

THERMAL COMFORT IN WARM, HUMID ATMOSPHERES

OBSERVATIONS IN A WARSHIP IN THE TROPICS

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(With 7 Figures in the Text)

An accurate knowledge of the climates which are reasonably comfortable for persons residing in the tropics is a requisite of the air-conditioning engineer, for these are the target conditions which he aims to produce in an air-conditioned office or dwelling. The thermal comfort sensation also provides a useful yardstick for assessing the effects upon a man of his total thermal environment, when he is not exposed to those conditions which impose severe stress.

The American Society of Heating and Ventilating Engineers (1950) concluded as a result of laboratory investigations that in the United States the optimum 'effective' temperature indoors in the summer ranges, according to geographical situation, from 69 to 73° F. for persons engaged in sedentary or light activities and wearing ordinary clothing. The 'effective' temperature expresses the combined effects of air temperature, humidity and air movement on human sensations of thermal comfort in terms of the temperature of still and saturated air at which equivalent sensations of warmth are experienced. An effective temperature of 73° F. within a compartment would thus cause the occupants to experience the same thermal comfort sensations as they would experience in still air with a temperature of 73° F. and saturated with moisture. A 'normal' chart for determining effective temperatures when persons are lightly clothed and a 'basic' chart for use if they are stripped to the waist have been constructed from observations on subjects passing between 'climate-controlled' rooms at the Society's Laboratories (Houghten & Yaglou, 1923; Houghten & Yaglou, 1924; Yaglou & Miller, 1925; Houghten, Teague & Miller, 1926; Houghten & Teague, 1928). Both charts apply to men engaged in a light occupation.

On the other hand, Bedford (1936) has found that the comfort zone for women factory workers during an English winter lies between effective temperatures of 57 and 63° F. In considering thermal comfort zones for persons in the tropics it was expected that new standards might have to be accepted. This was suggested by the laboratory studies of Mom, Wiesebron, Courtice & Kip (1947*a, b*) at Bandoeng in Java, which enabled them to reconstruct the effective temperature charts for tropically acclimatized persons. The effective temperatures obtained from their new charts were rather higher than those obtained with the same temperature conditions and air velocities from the charts produced in America, and when the air velocity was increased from a still condition to about 100 ft./min.—from an imperceptible condition to a barely perceptible condition in a warm

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climate—a greater increase in comfort was perceived by their subjects than the American effective temperature chart predicted. They attributed these effects to differences in clothing and acclimatization.

One objective of the research work at this Unit is to define the upper level of warmth at which persons exposed for a few hours may become less efficient, either mentally or physically, when engaged in different forms of activity. It has been suggested that there might be little difference between the temperature conditions at which a man is most efficient and those at which he is in thermal equilibrium with his environment and enjoying optimum thermal comfort (Ellis, 1950). If these optimum levels of warmth could be established for the average person by the simple process of asking sufficient numbers of men whether they are comfortable or not, recording their replies on an appropriate scale and measuring the temperature conditions in the compartment at the same time, this would provide useful corroborative evidence for the results of laboratory experiments, and information which could be brought into line with similar data derived for those who design ventilation systems in temperate climates.

Two investigations have been completed in a large aircraft-repair ship on passage from Singapore to Hongkong and on a double passage between Singapore and Japan. At the times of year chosen for the observations the ship was passing between the tropics and a relatively cooler zone. Thus it was possible to observe the subjects under different climatic conditions ranging from those which were too cool to those which were too warm. The first investigation was carried out when the ship's company had been in the tropics for 6 months, and the second investigation was carried out 6 months later, when four-fifths of the subjects were men who had participated in the first investigation.

METHOD

Observers visited the mess-decks where the stokers and the seamen, and in the first investigation the air petty officers, lived. The visits were made at the time of the mid-day or evening meal. About fifty comfort vote slips (as shown below), with pencils, were distributed by one observer on each mess-deck for the men to fill in. The coding of the comfort sensations was that adopted by Bedford (1936, 1948). The fourth question was omitted from the forms used in the first investigation and the numbers of men stripped to the waist were counted at each visit.

Whilst the forms were being completed and collected another observer measured the dry- and wet-bulb temperatures at eight different positions in each compartment and the mean temperature was ascertained. Globe thermometer measurements showed that there was no substantial difference between the average mean radiant temperature and that of the air within the compartments, except in the close vicinity of steam-pipes. Air movement around the mess-tables was measured with a silvered katathermometer (cooling range 130–125° F.). Nearly all the subjects were stripped to the waist when the investigations commenced.

The use of the effective temperature scale was appropriate in these experiments on healthy acclimatized young men wearing scanty clothing in a warm climate, where radiant heat was of little importance and very low air velocities were rarely

experienced. The basic scale was used in the first experiment when more than 50 % of the men were stripped to the waist during a mess-deck visit, and in the second experiment when a man indicated on his form that he was stripped to the waist. Otherwise the normal scale was employed.

Comfort vote slip

Compartment Name Date

I. Put a cross against the words which describe your sensation of comfort in relation to the temperature conditions in this compartment at the present time

1. Much too warm	
2. Too warm	
3. Comfortably warm	
4. Comfortable	
5. Comfortably cool	
6. Too cool	
7. Much too cool	

II. Put a cross in the following table against the line which describes most accurately the air movement you feel whilst answering these questions

1. 'Still Air'. No movement perceptible	
2. Slight air movement. Only just perceptible	
3. Moderately good air movement. Easily perceptible. Gentle breeze	
4. Very good air movement. Highly perceptible. Strong breeze	

III. *Perspiration.* Are you wet with perspiration on your face or chest at the time of answering this questionnaire?

IV. *Clothing.* Are you stripped to the waist?

RESULTS

From these two investigations 1829 and 3382 replies were suitable for analysis after a number had been excluded because of interference with the conditions when a number of the subjects had to wear blue winter uniform after arrival at Hong Kong and when the mess-deck ventilation, which was maintained otherwise at a constant level, was curtailed while the ship was passing through the fringe of a typhoon on the return journey from Japan.

The climate on the upper deck during the first trial consisted of an initial warm spell lasting about 4 days when the dry- and wet-bulb temperatures varied between 82/79° F. and 78/76° F., followed by 3 days of cooler weather when the temperatures were approximately 10° F. lower. The second trial commenced and ended with warm periods in tropical waters similar to the initial period of the first experiment,

and 9 days of cooler weather were experienced in Japanese waters during the middle period when the average dry- and wet-bulb temperatures on deck were 69/62° F.

Comfort

The replies obtained in the first investigation were sorted and tabulated to show the percentages of votes for each grade of comfort at different levels of dry- and wet-bulb and effective temperature, vapour pressure and the total heat content of the air on the mess-decks.

Table 1. *The effect of dry-bulb temperature on comfort sensation. Total replies*

Dry-bulb temperature range (° F.)	Total no. voting	Percentage stripped to waist	Percentage who were					Percentage who were sweating	
			M.T.W.	T.W.	C.W.	C.	C.C.		
94.0-94.9	39	100.0	64.1	35.9	0	0	0	0	92.3
93.0-93.9	109	100.0	20.2	60.6	18.3	0.9	0	0	65.1
92.0-92.9	291	100.0	15.5	67.7	15.1	1.4	0.3	0	69.1
90.0-90.9	254	100.0	12.6	57.5	27.2	2.4	0.4	0	72.0
89.0-89.9	103	100.0	7.7	55.3	33.0	3.9	0	0	50.5
88.0-88.9	35	100.0	11.4	34.4	45.7	8.6	0	0	37.2
87.0-87.9	277	89.9	9.0	31.0	49.1	9.7	1.1	0	42.6
86.0-86.9	181	92.3	1.1	26.0	50.3	21.5	1.1	0	33.7
85.0-85.9	132	59.1	0	9.1	50.8	36.4	3.8	0	12.1
84.0-84.9	124	42.7	0	6.5	46.8	36.3	10.5	0	12.9
83.0-83.9	88	54.5	0	5.7	38.6	48.9	6.8	0	12.5
82.0-82.9	53	75.5	0	3.8	30.1	52.8	13.2	0	0
81.0-81.9	54	33.3	0	1.9	29.6	57.4	11.2	0	5.6
77.0-77.9	89	26.5	0	0	9.0	43.8	44.9	2.2	0

M.T.W. = much too warm, T.W. = too warm, C.W. = comfortably warm, C. = comfortable, C.C. = comfortably cool, T.C. = too cool.

It is obvious from the distribution in relation to dry-bulb temperatures (Table 1) that the description 'comfortable' was comparatively useless for determining the upper limits of the thermal comfort zone, for at certain temperatures more than half of those who voted were either 'comfortably warm' or 'comfortably cool'. The data were therefore retabulated to show the number of votes for each temperature level in the 'zone of comfort' ('comfortably cool', 'comfortable' or 'comfortably warm'), or in the 'zone of discomfort' ('too warm' or 'much too warm'). The distributions of replies which fell within the comfort zone at various levels of dry- and wet-bulb and effective temperature in the first experiment are illustrated in Fig. 1, and the results of both investigations are summarized in Table 2.

The findings were similar except that during the 6 months between the two experiments the men had become less tolerant of the warmth and particularly of the humidity of the atmosphere. This was shown at nearly all levels of wet-bulb temperature near to the threshold level for comfort (Fig. 2). The distributions in relation to dry-bulb temperature were in much closer agreement.

The 'comfortably warm-comfortably cool' zone is fairly generous. A person will usually only report himself 'too warm' or 'too cool' when there is no doubt that he dislikes his environment. It is suggested that in terms of comfort criteria

the upper acceptable levels of warmth should be defined as those below which more than 80 % of men vote within the comfort zone, or, for these experiments, as effective temperatures of 80° and 79° F. respectively.

Table 2. *The thermal comfort zone*

	Exp.	Dry-bulb temp. of (° F.)	Wet-bulb temp. of (° F.)	Effective temp. of (° F.)	Total heat values of (B.T.H.U./lb.)	Vapour pressures of (mm.)
Less than 20 % of replies were in the comfort zone* above	1	91	82	84	40	27
	2	91	82	83	39	25
More than 50 % of replies were in the comfort zone below	1	89	81	82	38	25
	2	88	80	80	35	22
More than 80 % of replies were in the comfort zone below	1	86	80	80	35	23
	2	85	76	79	32	20

* Comfort zone: comfortable, comfortably cool, or comfortably warm.

Table 3. *Evident sweating on the face or chest*

	Exp.	Dry-bulb temp. of (° F.)	Wet-bulb temp. of (° F.)	Effective temp. of (° F.)	Total heat values of (B.T.H.U./lb.)	Vapour pressures of (mm.)
Less than 20 % noticed sweating below	1	86	80	79	35	22
	2	84	76	78	33	19
More than 50 % noticed sweating above	1	89	81	82	38	25
	2	88	79	79	34	23
More than 80 % noticed sweating above	1	94	84	85	40	27
	2	90	82	81	36	26

Sweating

The distribution of persons who reported that they were 'wet with perspiration' on their faces or chests at different levels of warmth were determined in the same way, and a similar but reversed distribution was found. The main conclusions are summarized in Table 3.

The face and chest were mentioned specifically in this question because these areas were readily accessible for examination when nearly all the subjects were stripped to the waist. A negative reply did not mean necessarily that a man was not sweating elsewhere on his body where he was wearing more clothing or where it was less exposed to a cooling and drying air current. The term 'wet' does not include 'clamminess' of the skin. Subjects were instructed, when in doubt, to test their skin surfaces with a dry finger tip and to reply 'wet' only if it was visibly moist afterwards. It is suggested that in terms of this criterion the upper acceptable levels of warmth should be defined as those below which less than 20 % of subjects report that they are wet with perspiration, or as effective temperatures of 79 and 78° F. for these observations.

The proportions of men who perceived that they were sweating and the proportions who were uncomfortably warm or reasonably comfortable at different levels

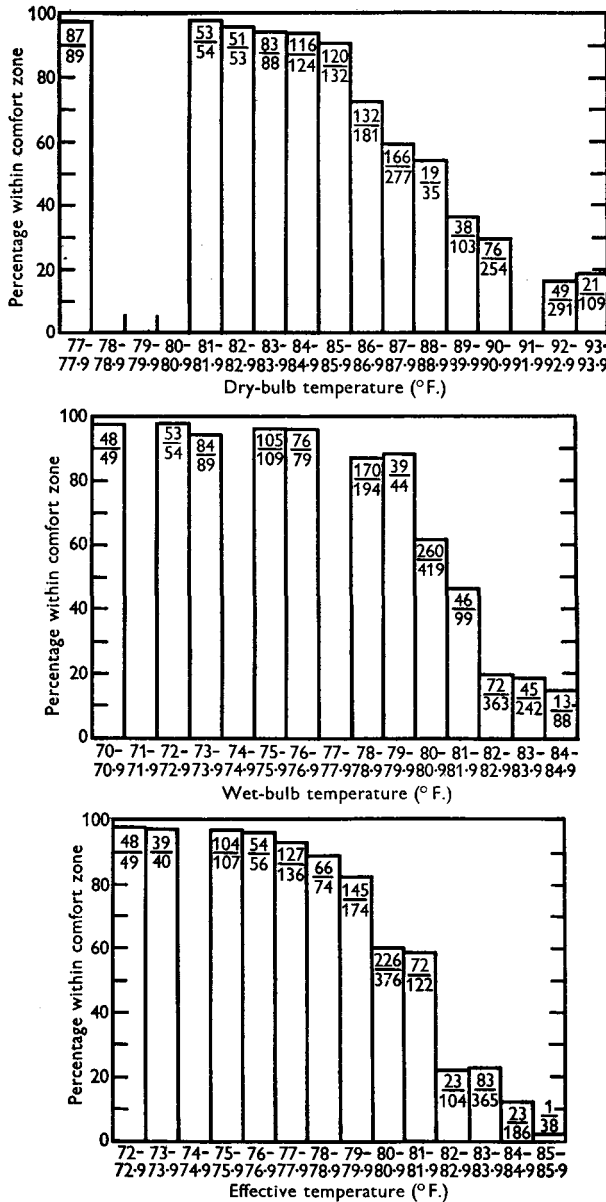


Fig. 1. Distribution of total votes falling within the comfort zone in relation to dry-bulb, wet-bulb and effective temperatures. The number of votes from which the percentages were calculated are shown on the histogram.

of air temperature, derived from the combined data of both experiments, are shown in Fig. 3. The presence of unevaporated sweat on the skin and thermal discomfort were reported by similar proportions of voters at different temperature levels. The

temperature at which approximately equal numbers were either reasonably comfortable or uncomfortably warm, and half of the voters reported sweat on their faces or chests was just above 89° F. under these conditions.

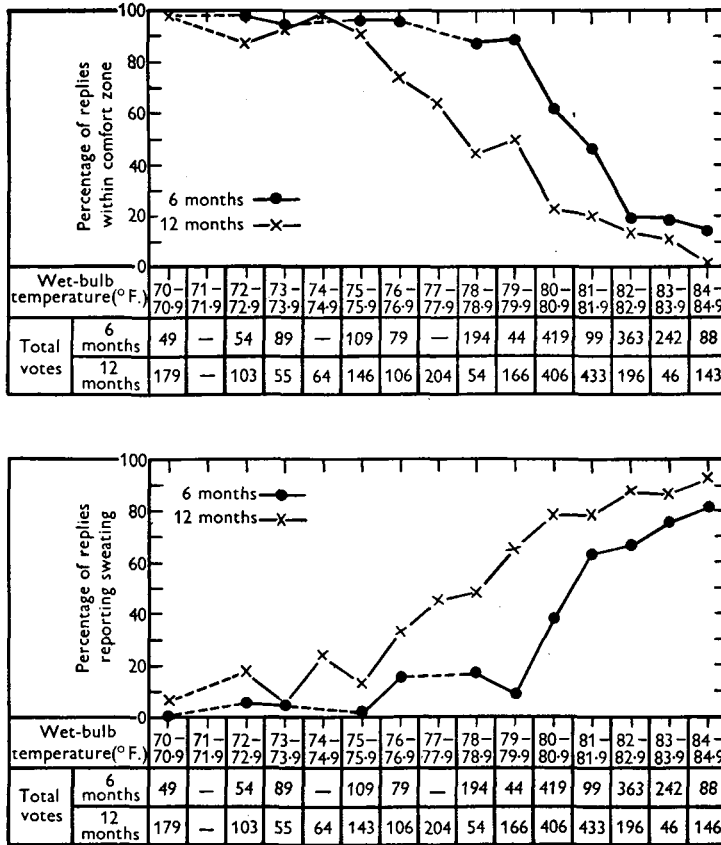


Fig. 2. Variations in comfort and sweating after 6 and 12 months residence in a hot humid climate.

Clothing

The amount of clothing a man chooses to wear provides another useful indication of whether he finds the environment cooler or warmer than the others in the compartment with him. Within reasonable limits ratings wore as much or as little clothing as they liked on the mess-decks. More than 80% of the subjects were stripped to the waist when the effective temperatures exceeded 80° F. in these two investigations (Table 4). In the second experiment less than 20% were stripped to the waist when the effective temperature was below 68° F. and the dry- and wet-bulb temperatures below 78 and 64° F. Approximately one-third of the subjects were still stripped to the waist in the first experiment when the dry- and wet-bulb temperatures lay below 82 and 73° F. and the effective temperature below 73° F.

It was fortunate that when each experiment commenced nearly all the subjects were stripped to the waist. Hardy & Oppel (1937), who used radiant heat as a stimulus, have demonstrated that the quality of warmth perception is influenced markedly by the area of skin exposed. Small areas, less than 7 sq.cm., required a rate of radiation so intense that pain resulted upon exposure of a larger area to the same stimulus. When the minimum stimulus for the face was applied to the whole body surface the subject perceived a marked sensation of warmth. If these

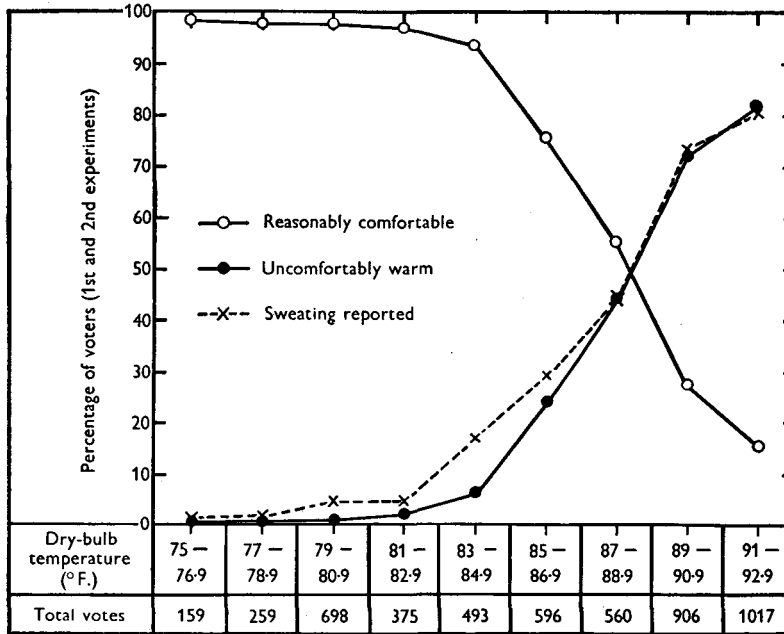


Fig. 3. Comfort and sweating at different levels of air temperature. *Note.* Reasonably comfortable includes all 'comfortably warm', 'comfortable' and 'comfortably cool' votes. Uncomfortably warm includes all 'much too warm' and 'too warm' votes. Each point plotted represents the average over a range of 2° F.

Table 4. *Levels of warmth when shirts were discarded*

	Exp.	Dry-bulb temp. of (° F.)	Wet-bulb temp. of (° F.)	Effective temp. of (° F.)	Total heat values of (B.T.H.U./lb.)	Vapour pressures of (mm.)
More than 80 % were stripped to the waist above	1	86	79	80	36	23
	2	88	78	80	36	22

naval ratings had been more fully clothed they would have given less accurate interpretations of variations in their sensations of warmth, and the presence of sweating would also have been more difficult to detect.

The relative effects on comfort of wearing or not wearing a shirt at different levels of warmth could not be determined because the choice either way was entirely voluntary and dictated by a man's own views as to what was comfortable

or uncomfortable. 'Warmth sensitive' individuals discarded their shirts at cooler temperatures than the others; whereas 'cold sensitive' men kept on wearing a shirt or vest when most of the others were stripped to the waist.

Air movement

At the levels of warmth under investigation air movement is usually imperceptible to a person if the average velocity is less than 100 ft./min. It is just perceptible at velocities between 100 and 200 ft./min., and easily perceptible when 200 ft./min.

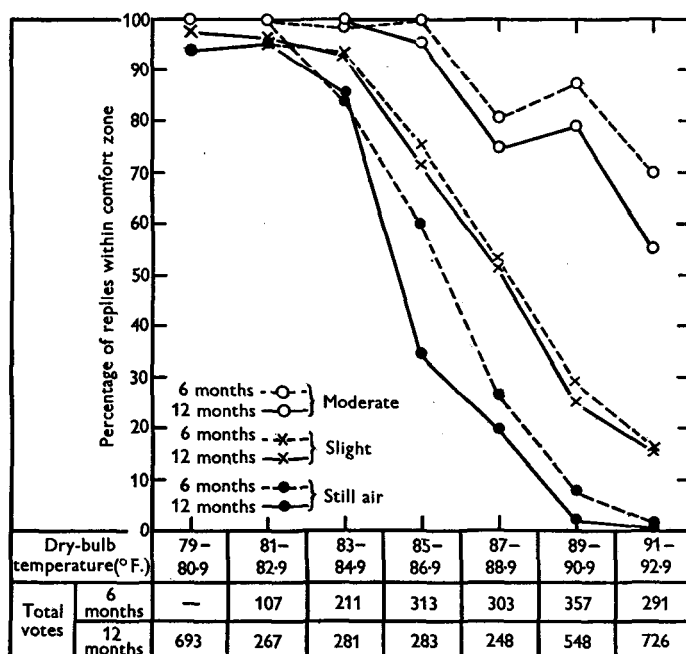


Fig. 4. Effect of air movement on comfort at various levels of dry-bulb temperature after 6 and 12 months service in a warm climate.

is exceeded. The average air movement on the mess-decks was estimated from the readings of the silvered katathermometer and was found to be between 140 and 150 ft./min. for each experiment. Seventy per cent of the voters in each investigation reported that the air movement was 'slight'. The remaining votes were divided fairly evenly between those who thought that the air movement was negligible or moderately good. Practically nobody reported very good air movement. All effective temperatures referred to here were derived for an average air velocity of 100 ft./min.

When the comfort votes are grouped according to the air movement characteristics identified by the subjects, and sorted in relation to variations in dry-bulb temperature, it is seen that variations in air movement have a marked influence on comfort (Fig. 4). Increasing the air movement greatly increased the proportion of those who felt comfortable above 85° F., whereas nearly everyone was reasonably

comfortable whatever the air movement below 83° F., but it is important to remember that really 'still' air (below 20 ft./min.) was encountered very rarely on the mess-decks. Most men found dry-bulb temperatures between 89 and 91° F. comfortable when the air movement was moderately good (air velocity probably between 200 and 400 ft./min.), whereas when the air was 'still' (air velocity probably between 20 and 100 ft./min.) less than 10% were comfortable.

The agreement between the results of the two experiments was so close that it was not possible to plot the proportions of votes in the comfort zone for 'all air velocities', as they were almost exactly superimposed, and corresponded closely to the curves for slight air movement.

The incidence of observed sweating over this temperature range was also consistently lower at high than at low air movements, until the dry-bulb temperature lay below 83° F. and the wet-bulb below 75° F., when very few men reported sweating.

Diurnal variations

It was suggested by several subjects taking part in the second experiment that, as they usually worked more vigorously in the morning and most of them (60%) were in the habit of taking their tots of rum with their midday meal, frequently before they filled in the forms, there might be a considerable difference between the average opinions as to the most comfortable air temperature at midday and in the evening. This possibility was examined by comparing the relative proportions of men who were reasonably comfortable or wet with unevaporated sweat at various dry- and wet-bulb temperatures during the midday and evening visits. It was concluded that this factor had little effect on the zones of warmth considered to be comfortable by this group of men.

Previous climatic experience

The possibility that rather more than a week of relatively cool weather in Japanese waters might have modified the comfort reactions of the subjects to variations in warmth was explored by comparing the proportions of replies within the comfort zone, or reporting unevaporated sweat on the skin, at the different levels of dry- and wet-bulb temperature encountered during the warm first and third periods at the beginning and end of the second experiment. There was no indication that this short sojourn in a cooler climate had affected the average opinion concerning the levels of warmth at which the men were reasonably comfortable.

Acceptable levels of warmth

According to the two criteria suggested above the upper acceptable levels of warmth, determined from a total of 5211 replies examined in both experiments, were an effective temperature of 79° F. for 'comfort' and 78° F. for 'sweating' (Table 5). This agrees also with the findings of the second and larger experiment, which was carried out half way through a 2-year commission in the tropics.

It should be remembered that these subjects were mostly at rest around their mess-tables when they filled in their questionnaires. Many of them were stripped

to the waist. As soon as they began to wear more clothing as a prelude to going ashore or for any other reason, or became more active, the threshold level of warmth for comfort would be lowered. On the basis of these findings it is suggested that designers should aim to keep the warmth of the thermal environment on the mess-decks in the tropics below the effective temperature of 78° F. to ensure that men engaged in sedentary or light activities shall be reasonably comfortable.

Table 5. *Acceptable level of warmth from combined data of first and second experiments*

	Dry-bulb temp. of (° F.)	Wet-bulb temp. of (° F.)	Effective temp. of (° F.)
More than 80 % of replies were in the comfort zone below	86	77	79
Less than 20 % reported sweating below	84	76	78

Upper limit of the optimum zone for thermal comfort

This arbitrary system for grading comfort sensations may be used to determine the most desirable levels of warmth for the majority of men, or the thermal conditions in relation to which the proportions of persons who are cool ('comfortably cool', 'too cool' or 'much too cool') are balanced by the proportions who declare that they are warm ('comfortably warm', 'too warm' or 'much too warm'), the remainder having stated that they are 'comfortable'. During the first experiment shortage of observations prevented the identification of the upper level of this zone with accuracy, but it appeared that it lay between the effective temperatures of 74 and 75° F., when about a third of the subjects were stripped to the waist. If they had all worn shirts it was estimated that maximum comfort would probably have been experienced by the majority when the effective temperature was lowered to between 73 and 74° F.

The second experiment provided more precise information (Fig. 5). Approximately equal numbers of persons were either cool or warm when the effective temperature was between 71 and 74° F. and about 25 % were stripped to the waist; and the proportion of those who were warm rather than cool steadily increased as the effective temperature rose above 74° F. and the dry- and wet-bulb temperatures exceeded 80 and 69° F. respectively, even though increasing numbers of men discarded their shirts. Under the conditions of these experiments the upper limit of the optimum zone for comfort was therefore an effective temperature of 74° F.

DISCUSSION

The designers of warship ventilation systems cater primarily for sedentary or light workers and should provide an optimum thermal environment for this level of physical activity in the domestic quarters, other than galleys, bakeries and serveries, and in most of the offices, communications compartments, stores and light workshops. When heavy physical exertion is necessary for storing or

ammunitioning ship, scrubbing the deck, or repairing heavy machinery, it is out of the question to base recommendations concerning the ventilation requirements on criteria which relate to thermal comfort. Gun's crews handling ammunition or working turret machinery require special arrangements to provide them with a thermal environment which will permit them to maintain a satisfactory supply

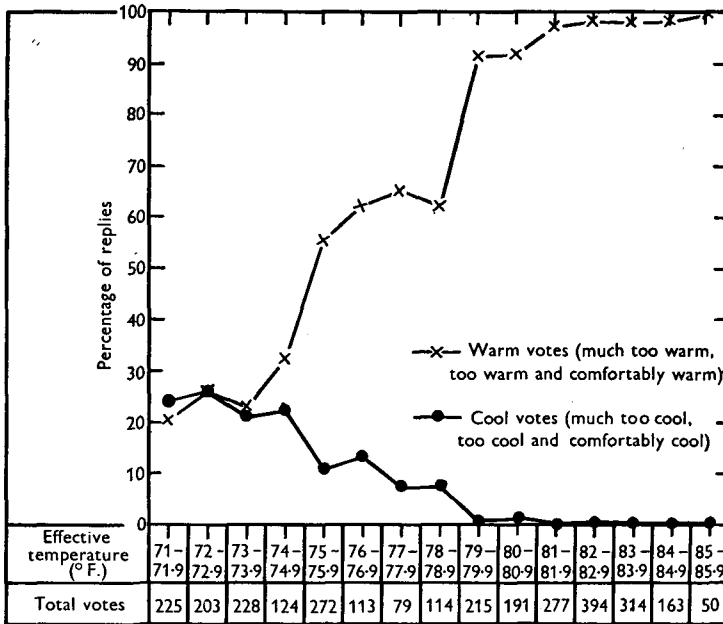


Fig. 5. Optimum comfort in relation to effective temperature.

of ammunition and rate of fire. This discussion is not concerned with these situations, but with the normal living and working environment of men who engage in sedentary or light occupations between decks in the tropics.

The most important difference between the results of the second experiment and the one carried out 6 months previously is that during the intervening period the men had become less tolerant of the warmth and particularly of the humidity of the atmosphere. Apart from this, the close relationship between the onset of thermal discomfort and the recognition of unevaporated sweat on the skin in the two investigations, the responsiveness of the average thermal comfort sensation to mild alterations in the warm humid climate, and the clear illustration of the beneficial effects of good air circulation within compartments when the air temperature exceeded 83° F. are in satisfactory agreement.

A person's ability to describe his sensations of warmth in terms of this arbitrary scale for assessing comfort becomes more critical with practice. A common tendency for the beginner is to describe himself as comfortably warm or comfortably cool at levels of warmth which he later considers to be too cool or too warm when he is more practised in discriminating between different sensations. During the first investigation the subjects only had the opportunity to vote on fourteen

occasions and only about half of the available community voted on each visit. Their experience of the method was slender even by the end of the experiment. In the second experiment, four-fifths of the subjects were indoctrinated before it began and each mess-deck was visited thirty-five times. Nearly twice the number of replies were available for analysis. The results of this experiment are therefore more reliable.

The observation during the second experiment that the wet-bulb temperature threshold for comfort, or for the recognition of unevaporated sweat, was lowered for similar proportions of the ratings who voted requires an explanation. It is possible that the first group failed at times to observe that they were sweating; or that on the average, as a result of an additional 6 months service in the tropics by most of the second group, the onset of sweating or output of sweat for the whole group was facilitated or increased, so that the presence of unevaporated sweat was recognized at lower wet-bulb temperatures than in the first experiment. The second alternative is the more likely one. The presence on the skin of unevaporated sweat at lower levels of warmth would contribute to the slightly lower threshold for acceptable comfort which was observed. Very few men reported that they were sweating in either experiment if the dry- and wet-bulb temperatures lay below 83 and 75° F. and the normal effective temperature below 77.5° F. (basic 75° F.), when about half were stripped to the waist. The estimated upper limit of the optimum comfort zone (74° F. E.T.) was, however, similar in both experiments. Intolerance of humidity was thus increased in the second experiment only on the fringe of the comfort zone. In other words, some men who previously were comfortably warm now felt too warm when they were exposed to the same environmental conditions, and more of them were aware of unevaporated sweat on the skin. It has been established that during the first few weeks when men are becoming acclimatized to living and working in a hot environment the onset of sweating is facilitated and output becomes more profuse. It may be that sweat secretion is stimulated by lower levels of warmth when persons reside continuously for long periods in warm and humid atmospheres than when they are relatively new arrivals in the tropics.

The upper acceptable level of warmth of 78° F. effective temperature, suggested for men engaged in sedentary or light occupations, agrees with Sims's (1945) estimate of the requirements in the design of ventilation arrangements for occupied compartments of warships in the tropics, and was the upper permissible limit accepted by the United States Navy during the last war. It is on the conservative side of the corrected effective temperature of 80° F. which the Royal Naval Personnel Research Committee provisionally recommended should not be exceeded if loss of efficiency was to be avoided (Bedford, 1946). It also corresponds closely to the indoor effective temperature of 77.5° F. (dry-bulb 85° F.) which according to Grocott (1948) is accepted after 20 years experience as the upper limit for comfort in the design of plant for the 'comfort-cooling' of staff houses and other buildings of the Anglo-Iranian Oil Company in Iran, where an annual indoor temperature range of 75 to 83° F. nowadays corresponds to outdoor temperatures of 95 to 125° F. This raises the interesting possibility that when adequate means for

climate control are available, the upper desirable limit for indoor warmth may be similar for warm humid and warm dry climates.

The effective temperature of 74° F. which was the upper limit of the optimum zone for comfort in this ship approaches the levels of warmth which are accepted as the optimum for summer comfort by the American Society of Heating and Ventilating Engineers. This Society's Committee on Sensations of Comfort (1942) reviewed experiments carried out in Toronto, Minneapolis, Pittsburgh, New York, Washington and San Antonio and concluded that, for the purpose of designing air-conditioning equipment for homes and offices in the summer, the United States should be divided geographically into four zones from north to south for which they recommended indoor effective temperatures of 70, 71, 72 and 73° F. for persons wearing normal indoor clothes. Yaglou & Messer (1941) record elsewhere that

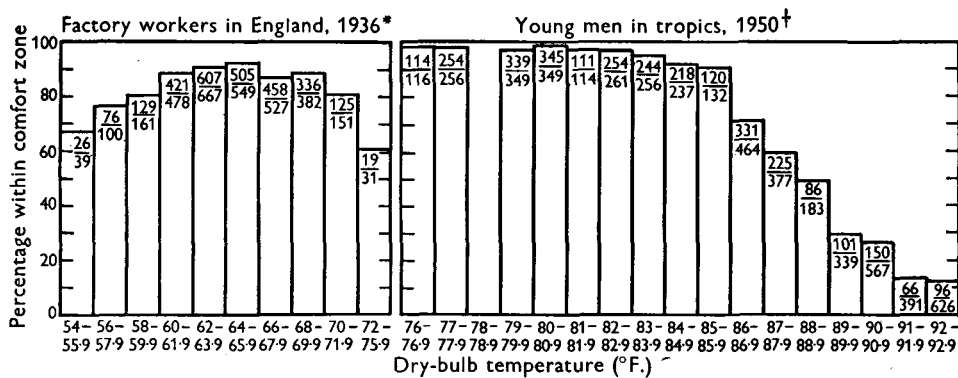


Fig. 6. The comfort zones in relation to air temperature for normally clad factory workers in England and lightly clad young men in a warship in the tropics. The votes within the comfort zone and the total votes for each temperature are shown on the histogram. * Bedford (1936). † Combined data of both experiments in the aircraft-repair ship.

during the summer in Boston men and women, who had been wearing a minimum of clothing in an air-conditioned room for 2 hr. at rest, were comfortable when the effective temperature was between 74 and 75° F. (82.3° F., R.H. 52%; 82.7° F., R.H. 48%). British and American opinion is thus in close agreement concerning the most comfortable levels of warmth for persons living in warm climates.

The difference between the conditions which are comfortable in English factories during the winter (Bedford, 1936) and those accepted by these naval ratings in the tropics is illustrated in Fig. 6. Apart from the wide difference in the air temperatures which most of the subjects found comfortable, warmth sensation appears to be stimulated by more narrow variations in temperature in the tropics where persons are lightly clad, than in the more temperate parts of the world where more clothing is worn. Whereas an increase in air temperature from between 54 and 56° F. to between 64 and 66° F. in English factories caused a reduction of only 25% in the proportions of persons voting within the comfort zone, a rise in temperature from between 84 and 85° F. to between 91 and 92° F. in the tropics reduced the numbers who were reasonably comfortable by 75%. As the average difference

between the air temperatures on the upper deck and on the mess-decks of a warship is also about 7° F. (Ellis, 1948), some idea may be gained of the increased thermal discomfort which results from living afloat in the tropics instead of ashore where the temperatures indoors are usually little different from those of the outside air.

The effects of different levels of effective temperature on the efficiency of naval ratings engaged for a few hours on work requiring sustained attention, concentration or skill were investigated by Mackworth (1945*a*, *b*, 1946, 1948, 1950) at Cambridge, with tests of ability in tracking (pointer following), in visual search (sustained alertness in monotonous surroundings), and in morse reception (high

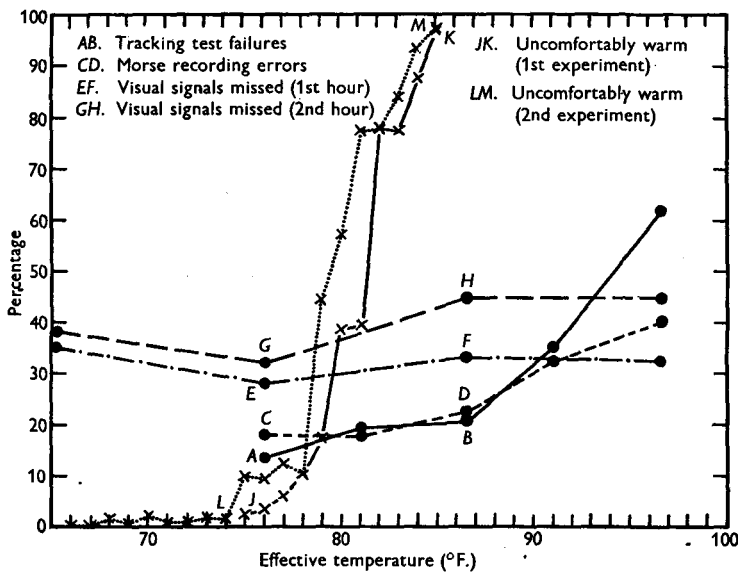


Fig. 7. Effects of varying levels of warmth on thermal discomfort in the tropics and the skill of artificially acclimatized men at Cambridge (Mackworth, 1950).

speed semi-automatic work). His subjects were stripped to the waist and 'artificially acclimatized' to heat by physical exercise at high temperatures for a few hours daily for several weeks before the experiments commenced. The standard of their performance was lowered to a degree which was statistically significant when the effective temperature (basic) of their environment was changed from 76° F. (Fig. 7, *ACEG*) to 86° F. (*BDFH*). In the experiments in this aircraft-repair ship only 10% of these 'naturally acclimatized' subjects were uncomfortably warm when the effective temperature was 78° F. (*LM, JK*), but 97% were uncomfortably warm when it was 85° F., which suggests that there might be a relationship between thermal discomfort and deterioration in efficiency.

Recently, however, Pepler (1951) employed experimental techniques similar to those used by Mackworth to examine the reactions to high temperatures of men accustomed to living in Singapore. He confirmed that deterioration in performance might occur as the environmental warmth of the operator increased within the temperature zone identified by Mackworth, but showed that the climatic zone

over which efficiency could be maintained for periods of 2 or 3 hr. varied with different working conditions from an effective temperature of 66° F. for the fairly strenuous non-automatic tracking test to an upper limit of 96.5° F. when highly skilled operators carried out the sedentary, but largely automatic, morse reception test. The level of warmth at which efficiency deteriorated varied with the ability, training and motivation of the subject, the energy cost and the difficulty of the task, and with the humidity of the atmosphere. The zone of increasing thermal discomfort identified above lies approximately in the middle of this expanded zone. The majority of Pepler's subjects attributed loss of efficiency under the warmest conditions in the tracking test to distractions and interference due to sweating, but such distractions did not spoil the performance of the expert in *high-speed morse reception*, although the efficiency of less highly skilled operators was impaired. It would appear that thermal discomfort is more likely to interfere with the performance of work which has not a considerable automatic or repetitive component, and if the operator is not highly trained. Much of the work in a ship falls into this category. The evidence available from the experiments carried out so far thus supports the contention that ventilation standards based on comfort criteria will be consistent usually with the maintenance of efficiency by the average sedentary worker on duty, as well as with his comfort when he is off duty on the mess-decks.

SUMMARY

Naval ratings serving in a warship in the tropics answered a questionnaire concerning their sensations of warmth at meal times on the mess-decks during two investigations carried out at an interval of 6 months when the ship was proceeding between tropical and more northerly waters. Temperature measurements were recorded at the same times as the questionnaires were completed by the subjects.

It is proposed that the upper level of warmth to be accepted in the design of ventilation systems for accommodation spaces should be those conditions when either more than 80% of persons feel reasonably comfortable or less than 20% observe the presence of unevaporated sweat on their skin, which corresponds to effective temperatures of 79 and 78° F. respectively, according to the majority opinion in these two investigations. The latter figure of 78° F. is suggested as the upper level to be accepted for men living under these conditions.

The upper level of the optimum or ideal zone for comfort, when equal proportions of persons reported that they were either cool or warm, was observed to be at 74° F. effective temperature.

The proportions of men who were uncomfortably warm at different levels of warmth were related to the proportions who reported that their skin was wet with unevaporated sweat. Very few observed that they were sweating, whatever the air velocity or their clothing, when the dry-bulb temperature was below 83° F., and the wet-bulb temperature below 75° F.

Brisk circulation of the air on the mess-decks made an increasingly large contribution to the comfort of these very lightly clad men as the air temperature rose from 85 to 89° F., but as the temperature fell below 83° F. variations in air

movement had little effect on the proportions of persons who were reasonably comfortable under these warm conditions.

Thermal discomfort was reported by an increasing number of men within a temperature zone where others have shown by experiment that there will occur a statistically significant decrease in the skilled performance of men who are acclimatized to working at high temperatures.

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