TOLERABLE AND DESIRABLE LEVELS OF WARMTH IN WARM CLIMATES, WITH SPECIAL REFERENCE TO THE REQUIREMENTS OF MEN IN THE ROYAL NAVY

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by

F. P. Ellis, O.B.E., M.D., M.R.C.P.

Surgeon Commander, Royal Navy; Late Director, Medical Research Council's Royal Naval Tropical Research Unit, University of Malaya, Singapore

Nine years ago the main theatre of the war at sea moved from the Atlantic, the Mediterranean and Home Waters to the Indian Ocean, the Bay of Bengal and the Pacific. It was more than 130 years since the Fleet had operated in strength against an enemy in tropical waters. The pestilences and nutritional deficiencies of earlier centuries no longer ravaged ships' companies, but excessive warmth between decks was the subject of almost universal comment by those who served afloat in the tropics. This was due to many factors, including the replacement of wooden sailing ships with steel vessels driven by machinery generating great quantities of heat, compartmentation and reductions in ventilation trunking to prevent rapid flooding in the event of damage below the water line, " black-out " restrictions and expanded wartime complements (Ellis, 1948a).

Their Lordships, Commissioners of the Admiralty, were seriously concerned by the possibility that adverse affects on the fighting efficiency of the Fleet might result and they requested the Medical Research Council's Royal Naval Personnel Research Committee to appoint a sub-committee to examine the effects of climate on naval warfare in the tropics. The Chairman of the sub-committee, Surgeon Captain Macdonald Critchley, R.N.V.R., had just completed a survey of naval living and working conditions in the Mediterranean and Eastern Fleets with Surgeon Lieutenant Commander H. E. Holling, R.N.V.R., and their evidence was reviewed in the light of contemporary naval opinion and the experiences of the United States Navy and the Council's Industrial Health Research Board.

The effective temperature charts, recommended for use by the American Society of Heating and Ventilating Engineers (1951), were selected as the most convenient way for describing environmental warmth. A " correction " to them proposed by Dr. Thomas Bedford (1946) was accepted to allow for radiant warmth, by the substitution of globe thermometer temperatures in place of those recorded with the dry-bulb thermometer, when effective temperatures were computed for compartments where radiant heat was likely to cause added thermal stress. The sub-committee's provisional opinion (1944), derived mainly from investigations in temperate parts of the world on men who were exposed to high temperatures for only a part of each day, was that thermal conditions corresponding to an average effective temperature (or corrected effective temperature) of 80°F. constituted the upper desirable level of warmth for compartments in the tropics where men lived and worked continuously, and that inefficiency would have to be accepted when the average effective temperature exceeded 86°F. It was not known, however, whether ships' companies in the tropics, who were exposed continuously to incessant warmth, would be more or less tolerant of high temperatures than the subjects of these earlier investigations.

A second party of observers, including Surgeon Lieutenant Commander Holling, Constructor Lieutenant Commander E. A. Brokensha, R.C.N.C. and myself, was sent to the Eastern Fleet in August, 1944, to measure the thermal conditions afloat and to observe their effects on the men. Surgeon Captain Critchley and the late Professor H. C. Bazett visited Bombay and selected a site for a laboratory where the effects of high temperatures on acclimatised men could be investigated in the tropics, and two groups of civilians and naval workers, led by Dr. Brian McArdle and Dr. N. H. Mackworth respectively, developed suitable techniques for measuring the physiological and psychological effects of excessive warmth at the Medical Research Council's Units at the National Hospital for Nervous Diseases, London, and in the Psychology Department, Cambridge.

By the time Surgeon Captain S. G. Rainsford, Royal Navy, arrived at Bombay to take charge of the tropical laboratory early in 1945, the likelihood of the results of the research being used in the prosecution of the war was becoming remote. He recommended that more ample accommodation should be found near to a Naval Base. The experiments in the tropics were thus postponed until January, 1949, by which time facilities were available at the King Edward VII College of Medicine, Singapore (later the Medical Faculty of the University of Malaya) where a Unit, administered jointly by the Medical Research Council and the Admiralty, was established for studying the problems of men working at high temperatures.

The objectives of this Unit were to investigate the ability of tropically-acclimatised British sailors or soldiers to withstand varying combinations of air temperature, humidity, radiant warmth and air movement whilst they were wearing different types of clothing and doing various kinds of work; to compare the acclimatisation levels of "naturally-acclimatised" men on the Far East Station and of "artificially-acclimatised" men who took part in the earlier experiments in England; to examine the predictive accuracy of an index, based on sweat losses, constructed by the team at the National Hospital for comparing the physiological effects of different warm environments; to assess the value of the effective temperature scale when it was used for the same purpose; to test the globe thermometer with other instruments for measuring radiant warmth and to check by experiment Bedford's theoretical correction to the effective temperature scale; to determine the effects of warmth on the efficiency with which work was done and on thermal comfort; and lastly to define

TABLE I

AVERAGE THERMAL ENVIRONMENT IN ELEVEN SHIPS OF THE EASTERN FLEET (1944)

	COMPARTMENT CONDITIONS				
	Norm. eff. temp. (°F.)[1]	Dry bulb temp. (°F.)[1]	Wet bulb temp. (°F.)[1]	Air speed (ft./min.)[2]	Obs.
Messdecks	84·0	90·0	82·0	100	947
Machinery-spaces	88·7	102·7	87·7	468	359
Gunnery-control positions	86·5	95·5	84·2	172	364
Gun-turret lower quarters	86·6	91·9	84·9	60	125
Radar Offices	86·9	97·7	83·8	160	59
Electrical spaces	89·5	104·7	82·6	147	81
Workshops	87·5	100·3	83·7	193	55
Sick Bays	83·0	90·9	82·1	239	82
Communication offices	85·8	95·9	83·9	163	168
Galleys	87·4	97·5	84·2	192	168

[1] To convert °F. to °C., subtract 32 and multiply by 5/9.
[2] 1 foot = 30·5 cm.

TABLE II

RADIANT WARMTH BETWEEN-DECKS IN THE EASTERN FLEET (1944)

Mean effective temperature (E.T.), corrected effective temperature (C.E.T.), and mean radiant temperature (M.R.T.).
Ranges in brackets

COMPARTMENTS	E.T. (°F.)	C.E.T. (°F.)	M.R.T. (°F.)	Obs.
Engine rooms	88·6 (77·4—99·0)	90·3 (79·0—101·0)	129·0 (103·0—170·0)	116
Boiler rooms	86·4 (75·0—93·9)	87·8 (77·5—94·3)	119·6 (103·0—154·0)	59
Gearing rooms	87·5 (80·2—93·8)	89·3 (80·0—95·0)	108·4 (86·0—128·0)	62
Electrical spaces	89·3 (84·5—92·0)	90·3 (86·0—92·7)	114·8 (93·0—145·0)	50
Galleys	87·2 (73·0—101·0)	89·9 (74·0—106·0)	130·0 (93·5—187·0)	125
Workshops	87·4 (82·8—96·0)	87·1 (83·7—97·0)	107·7 (96·0—138·0)	36
Radar compartments	85·4 (78·0—92·5)	86·6 (79·0—93·9)	100·6 (89·0—136·5)	73
All compartments of all ships	87·4 (73·0—101·0)	89·1 (74·0—106·0)	118·9 (86·0—187·0)	519

the upper tolerable and desirable levels of warmth for men engaged in different occupations in the compartments of warships in tropical waters (Ellis, 1950). Work on these lines was continued until the end of January this year.

The Conditions Between Decks

The average thermal conditions under which men lived and worked in 11 ships of the Eastern Fleet in 1944 are shown in Table I. The average temperature in the living spaces lay between the " upper desirable " and " upper tolerable " effective temperatures of 80 and 86°F. whilst in many compartments the latter limit was exceeded and at times to a very marked degree (Ellis, 1947). Radiant heat added further to the burden of the workers in some compartments, so that the average corrected effective temperature for the compartments in which this was investigated was nearly 2°F. above the effective temperature (Table II). The upper limits of the range of conditions observed were excessively severe by any contemporary standards. These climates may now be considered in the light of what we know about the upper tolerable levels of warmth.

THE UPPER TOLERABLE LEVELS OF WARMTH

State of knowledge before the 1939-1945 War

Even in the time of John Hunter the ability of the human animal to withstand high temperatures aroused considerable interest. In 1775 Dr. Charles Blagden described to the Royal Society how he, Sir George Home, Lord Seaforth, Mr. Dundas and Dr. Nooth were exposed by a Dr. George Fordyce to temperatures above 240°F. without sustaining ill-effects, when they were either clothed or stripped to the waist. Although an egg was " roasted " in 20 minutes and a steak was over-cooked in 30 minutes in the same compartment, Blagden endured the climate for eight minutes and remarked that evaporation of sweat was the sole agent keeping his body cool (Blagden, 1775b). He also mentioned experiments by M. Tillet, reported in 1764, in which girls who had been used to attending ovens " bore for 10 minutes temperatures which could raise Fahrenheit's thermometer to 280°F.", and others by Mr. Hunter, who had found that " a carp preserved a coat of fluid water around him long after the rest of the water had been congealed by a very strong freezing mixture," which he submitted as evidence for the generation of heat by living organisms (Blagden, 1775a). Recently Blockley and Taylor (1948) investigated for the United States Air Force the consequences of failure of the cooling arrangements for the cabins of supersonic aircraft, and added to this story. Two men at rest, wearing cotton-and-wool union suits, tolerated a very dry atmosphere of 240°F. for over 20 minutes. At Singapore we have observed that heat-acclimatised young men, wearing naval overall suits, at rest can withstand almost completely saturated air at the temperature of the body (99°F.) when convective, radiant and evaporative cooling can no longer occur—for periods ranging from one and a half to upwards of four hours, provided they have a plentiful supply of cool drinking water. In a less saturated but warmer atmosphere, with a dry-bulb temperature of 130°F. and a wet-bulb temperature of 105°F. only two out of a group of nine men tolerated the conditions for more than half an hour and even they had to retire within an hour (Ellis, Lind and Newling, 1953). The Navy, however, was not usually concerned with such severe environments or such short exposures as these. Information was required first on the ability of ships' companies to survive and work efficiently in the gradually increasing humid warmth of warships closed down for action, and second on the effect on comfort and health, and therefore on efficiency, of living for many months in a warm climate.

This problem is not new. Over a century ago Reid (1844) interpreted the relative significance to human comfort of air temperature, humidity and air movement with an accuracy which accords closely with our ideas to-day. Sixty years later, J. S. Haldane (1905) concluded from experiments, performed on himself and colleagues in a Cornish tin mine and at Oxford, that the wet-bulb temperature of the air was the most reliable thermal measurement with which to assess the tolerability of an atmosphere, and that the upper endurable limit of warmth for lightly-clad resting men in England was a wet-bulb temperature of 88°F. with moderately good air movement (150ft./min). He found that the limiting wet-bulb temperature was lowered by eight or 10°F. by heavy work, and added carefully " practice may increase to some extent the limit which can be tolerated."

Some years later the Effective Temperature Scales were constructed at the Research Laboratory of the United States Bureau of Mines at Pittsburgh (Houghten and Yaglou, 1923, 1924 ; Yaglou and Miller, 1925). Trained observers, passing between two controlled-climate rooms, identified varying combinations of dry- and wet-bulb temperatures with relative humidities which gave rise to the same subjective sensations of comfort. " Equal comfort lines " for " still air " fitting the corresponding dry- and wet-bulb temperatures in the two rooms were superimposed on a standard psychrometric chart. The effects of higher air velocities were then investigated and alignment charts were constructed for determining the " effective temperature," which related the effect of different combinations of temperature, humidity and air speed to the temperature of " still " and saturated air at which the same effect on thermal comfort would be experienced. Clothing reduces the effect of air movement ; so a " normal " scale was constructed for people wearing ordinary indoor clothes and a " basic " scale for those who were stripped to the waist. Furthermore it was found that changes in body temperature and pulse rate also corresponded more closely with variations in effective temperature than with dry- or wet-bulb temperature alone, which suggested that this scale could be used as an index of physiological effect as well as a comfort index (Houghten and Yaglou, 1923 ; Vernon and Warner, 1932). The limiting conditions to which men might be exposed without sustaining serious ill-effects were said to lie between effective temperatures of 90°F. if they were at rest and 80°F. if they were engaged in heavy work (Yaglou, 1926). If the temperature of the surroundings exceeded the air temperature, Bedford (1946) suggested that when these charts were used the globe thermometer temperature should take the place of the dry-bulb temperature to allow for the added effect of radiant heat.

Studies in London during the 1939-1945 War

During 1944 and 1945 McArdle and his colleagues in London observed the physiological effects on man of a wide range of warm climates.

Individual differences between the naval ratings and soldiers who were the subjects of the experiments were eliminated beforehand as far as possible by daily work at high temperatures for at least two weeks, and during the experiments they were exposed to hot-room conditions 6 days a week so that their level of acclimatisation was maintained. A dummy ammunition-handing exercise which had been carried out by the Fleet observers in one of the main gun turrets of H.M.S. Howe off Trincomalee was repeated under the same climatic conditions in London and the results suggested that the "naturally-acclimatised" ships' companies in the tropics were less able to withstand work at high temperatures than the "artificially-acclimatised" men in London, even when the intoxicating fumes of "live" cordite were not permitted to confuse the picture (Benson, Colver, Ladell, McArdle and Scott, 1945a ; Ellis, 1947).

They confirmed Haldane's (1905) observation that if the speed of air movement was increased from a still condition to one of moderate movement in hot, humid conditions the upper tolerable wet-bulb temperature could be raised by several degrees (Dunham, Holling, Ladell, McArdle, Scott, Thomson and Weiner, 1946), and they evolved an empirical nomogram from which the "predicted four-hour sweat rate," a numerical measure of the stress imposed by a given climate, could be ascertained, provided that the energy expended in the work, the clothing worn and the air temperature, humidity and air speed were known. They suggested that conditions which corresponded to a predicted four-hour sweat rate of 4·5 kg. should be accepted as the "upper limit for fit acclimatised young men above which an increasing number would find the conditions beyond their endurance" (McArdle, Dunham, Holling, Ladell, Scott, Thomson and Weiner, 1947). Combinations of dry- and wet-bulb temperatures which correspond to this for men at rest or engaged in moderate activity are shown in Table III and Fig. 4. This index of climatic effect is still on trial.

TABLE III

THE UPPER ENDURABLE LEVELS OF WARMTH DEFINED* FROM EXPERIMENTS ON MEN WORKING AT HIGH TEMPERATURES BUT LIVING IN A TEMPERATE CLIMATE

(Fit young men wearing overalls will find the conditions beyond their endurance during a 4-hour exposure when the average air speed is moderate (150 ft./min) and they are either "working" (average energy expenditure 111 kcal./m²/hr.) or sitting at rest (average energy expenditure 54 kcal./m²/hr.).)

DRY-BULB TEMP. (°F.)	93	95	100	105	110	115	120	125	130
Corresponding limiting wet-bulb temp. (°F.) for "working" men ..	90·5	90·3	90·2	89·8	89·5	88·3	86·4	81·2	*
Corresponding limiting wet-bulb temp. (°F.) for "resting" men	—	*	95·9	95·7	95·6	95·5	95·0	94·4	91·8

* by McArdle *et al.* (1947).

Studies at Singapore between 1949 and 1952

During the first two years at Singapore four groups of naval ratings were exposed to similar conditions to those used in the London experiments (Dunham *et al.*, 1946). The men in the first two groups were only exposed to the test conditions once every three or four days in an endeavour to preserve their natural level of acclimatisation to the tropics. In subsequent experiments the subjects were acclimatised intensively beforehand with a similar routine to that used in London and were then exposed each day ; and finally 32 tropically-acclimatised seamen from two operational frigates were investigated, each man on two occasions only, to find out whether there were differences between the reactions to heat of men living in ships in the tropics and of the laboratory-trained subjects who lived on shore in Singapore or in London.

In these experiments each subject either sat at rest or performed a set task which consisted of stepping on and off a 12-inch stool in time to a metronome in a room in which the air temperature, humidity, air speed and mean temperature of the surroundings were controlled and recorded, and his ability to withstand the climate was assessed by intermittent observations of his body temperature, heart rate, sweat loss, clinical condition and working efficiency.

Nearly 1,700 individual experiments were completed. Although there were differences in detail which were sometimes of importance, in general the physiological reactions to work at high temperatures of artificially-acclimatised young men exposed to warm working conditions every day in London and those of naturally-acclimatised young men exposed twice weekly to warm conditions in Singapore were found to be very similar. If anything, the Singapore men were less heat-tolerant under these experimental conditions than the men in London (Adam, Ellis, Irwin, Thomson and Weiner, 1952). Provided the effective temperature was used correctly, the first series of experiments showed that it predicted the physiological effect of warm conditions nearly as well as the London workers' new stress index.

The examination, by my colleagues Mr. R. Morley Jones and Dr. R. K. Macpherson, of the results of the subsequent experiments is not yet complete but, so far, it indicates that for short exposures to work at high temperatures many of the conclusions to be derived from the study of heat-acclimatised subjects in England are broadly applicable to heat-acclimatised men working at high temperatures in the tropics either in ships or on shore. On the other hand, Dr. J. S. Weiner (personal communication) has repeated the Singapore experiment on ship-acclimatised men at Oxford to show that completely unacclimatised men in England are less heat tolerant than any of these groups.

The second two years' work at Singapore was devoted to investigating the effects of radiant heat and of varying the rates of work or the arrangements

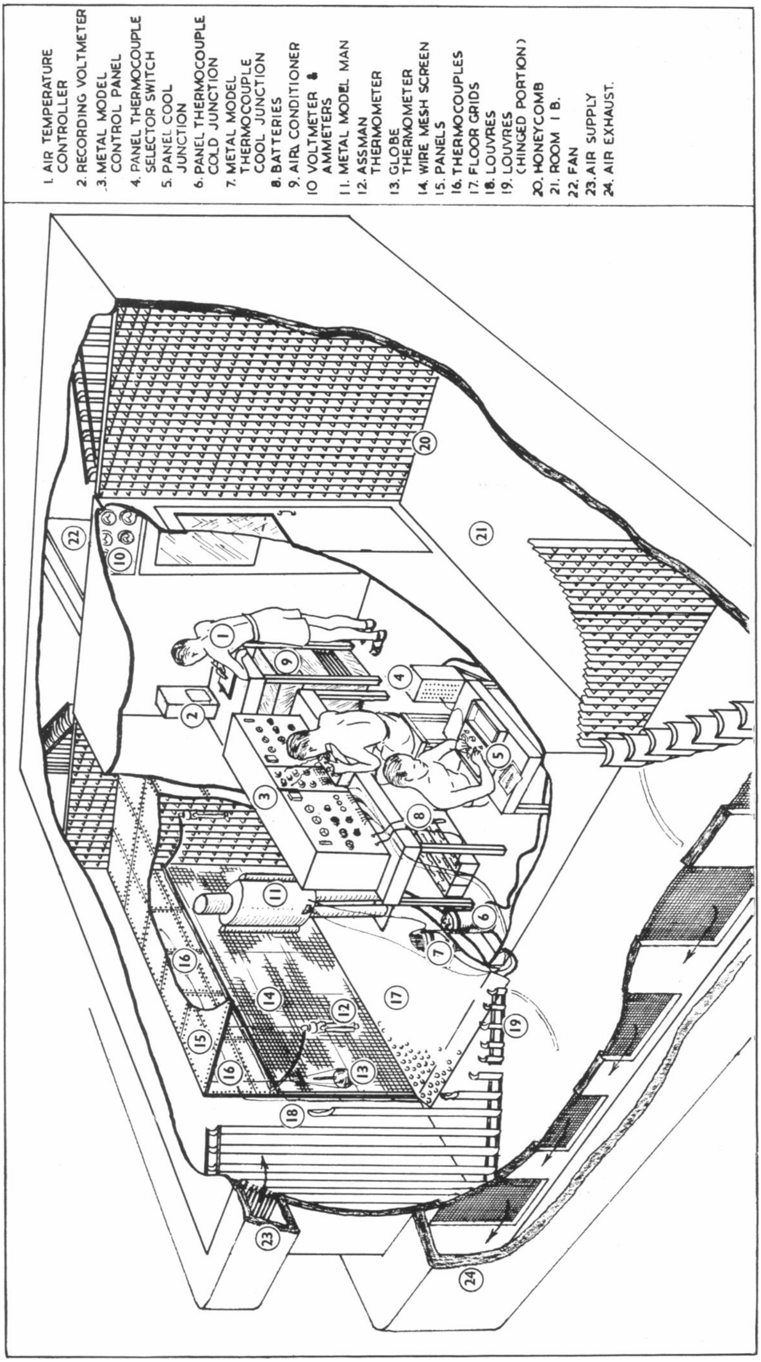


Fig. 1 Measuring the mean radiant temperature in the radiant heat tunnel with the metal models.

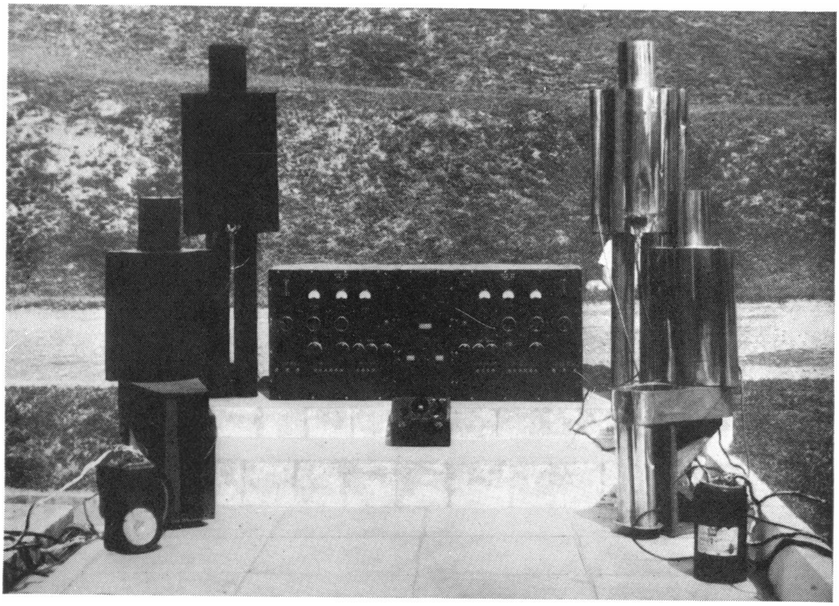


Fig. 2. " Seated " and " standing " metal models for measuring the amount of heat a man will absorb in a given position in the radiant heat tunnel.

of work, and to identifying the levels of warmth at which heat incapacitation occurs. A radiant heat tunnel, built at the Royal Naval Dockyard at Chatham to the specification of the Royal Naval Personnel Research Committee's Heat Radiation Panel (Smith, Underwood, Hickman and Griffiths, 1949) was installed in the wind tunnel in the larger of the two " hot rooms " at the Unit (Fig. 1) and a device, also built at Chatham to the design of Dr. Ezer Griffiths of the National Physical Laboratory, which consisted of life-sized metal " men " (Fig. 2) with different radiation emissivities, was provided to measure the amount of radiant heat a man was likely to absorb under different test conditions. One pair of " men " were highly polished and reflected about 80 per cent. of the radiant heat incident on them ; the other pair were matt black and absorbed about 90 per cent. They were each fitted internally with heaters and with fans to circulate the air and it was possible to record their mean surface temperatures with thermocouples soldered to their internal surfaces. By measuring the amount of heat which had to be put into a polished " man " to bring its surface temperature to that of a black " man " it was possible to estimate the amount of radiant heat which a man of that size in that position would absorb under the test conditions, for the human body behaves virtually as a black body when exposed to long wave-length radiations. These metal models enabled my colleague

Mr. P. S. B. Newling to compare the mean radiant temperatures derived with the nomograms constructed by Bedford (1946), from the air temperature, globe thermometer temperature and air speed, with mean radiant temperatures, determined directly with the metal models, and calculated from the recorded surface temperatures of the 70 panels which comprised the radiant heat tunnel and of the other surfaces to which a man in the tunnel was exposed. The values obtained in these three ways agreed closely, which provides support for the continued use of the globe thermometer for the assessment of the stress imposed by radiant heat.

Although radiant heat has quite a profound effect in increasing sensations of bodily warmth under comfortable or relatively cool temperature conditions, under excessively warm conditions even large differences between the mean radiant temperature and the air temperature do not add very greatly to thermal stress. Increasing the mean radiant temperature of the surroundings by 39°F. when the air temperature was 115°F., the wet-bulb temperature 90°F., and with a moderate degree of air movement (150ft./min), had approximately the same overall effect on men who were well hydrated as causing them to wear naval overalls on top of their shorts (Ellis, Ferres, Lind and Newling, 1953). Under these severe conditions men were much better off when they worked stripped to the waist and so gained maximum benefit from evaporative cooling than when they wore overalls, despite the fact that the latter provided partial protection against radiant heat.

An anonymous report from the American Society of Heating and Ventilating Engineers to the United States Navy (1943) states " the effect of radiant heat on physiological reactions decreases as the effective temperature increases." This is not confirmed by a series of experiments in rather less strenuous climates carried out by Macpherson and the physiological team at Singapore. A further observation that the effect of radiant heat is " surprisingly small as the upper limits of endurability are reached " is supported by the Singapore results, but it is only the effect of radiant heat relative to the effect of the other thermal factors which decreases, not the absolute effect. Radiant heat in ships is not such a serious menace as at one time it was feared it might be. This series also provides substantial support for Bedford's (1946) correction to the effective temperature scale. There are inconsistencies, but these lie in the use of the effective temperature scale as an index of physiological stress rather than in Bedford's correction to it.

In another investigation, Captain R. H. Fox, R.A.M.C., Mr. A. R. Lind and Miss Helen Ferres have shown, with men marching at different speeds on a treadmill, that, provided the average amounts of energy expended in different kinds of work are the same over a given period and the work is within the physical capabilities of the workers, the strain imposed by the work will be similar even though the durations and the arrangements of the working and resting periods may be different. This

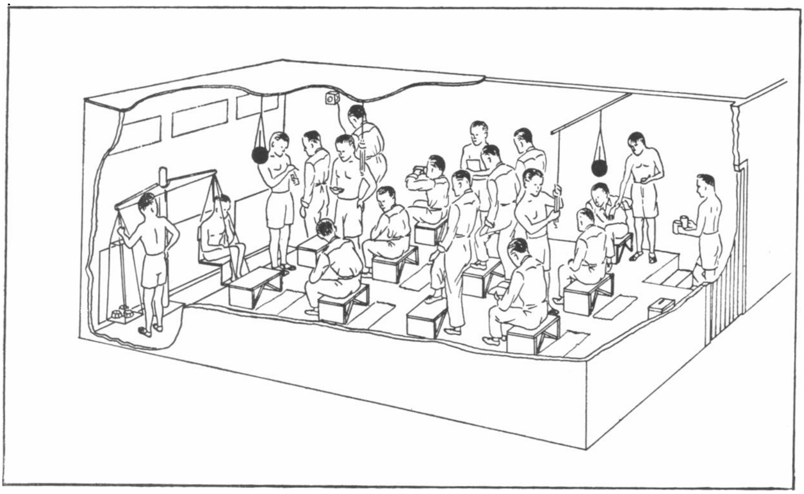


Fig. 3. The upper tolerable levels of warmth. Twelve men under observation.

is of considerable importance as a standard "working" routine* involving alternate periods of rest and step-climbing was employed in many of the experiments carried out in London and at Singapore ; and it was desirable to establish that the strain imposed by this routine would be similar to that imposed by other types and arrangements of work entailing the same average energy expenditure.

The last experiments in this series were designed to identify the levels of warmth at which some or all of a group of men would be incapacitated even though they were highly acclimatised and trained to work at high temperatures (Ellis *et al.*, 1953). After 14 days acclimatisation and training in a hot wet atmosphere (dry-bulb 100°F., wet-bulb 94°F.), 11 soldiers were exposed to different climates every other day wearing naval overalls and doing the work* which had been done by the subjects of the previous experiments (Fig. 3). A moderate degree of air movement—150ft./min—was maintained in all the experiments. The climates at which all of them survived, one to three were incapacitated or five or more had to retire, are plotted on the psychrometric chart shown in Fig. 4. The "upper endurable" dry- and wet-bulb temperature combinations estimated for heat-acclimatised men working under the same conditions in London (Table 3) are also shown and are about 2°F. wet-bulb temperature below the levels at which some of these heat-acclimatised soldiers were observed to be incapacitated in Singapore. In other words, with uniform air movement, work and clothing, there is not very much difference between the incapacitating levels of dry- and wet-bulb temperature

* "Resting" 10 minutes, stepping on and off a 12in. stool 12 times per minute for 30 minutes, resting 30 minutes, "step-climbing" 30 minutes, resting 30 minutes, step-climbing 30 minutes, resting 1 hour, step-climbing 20 minutes.

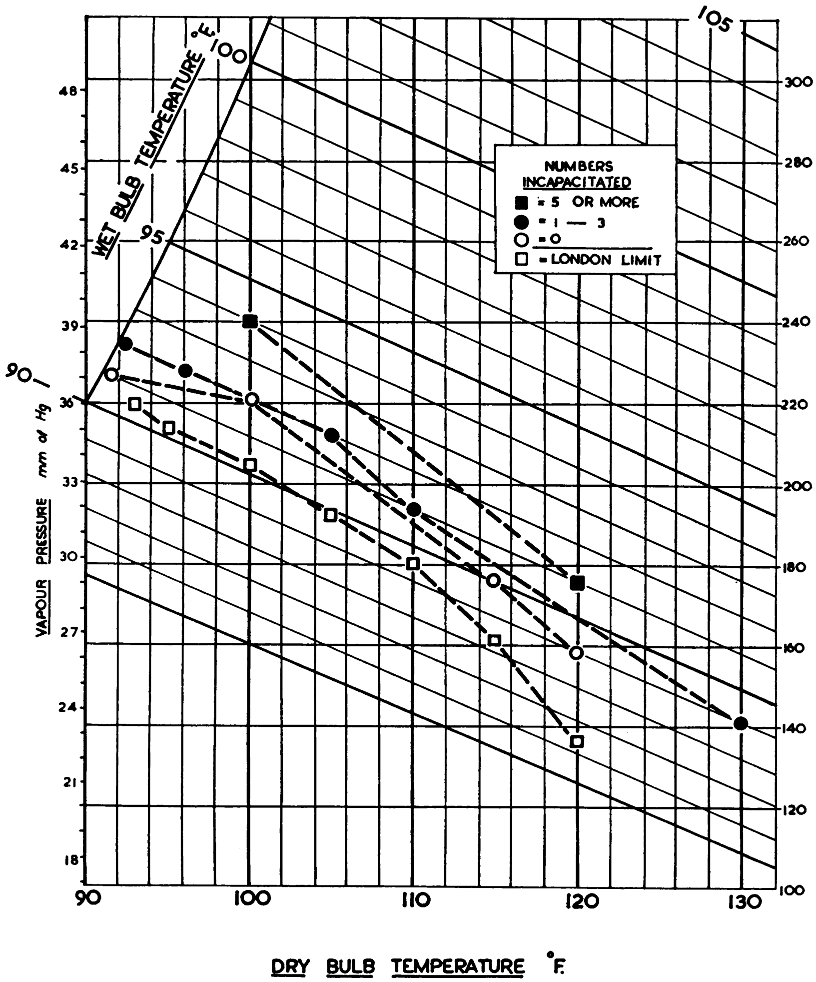


Fig. 4. Numbers (out of 11) of tropically-acclimatised young men working in overalls in Singapore (100 kcal/m²/hr) who were incapacitated by different climates (mean air speed 150ft./min) and corresponding "limiting conditions" estimated for "fit acclimatised young men" in London (P4SR = 4·5 kg.).

for men trained to do similar work at high temperatures whether they work in London or in Singapore. At these critical levels of warmth only small variations in the wet-bulb temperature are necessary to turn a "work-climate" situation which can be tolerated with comparative ease into a condition which none can withstand.

The effects of repeated exposure to conditions such as engine-room personnel must tolerate when they are working in "two-watches" at action stations in wartime were also examined. The subjects worked for four hours in an atmosphere with a dry-bulb temperature of 115°F. and a wet-bulb temperature of 87°F., with a moderate air speed (150ft./min) and a mean radiant temperature of 132°F. They then rested for four hours in an atmosphere similar to that of a warm mess deck (dry-bulb 98°F., wet-bulb 84°F., effective temperature 86°F.). The experiment was continued throughout a 24-hour period in which the subjects were exposed alternately to these conditions. They did not become noticeably less heat tolerant as a result of this experience, although there was a diurnal variation in the levels of their body temperatures, but excessive fatigue due to lack of sleep and repeated work, and probably aggravated by the warm environment, overshadowed all other effects.

These observations only apply to healthy young men who are acclimatised to the tropics, accustomed to working at high temperatures and not salt deficient, and to the working conditions described. The experiments in London showed that if they had worked stripped to the waist the upper endurable level of warmth would probably be raised by an amount corresponding to about 3°F. rise in wet-bulb temperature (Benson, Colver, Ladell, McArdle and Scott, 1945b) and on the other hand that if the air movement was reduced from a moderate to a still or stagnant condition the threshold would be lowered by a similar amount or even more (Dunham *et al.*, 1946). If the mean radiant temperature exceeded the air temperature appreciably this would also lower the tolerable threshold to some extent.

The evidence available from a limited number of experiments and from the earlier investigations in London suggests that the limiting wet-bulb temperature for human activities will be raised by 4-5°F. for a given air temperature if those exposed remain completely at rest instead of carrying out the moderate amount of work which was customary in these experiments.

The amount of cool water (70°F.) men can drink influences not only the amount of sweat they produce and the increment in their body temperatures (Ellis, Ferres and Lind, 1953), but it is also related closely to the length of time for which they can withstand excessively warm humid conditions (Ellis, Lind and Newling, 1953). In addition the more men sweat and drink the more salt is washed out of their bodies and the more necessary it is to supplement their salt intake. A supplement of one gram of salt (as sugar and enteric-coated tablets) for each kilogram of sweat lost during experiments was sufficient to keep our subjects in salt balance during eight weeks of daily experiments at high temperatures but was probably not enough when they were exposed repeatedly to excessively warm conditions in the same day.

Salt appears to be the only solute in sweat identified so far which the body cannot afford to lose without replacement. In temperate climates the water-soluble vitamin B complex and ascorbic acid are known to be eliminated in the sweat of men who work in warm atmospheres, but the total amounts are usually less than the urinary losses (Nutrition Reviews, 1945). Professor J. W. H. Lugg of the University of Malaya examined sweat produced by several acclimatised colleagues and myself in Singapore whilst we were working at high temperatures. The amounts of thiamin and ascorbic acid detected by him were very small and insufficient to justify, on the grounds of losses in sweat alone, the practice of supplementing the daily vitamin intake of those who engage in continuous work at high temperatures in the tropics (Lugg and Ellis, 1953).

DESIRABLE LEVELS OF WARMTH

Information is also required on the levels of warmth at which ships' companies can live a reasonably comfortable existence and maintain reasonable standards of efficiency and health.

The effects of warmth on comfort

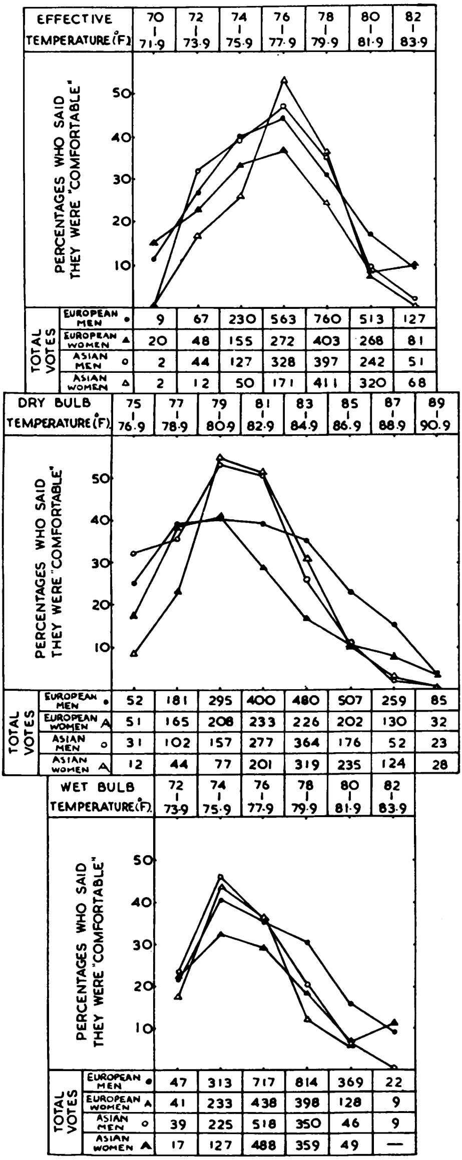
A survey was carried out to determine the thermal comfort zone for acclimatised European men and women and Asian men and women who were engaged in sedentary or light indoor occupations in Singapore, where the air temperature rarely falls below 70°F. or exceeds 90°F. (Ellis, 1953a). The largest proportion of opinions that the climate was " comfortable " rather than " cool " or " warm " were recorded by European and Asian men and women when the effective temperature was between 76°F. and 78°F. (Fig. 5) ; and provided the effective temperature was above 73°F. and below 78°F. over 80 per cent. of European men and women were reasonably comfortable (Fig. 6).

Comfort in Singapore is achieved by the average person at rather warmer climatic levels than in more northerly latitudes, probably because less clothing is worn and seasonal or diurnal variations in temperature are less marked.

Another 5,000 opinions were collected from naval ratings on the mess-decks of an aircraft-repair ship operating between Singapore, Hongkong and Japan over a rather wider range of temperature conditions (Ellis, 1952a). The comfort zone was very similar to that for the Singapore men but as a group the less well-acclimatised naval ratings were rather less tolerant of uncomfortably warm conditions.

The effects of warmth on skill

The effects of warmth on skill were investigated for unacclimatised young men who had passed the enlistment tests for the United States Navy before America entered the last war (Houghten, Stacey, Urdahl and Watt, 1942). Adverse effects were not observed when the effective temperature was 73°F. or 80°F., but efficiency was reduced when it was raised to 87°F. At Cambridge, towards the end of the war, Mackworth (1950) used tests based on the work of radar operators, gun crews, wireless operators and transmitting station watch-keepers and concluded " There is a critical



EFFECTIVE TEMPERATURE (°F)	70–71·9	72–73·9	74–75·9	76–77·9	78–79·9	80–81·9	82–83·9
TOTAL VOTES: EUROPEAN MEN ●	9	67	230	563	760	513	127
EUROPEAN WOMEN ▲	20	48	155	272	403	268	81
ASIAN MEN ○	2	44	127	328	397	242	51
ASIAN WOMEN △	2	12	50	171	411	320	68

DRY BULB TEMPERATURE (°F)	75–76·9	77–78·9	79–80·9	81–82·9	83–84·9	85–86·9	87–88·9	89–90·9
TOTAL VOTES: EUROPEAN MEN ●	52	181	295	400	480	507	259	85
EUROPEAN WOMEN ▲	51	165	208	233	226	202	130	32
ASIAN MEN ○	31	102	157	277	364	176	52	23
ASIAN WOMEN △	12	44	77	201	319	235	124	28

WET BULB TEMPERATURE (°F)	72–73·9	74–75·9	76–77·9	78–79·9	80–81·9	82–83·9
TOTAL VOTES: EUROPEAN MEN ●	47	313	717	814	369	22
EUROPEAN WOMEN ▲	41	233	438	398	128	9
ASIAN MEN ○	39	225	518	350	46	9
ASIAN WOMEN △	17	127	488	359	49	—

Fig. 5. Relation between votes recorded by European men and women and Asian men and women who were " comfortable " and 2°F. variations in " effective," dry- and wet-bulb temperatures.

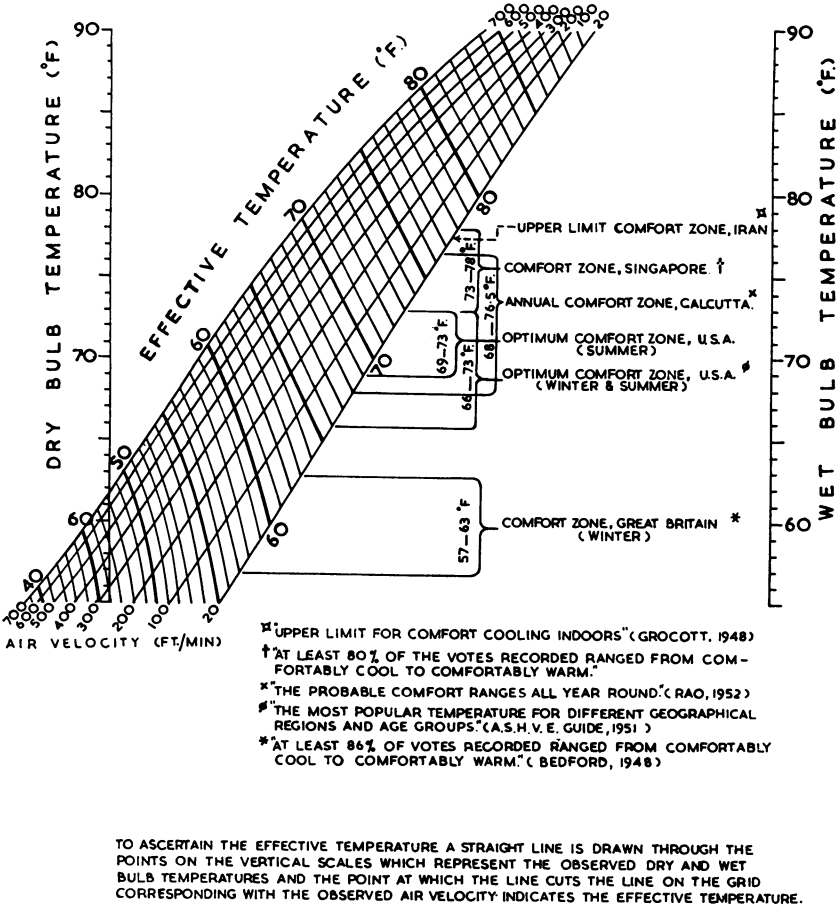


Fig. 6. Comfort zones for different parts of the world.

region on the room temperature scale above which most acclimatised men dressed in shorts will not work so accurately or sleep restfully. This region lies between the effective temperature readings of 83°F. and 87·5°F., that is to say between dry-bulb/wet-bulb readings of 90/80°F. and 95/85°F. when the air movement is 100ft./min. This conclusion is believed to apply to all forms of work both physical and mental." He used the " normal " chart to obtain these effective temperatures rather than the more appropriate " basic " chart for men stripped to the waist according to which the approximate effective temperatures for the conditions he describes are 81°F. and 86°F. In the aircraft-repair ship mentioned above, only 10 per cent. of the ship-acclimatised men were uncomfortably warm when the effective temperature was 78°F. but 97 per cent. were uncomfortably warm when it was 85°F., which suggests that for sedentary persons the onset of thermal discomfort and deterioration in efficiency may be associated.

Experimental techniques similar to those used by Mackworth were employed by my colleague Mr. R. D. Pepler (1951) at Singapore to examine the effect of high temperatures on the performance of men accustomed to living in the tropics. He confirmed that deterioration in performance might occur as environmental warmth increased within the temperature zone identified by Mackworth ; but the range of climates over which maximal efficiency could be maintained for two or three hours varied widely with the ability, training and motivation of the subjects, and the energy cost and the difficulty of the work.

The evidence available supports the contention that ventilation standards based on comfort criteria are consistent with the maintenance of efficiency by the average sedentary worker when he is on watch as well as with his comfort when he is off duty. It is not clear, however, why efficiency falls off as the warmth of the atmosphere increases. Mackworth and Pepler were unable to find a direct relationship between lowered efficiency and a rise in body temperature. There is no evidence that there is a direct effect on the central or peripheral nervous systems at the levels of warmth at which significant reductions in efficiency occur. It might be due partly to the distractions or changes in incentive associated with thermal discomfort or sweating. How far the diversion of blood flow to the periphery to aid in heat dissipation and the resultant reduction in the blood supply to the brain may be factors which contribute to drowsiness and difficulty in concentration is not known, but this would seem to be a logical sequence of events. It is even more problematical whether or not reduced efficiency may be in part a side effect of essential endocrine adjustments, particularly for unacclimatised persons introduced suddenly into a warm climate. It is established that men work less efficiently as the warmth of the atmosphere increases beyond certain critical levels for different forms of activity, but the physiological and psychological explanations of this deterioration require further consideration.

The effects of warm climates on health

During 1944 ill health, as revealed by naval attendances at the sick bay, was shown to be nearly twice as great in the ships of the Eastern and British Pacific Fleets as it was in the cooler naval establishments on shore (Ellis, 1947, 1948b). Working days lost because of sickness were doubled or trebled when ships joined the Eastern Fleet from the Mediterranean or Home Fleets. During the first year after the war ended—1945-1946—the minor sickness incidence in tropical waters was more than double the incidence in northern and temperate waters, and the incidence of skin disease was increased three to four times (Fraser Roberts, 1948). The Naval sickness returns for the year 1948-1949 have been analysed by Mr. F. E.

Smith and Mr. C. R. Underwood in relation to variations in the average air temperature on deck and reveal that the percentages of men with minor complaints increase steadily as the average midday air temperature on the upper deck exceeds 80°F., which corresponds approximately to an increase in the average messdeck effective temperature above 80°F. (Ellis, Smith and Underwood, 1953). Without air conditioning, the effective temperatures encountered between decks in the tropics will exceed 80°F. more often than not. It is not surprising that the syndrome which has been described as hot-climate fatigue or tropical fatigue becomes increasingly apparent as service afloat is prolonged under these conditions (Ellis, 1952b, 1953b), and the ability of some men to withstand warm atmospheres may be impaired further by unrecognised salt deficiency or widespread damage to the sweat glands by prickly heat (Ladell, Waterlow and Hudson, 1944; O'Brien, 1947).

UPPER TOLERABLE AND UPPER DESIRABLE LEVELS OF WARMTH

We have suggested tentatively, on the basis of the data which have been examined so far (Adam *et. al.*, 1952) and in terms of the National Hospital stress index, that the " upper tolerable " levels of warmth, to which it is reasonable in everyday practice to expose men in the same state of acclimatisation as that of the Singapore subjects, are those for which the predicted four-hour sweat loss for different combinations of climate, work and clothing is 3·5 kg., although the majority of acclimatised men can withstand warmer conditions for a few hours. In warships, however, men in hot spaces work two or sometimes three four-hour watches every 24 hours, and may continue with this routine for many days on end. Between watches they retire to cooler, but frequently unduly warm, messdecks to recuperate. Many men are older, less healthy or less well acclimatised than the fit young volunteers for these experiments. Their work may be more strenuous, more monotonous or more mentally exacting than the most monotonous or exacting experimental situations which can be contrived in a laboratory. In action, anti-flash hoods and gloves and lifebelts are a clothing burden which our subjects did not have to tolerate. So we suggested that the upper tolerable levels of warmth to be allowed for by design under action conditions in ships should not exceed those for which a four-hour sweat loss of 3·0 kg. is predicted. Effective temperatures corresponding to these conditions are shown in Table IV for men carrying out moderately active work.

The general recommendation that effective temperatures or corrected effective temperatures exceeding 86°F. are unacceptable for compartments where men live and work is supported by the evidence of these physiological and psychological experiments, and the view that effective temperatures above 80°F. are undesirable in the tropics is supported by the evidence of the comfort surveys and the examination of the minor sickness incidence; although there would seem to be some justification

TABLE IV

UPPER TOLERABLE LEVELS OF " EFFECTIVE TEMPERATURE " FOR YOUNG EUROPEAN MEN ENGAGED IN MODERATE ACTIVITY (111* kcal/m²/hr.) IN THE TROPICS WHICH CORRESPOND TO AN UPPER TOLERABLE " PREDICTED 4-HOUR SWEAT RATE " OF 3 KILOGRAMS.

Mean Air Speed (ft./min)	Men Wearing Overalls†				Men Wearing Shorts†			
	Effective temperatures corresponding to a P4SR of 3 kg. and dry-bulb temperatures (°F.) of				Effective temperatures corresponding to a P4SR of 3 kg. and dry-bulb temperatures (°F.) of			
	90	100	110	120	90	100	110	120
20	87·7	88·8	87·2	—	89·1	90·5	90·5	—
100	88·2	89·9	88·5	—	—	91·5	92·2	—
300	—	89·2	84·8‡	—	—	91·0	91·2	—

*The observed energy cost of the same working routine was 111 kcal/m²/hr. in London but only 100 kcal/m²/hr. in Singapore, a difference which has not been explained entirely satisfactorily yet. The P4SR's here were calculated for 111 kcal/m²/hr., and would be slightly less for 100 kcal/m²/hr.

†The higher basic effective temperatures for men wearing shorts emphasises that the normal and basic scales are not interchangeable.

‡This unlikely figure is probably due to an error in the construction of the P4SR nomogram over the range of the lower wet-bulb temperatures.

for lowering the upper desirable levels of effective temperature from 80°F. to 78°F.

The climatic conditions which occur between decks in warships under cruising conditions in the tropics are often unduly warm but will not cause serious heat-incapacitation amongst acclimatised ships' companies provided reasonable precautions are exercised. Heat incapacitation is more common amongst unacclimatised men in troopers or other ships passing to, or through, the tropics from temperate waters. The experimental evidence suggests that in action men with work which requires skill, mental alertness and intelligence are less efficient in the tropics than they are under cooler conditions unless they work in air-conditioned compartments ; although it is hard to gauge the relative importance of climatic factors when men have the incentive of fighting for their lives. Those engaged in work which involves the expenditure of energy much above the resting value will certainly succumb first.

A satisfactory comprehensive system for describing the effects of the thermal environment on man has yet to be discovered and the search for this is continuing. Until this is available the effective temperature will probably be the most convenient to use for the majority of purposes. The dry- and wet-bulb and globe thermometer temperatures, the estimated air speed, the clothing, the type of activity and the duration of activity for those in a compartment should be stated as well in reports on undesirably warm working conditions.

Less is known about the effects of warm climates on women. According to Drysdale (1950) the comfortable levels of warmth for women in Sydney are higher than those preferred by the men. In Singapore, European women, residents of six months to two years duration, tended to feel rather warmer under similar conditions than European men or Asians (Ellis, 1953a). Yaglou and Messer (1941), however, found that in a relatively still atmosphere in an air-conditioned room in Boston the comfortable levels of warmth for very lightly-clad sedentary men and women in the same state of acclimatisation were almost the same. If differences in clothing, activity, acclimatisation and age can be eliminated there is probably little difference in this respect between the two sexes. M. Tillet's (1764) observation on kitchen girls suggests that women may tolerate extreme warmth equally as well as most men but this should be investigated further.

The effects on different races are also understood incompletely. In Singapore acclimatised European men and Asian men are reasonably comfortable at similar levels of warmth when they are engaged in sedentary occupations. In a preliminary hot room study Asians (two Indians and one Malay) were found to be more tolerant of work in climates which were not very different from the normal Singapore climate than British naval ratings (6), but they were less heat tolerant than the sailors in hot dry atmospheres (Adam, Ellis, and Lee, 1953). The most striking differences between the two groups were the very much lower sweat losses and chloride losses of the Asians under similar climatic and working conditions. Ladell (1950a and b) and Weiner (1949) have shown that naturally acclimatised Nigerians and Bantu in Africa are not usually more tolerant of warm atmospheres than the artificially-acclimatised Europeans investigated at the National Hospital during the war, and those who have not been down mines are less tolerant, but Wyndham, Bouwer, Devine, and Paterson (1952) have found recently that it is possible to acclimatise Bantu so that they become even more heat tolerant than the National Hospital subjects were.

When the effects of climate on human beings are estimated, differences in levels of acclimatisation and in the levels of training of groups of people are probably more important than differences in either sex or race; and variations between the individuals of each group may be of greater importance than differences due to their race, sex or level of acclimatisation. There are wide gaps to be filled in the information available concerning the effects of high temperatures on men and women in the different age groups, on infants, children and the aged; and the long-term effects of life in an unduly warm climate, which have not been discussed here, will require considerable systematic investigation before the effects of climate alone can be distinguished clearly from the effects of the numerous other environmental factors which may differentiate life in the tropics from life in more temperate or colder parts of the world.

Finally, we may consider briefly whether the techniques of climatic research have applications in the practice of surgery. The need for an operating theatre cap which will prevent sweat from dripping off a surgeon's brow aroused discussion in the medical press recently. Here, surely, an attempt is being made to deal with an effect rather than a cause. Mackworth found that the skill of young naval ratings, who were stripped to the waist and engaged in sedentary work, deteriorated when the effective temperature was between 81°F. and 86°F. It would seem not unlikely, if his conclusions can be applied to other working situations, that the heavier clothes and rubber boots worn by a surgeon and his staff, interference with their respiratory exchanges by close-fitting impermeable masks, warmth radiated from the powerful operating theatre lamps, the exacting work, the mental strain and the long hours may lower this critical effective temperature level for surgical teams to a level which may be encountered not infrequently in operating theatres.

The last edition of the Guide of the American Society of Heating and Ventilating Engineers (1951) also reminds us that " Little is known about optimum air conditions for maintaining normal body temperatures during anaesthesia and the immediate post-operative period." It is for serious consideration whether a climate which is too warm for the surgeon is not at times imposing undesirably warm and possibly harmful conditions on the unconscious patient underneath the operating towels. Professor Stammers (1953) drew attention only last year to the dominating influence of variations in climate, terrain and communications in the choice of treatment for war wounds, and to the impact of a tropical climate on surgical practice. This all leads one to consider whether or not the elucidation of some of the climatic problems of surgery might not be assisted by more detailed studies than have been made in the past of the thermal environment of surgeons, anaesthetists and nurses and of their patients, in the operating theatre and in the wards, and not only in parts of the world where extreme climatic conditions are encountered but also in the so-called temperate zones. At least, investigations similar to those which are helping in the clarification of this naval problem could do no harm; they might assist in the design of operating theatres and hospitals to meet the requirements of the patients and of the staff, or help hospital engineers to make the best use of the equipment with which they are provided; they would certainly provide valuable additions to the brief chapter in the story of man and his thermal environment to which I have referred here.

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