variables (T_a, V and R.H.) as they would generally affect the whole cycle.

8. Alter the workplace by shielding, air ducting etc. in compliance with the decision of step 7, and measure the factors given in step 2.

The procedure outlined in the above steps is rational and depends upon the validity of heat stress indices being applied to industrial workers and this remains to be shown.

It is necessary to comment upon certain aspects of air conditioning in which common faults are often present in work places, in order to better effect lower heat stress.

7.1. Dry Bulb Temperature

Assuming no cooling air conditioning is fitted, the dry bulb temperature at the work place depends primarily upon the atmospheric dry bulb air temperature in a well designed system. As atmospheric temperature is seasonal, allowance will have to be made for possible high summer values occurring and therefore some appreciation of meteorological data is required, to make suitable forecasts.

Air temperature is often increased greatly before it reaches the worker by passage over hot apparatus. This can be obviated by ducting air to the workplace, care being taken to insulate the ducting.

7.2. Wet Bulb Temperature

This depends upon both air moisture content and dry bulb temperature. For a given moisture content, wet bulb temperature increases with dry bulb (1°F increase in dry bulb results in approximately ½°F increase in wet bulb). In cases in practice high wet bulb conditions may sometimes be avoided by ducting air to the workplace and avoiding any ventilating air passing over (through) steam leaks or hot apparatus. Diurnal and seasonal variation occurs with wet as well as with dry bulb temperature and again appreciation of meteorological data is required.

7.3. Shortcircuiting of Air Flow

Although ducting and fans are often installed in workshops, bad siting of the ducting or fans results in the ventilating air passing from air inlet to outlet without passing through the work position. The stagnating air at the workplace increases in temperature to the detriment of working efficiency. In one workshop known to the writer, incoming air at the duct was 56°F and in the workshop generally 80°F although a temperature of 65°F would have been expected if the ducting had been redesigned to give a proper circulation of air.

8. Conclusions

This paper has attempted to present a rational system of study of hot working conditions for work study technicians. The system depends upon the determination of heat stress indices using mainly measurable quantities at the workplace in terms of temperature and airspeed. Such a system of study is an alternative but not a replacement of the conventional experimental physiologists techniques determining various quantities such as rectal temperature, pulse rate, etc. The system proposed does not require co-operation of workers for its operation but care should be taken in applying such a system to the establishment of rest allowances in that the validity of such indices is not established in the industrial situation for such a purpose. If the indices are used for a rest allowance basis then a scaling factor ' may be required. The system discussed should be suitable for method study as in that case relative rather than absolute values are required and such values are given in the system.

9. Acknowledgements

The author wishes to record his thanks to numerous workers in this field especially physiologists for their critical comments. This work derived from research sponsored by the Committee on Individual Efficiency in Industry set up jointly by the Department of Scientific and Industrial Research and the Medical Research Council and financed from United States economic aid.

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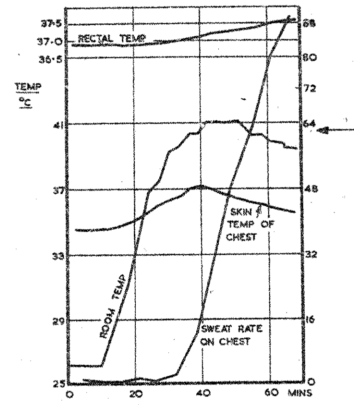


FIG. 1a. ORDINARY SWEATING WITH RAPID RISE OF ROOM TEMPERATURE.

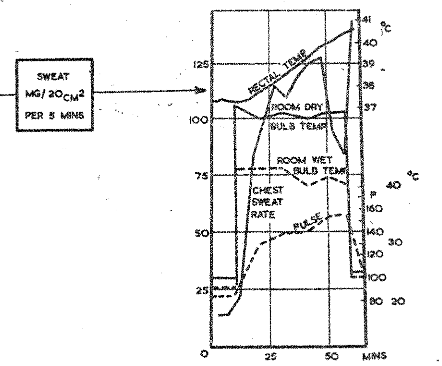


FIG. 1b. SWEATING WITH HEAT STROKE.

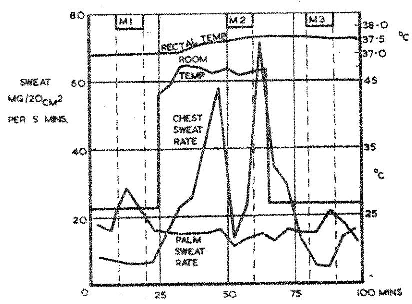


FIG. 2a. SUPPRESSION OF GENERAL SWEATING BY MENTAL ARITHMETIC AT HIGH TEMPERATURE. MENTAL ARITHMETIC GIVEN AT M_1, M_2 & M_3.

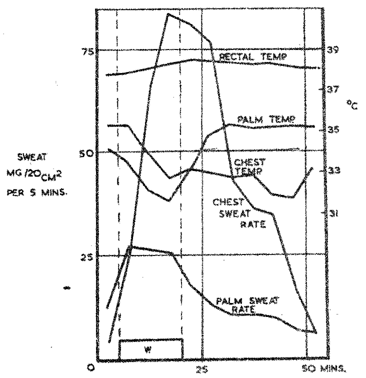
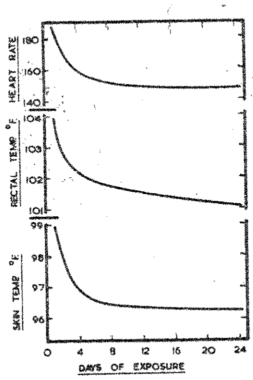
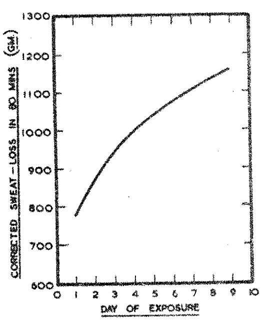


FIG. 2b. SWEATING DUE TO STRENUOUS EXERCISE (W) ROOM TEMP 23·5°C (74·3°F)



(a.) HEART RATE AND BODY TEMPERATURE



(b.) RATE OF SWEATING

FIG. 3. ACCLIMATIZATION TO HEAT.

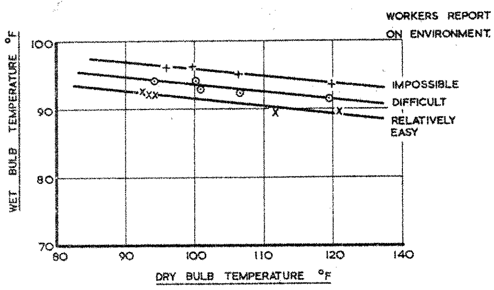


FIG. 4. VARIATION OF DRY & WET BULB CONDITIONS FOR THREE CONDITIONS OF WORK REPORT (FROM EICHNA ET AL)

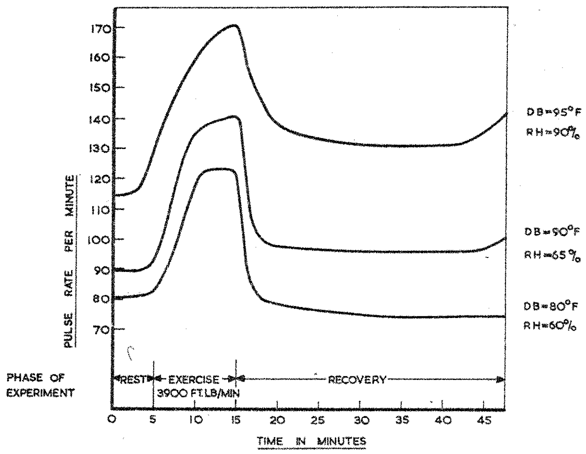


FIG. 5. HEART RATE BEFORE, DURING, AND AFTER A STANDARD EXERCISE FOR VARIOUS ENVIRONMENTAL CONDITIONS.

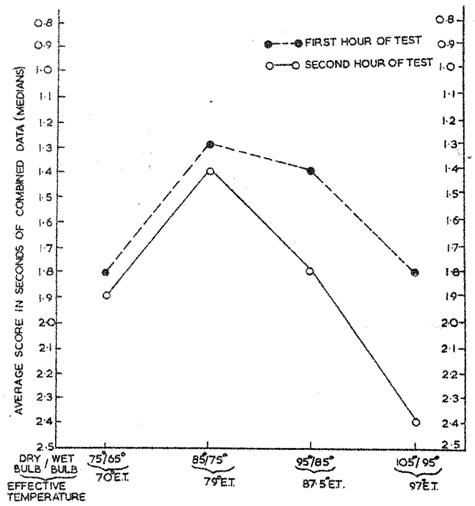


FIG. 6. PERFORMANCE ON CLOCK TEST AT VARIOUS TEMPERATURES. MACKWORTH (19)

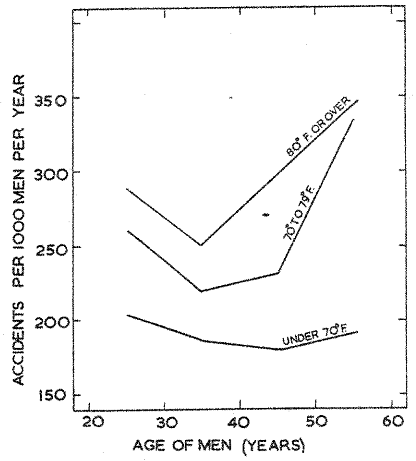


FIG.7. ACCIDENT FREQUENCY RATES OF COAL FACE WORKERS IN RELATION TO AGE & TEMPERATURE OF WORK PLACE (FROM BEDFORD (41))

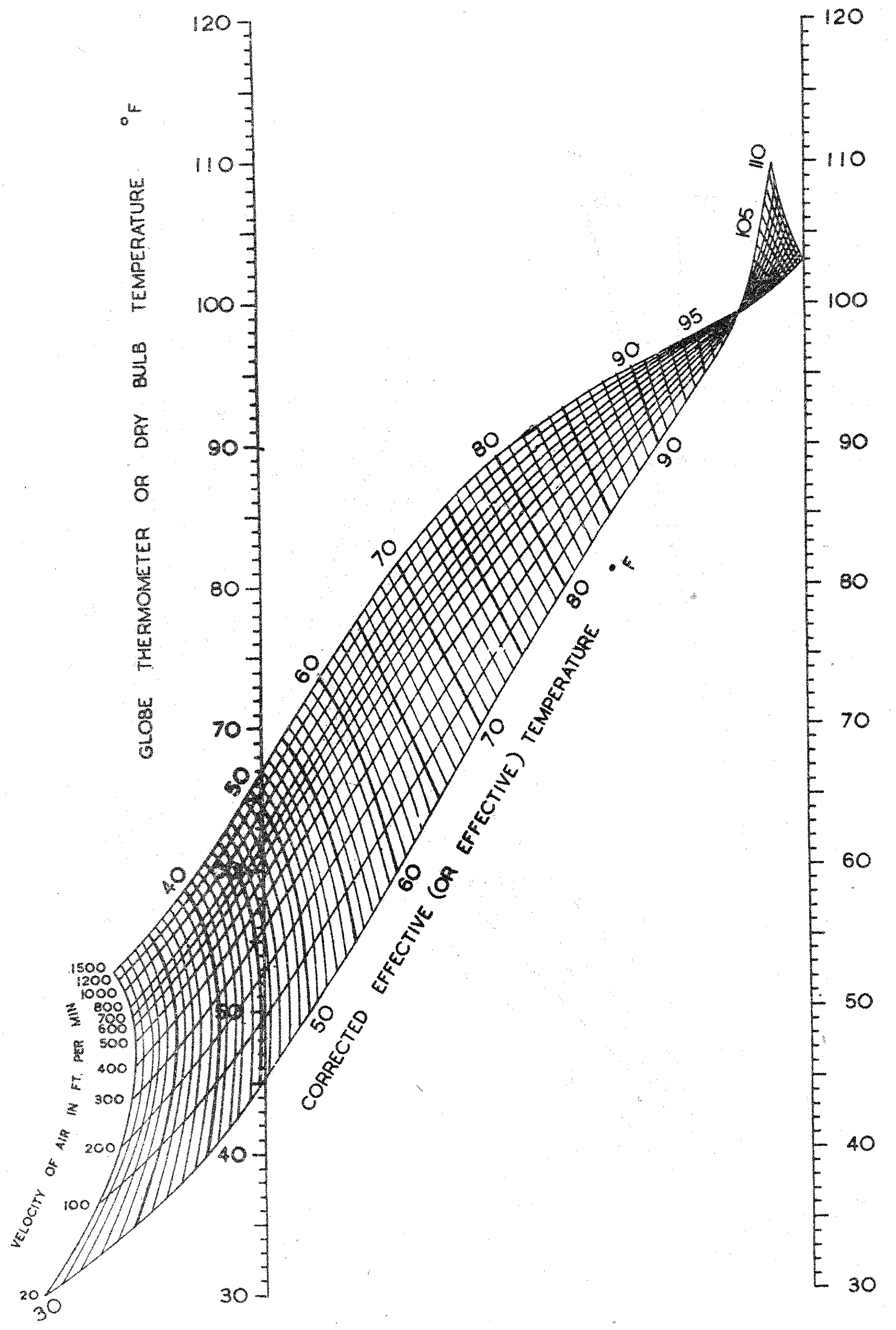


FIG. 8

CHART SHOWING NORMAL SCALE OF CORRECTED EFFECTIVE (OR EFFECTIVE) TEMPERATURE

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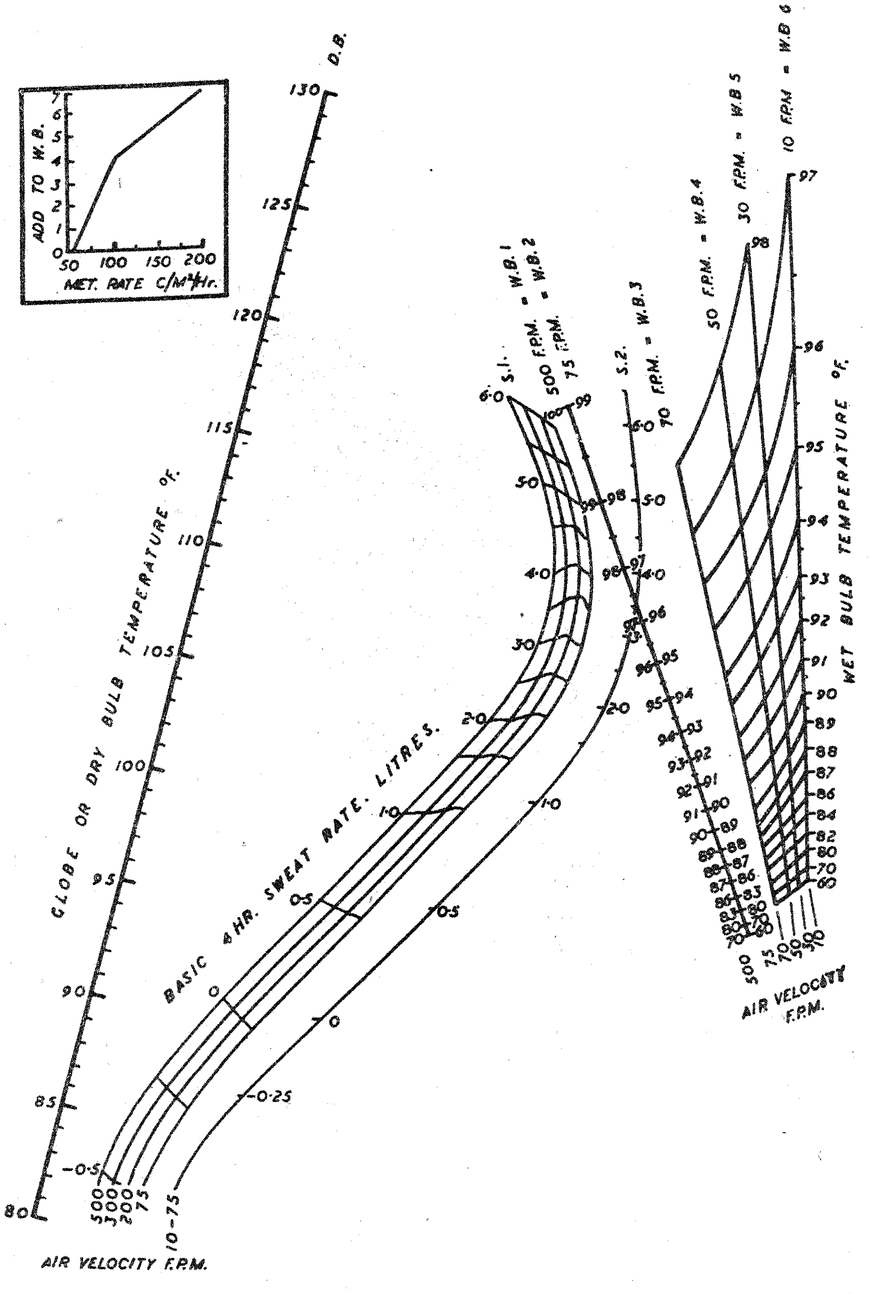

FIG. 9

NOMOGRAM FOR PREDICTION OF 4 HOUR SWEAT LOSS

(Reproduced by kind permission of the Controller, H. M. S. O.
From M. R. C. Memo No. 29)

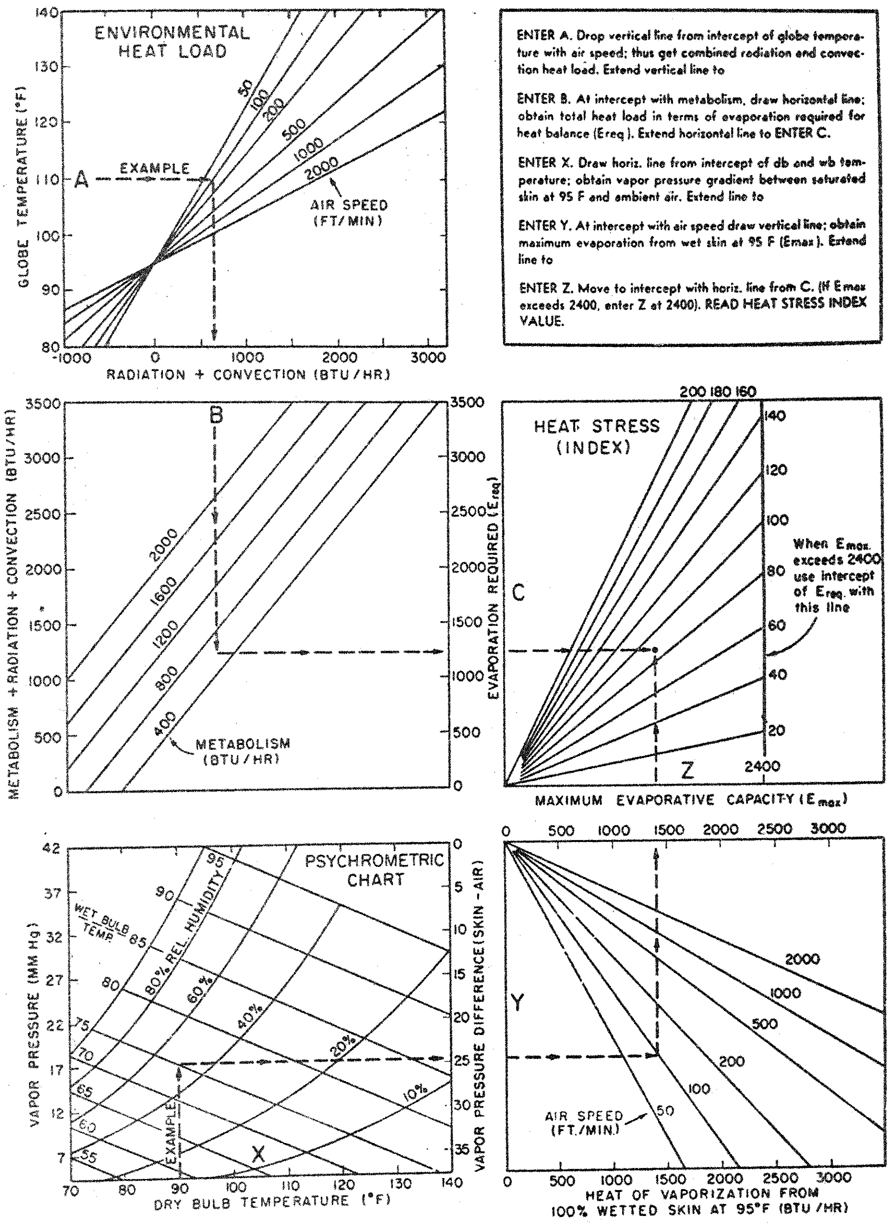

FIG. 10

FLOW CHARTS FOR DETERMINING HEAT STRESS INDEX VALUES

Example: Globe 110, dry bulb 90, wet bulb 75, air speed 100, metabolism 600 (light arm work standing at bench). For solution follow broken lines: Heat stress = 90.

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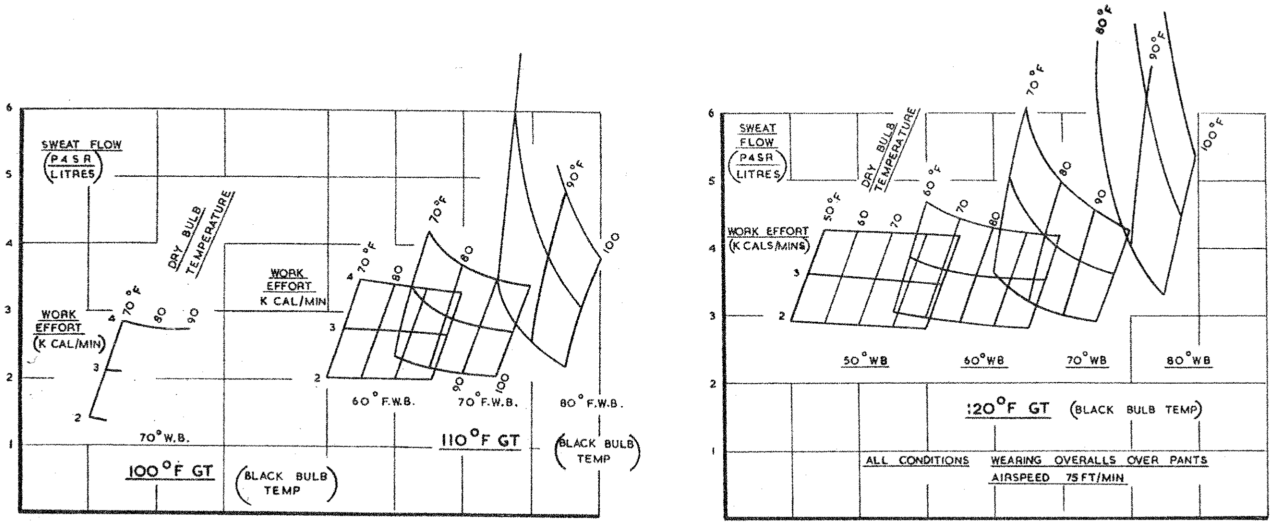
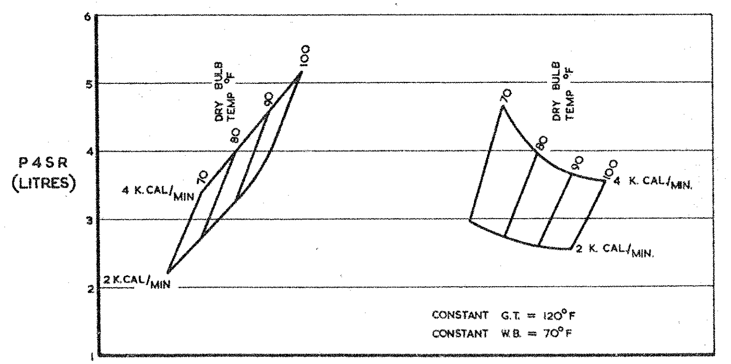


FIG. 11. PREDICTED SWEAT LOSS IN 4 HRS FOR VARIOUS CONDITIONS OF TEMPERATURE & WORK



(a.) VARYING D.B. & METABOLIC RATE
CONSTANT MEAN RADIANT TEMP
CONSTANT MOISTURE CONTENT

(b.) VARYING D.B. & METAB. RATES WITH
CONSTANT G.T. & W.B.

FIG. 12. P4SR CURVES DRAWN FOR TWO DIFFERENT SYSTEMS OF THE VARIABLES
COMMON CONDITIONS 120°F GLOBE TEMPERATURE. 80°F DRY BULB.
70° F WET BULB. 75 FT/MIN PANTS ONLY.

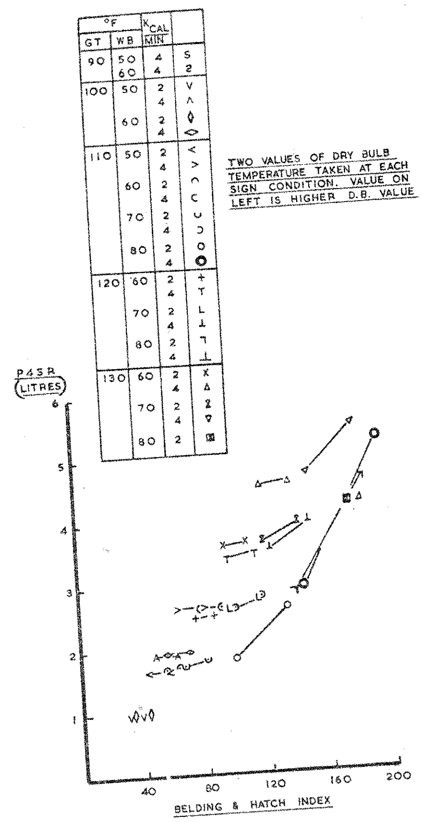


FIG. 13.
CORRESPONDENCE VALUES OF P4SR & B & H INDEX FOR ARBITRARY CONDITIONS.
PANTS ONLY & 75 FT/MIN AIR SPEED.

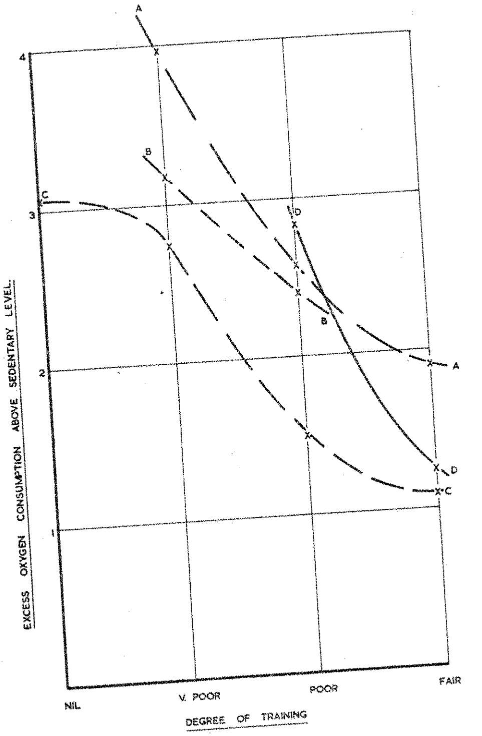


FIG. 14. EXCESS OXYGEN CONSUMPTION FOR BARROW WHEELING WITH VARIOUS WORKERS UNDERGOING TRAINING (FROM CROWDEN (33))

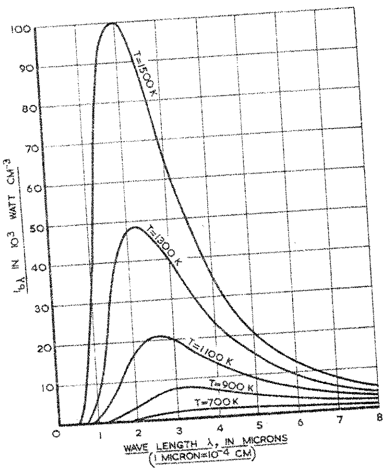


FIG.15. MONOCHROMATIC INTENSITY OF RADIATION FOR A BLACK BODY AT VARIOUS ABSOLUTE TEMPERATURES (PLANCK'S LAW).
(TEMPERATURE ON ABSOLUTE CELSIUS SCALE)

FIG. 16

ALUMINIUM CLAD WORKER

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